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Burning wood pellets for US electricity generation? A regime switching analysis

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ABSTRACT

Applying a regime switching model under the theoretic framework of real options, we inspect the optimal timing boundaries for coal and coal mixed wood pellets as two alternative fuels for a power plant in Georgia, United States. Results indicate that cofiring wood pellets with coal is generally not a commercially viable option. However, lower-level (with wood pellets < 15%) cofiring could have been feasible during the infancy period (2009–2011) when wood pellet price was declining. Sensitivity analysis shows that our conclusions are robust and the most important factors are relative prices of coal and mixed fuel. Therefore, we reject the null hypothesis that cofiring is economically feasible and suggest using policy vehicles to stimulate the bioenergy market and meet the greenhouse gas emission reduction target. In particular, a subsidy of \$1.40/mmbtu to the 10% mixed fuel or a tax of \$1.50/mmbtu on coal would prompt the conversions of coal-only power plants to cofiring ones, and a subsidy of \$0.45/mmbtu to the 10% mixed fuel or a tax of \$0.50/mmbtu on coal would maintain existing cofiring power plants in the status quo.

1. Introduction

Historically, coal is the major fuel type for power plants. Electricity generated from coal-fired power plants accounts for >40% and 39% globally and within the United States, respectively (EIA, 2016). On a per-unit energy basis, coal is one of the largest emitters of carbon dioxide among all fossil fuels, and coal-fired power plants represent a major source of man-made carbon dioxide emissions. To reduce greenhouse gas (GHG) emissions, most countries have set reduction targets. The world-leader in this effort is the European Union (EU) with the United Kingdom (UK) as an EU leader. In recent years, the EU in general and the UK in particular have burned an increasing amount of biomass for electricity generation. In 2015, the United States launched the Clean Power Plan aimed to lower carbon dioxide emitted by electrical power generation by 32% within 25 years relative to the 2005 level. The plan is focused on reducing emissions from coal-burning power plants, as well as increasing the use of renewable energy, and energy conservation.[1] Given the fact that electricity produced from renewable resources is <7% in the US (EIA, 2016), there remains a great expansion potential in the bioenergy market.

A typical coal-fired power plant bears a huge capital investment with a design life of 20 to 50 years. Therefore, it is usually not economical to totally abandon a coal-fired power plant and replace it with cleaner technology prior to the end of its useful life. Nonetheless, it is feasible to substitute some portion of the coal by biomass (cofire coal with biomass) so as to reduce carbon emissions. In particular, wood

[1] Specifically, the Environmental Protection Agency requires individual states to implement their plans by focusing on three building blocks: increasing the generation efficiency of existing fossil fuel plants, substituting lower carbon dioxide emitting natural gas generation for coal powered generation, and substituting generation from new zero carbon dioxide emitting renewable sources for fossil fuel powered generation. This study focuses on the last one.

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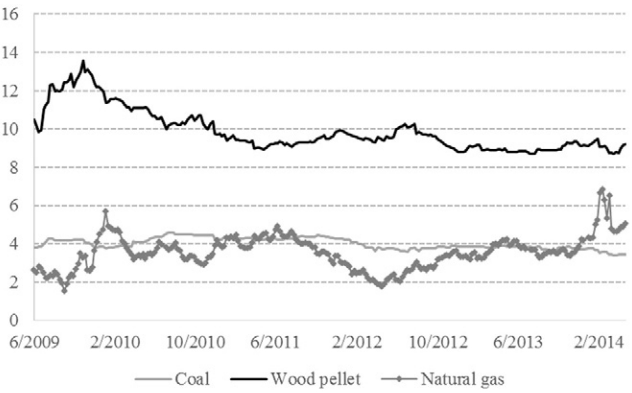

Fig. 1. Weekly real energy prices ($/mmbtu) for 06/05/2009–04/25/2014. Deflator: PPI for crude material, base time period January 2013.

pellets[2] are easily adaptable to automated combustion systems and the cost to convert existing coal boilers to mixed fuel burning is less prohibitive than plant retirement (Zhang et al., 2010). The saving of GHG emissions from wood pellets ranges from 72.6% to 82.4% for each kWh of electricity (Dwivedi et al., 2011). Within the EU and specifically in the UK, many power plants are cofiring wood pellets with coal as a transition option toward a carbon-free power sector. This has created a rapidly growing international market for wood pellets. Given the high productivity of the forest sector in the US Southeast, much of this market is supplied by southeastern wood pellet mills (Spelter and Toth, 2009). Forisk Consulting (2015) projects that US wood pellet production could grow from about 5 million tons in 2009 to near 18 million tons by 2018, of which, 97% would be intended for export markets.

Corresponding to the expanded supply, real wood pellet prices have been generally declining from 2009 to 2012 and since stabilized (Fig. 1). In the same period, coal prices have steadily declined, primarily because of the competition from declining natural gas prices, resulting from the advent of commercially viable hydraulic fracturing technologies and horizontal drilling methods. In terms of price volatility, both wood pellet and natural gas exhibit higher variations than coal. Therefore, an intriguing question for coal power-plant managers is how to make the optimal decision on fuel selection. In the energy economics literature, a few studies have examined this issue. Specifically, applying real options analysis, Pederson and Zou (2009) evaluate ethanol plant investments; Lee and Shih (2010), Lima et al. (2013), and Monjas-Barroso and Balibrea-Iniesta (2013) study solar- and wind-energy projects; Song et al. (2011), and Gazheli and Corato (2013) examine the conversion option of traditional farmland for energy crops; Bednyagin and Gnansounou (2011), Detert and Kotani (2013), and Zambujal-Oliveira (2013) investigate the investment decisions among combined-cycle, coal-fired, wind, solar, and nuclear power plants; Cheng et al. (2011) assess the clean-energy mix policy; and Siddiqui and Fleten (2010) analyze the staged commercialization and deployment of alternative energy technologies.

Past research on wood pellets mainly focuses on decentralized household heating systems (e.g., Claudy et al., 2011; Hyysalo et al., 2013; Michelsen and Madlener, 2012). Studies on wood pellets for electricity generation, however, have been limited. Steininger and Voraberger (2003) employ a computable general equilibrium model of the Austrian economy and demonstrate that fostering the use of cofiring could lead to a decline in both gross domestic product (GDP) and employment. Ehrig and Behrendt (2013) assert that cofiring wood pellets with coal represents one of the most cost-attractive ways to reach the EU-2020 carbon targets. Dwivedi et al. (2014) reveal that the use of wood pellets for electricity generation could reduce the UK's GHG emissions by 50–68% relative to fossil fuels. Xian et al. (2015) account for uncertain energy markets and examine the economic feasibility of cofiring wood pellets with coal for electricity generation. In this study, we apply a regime switching model under the framework of real options analysis to investigate the economic boundary conditions between coal and coal mixed with wood pellets as the fuel for power plants. We intend to contribute to the current literature by considering reciprocal switch options between coal-only and cofiring for a power plant, and incorporating the switch cost explicitly as a function of the energy prices. Considering the shifting energy patterns in the US market (Fig. 1), we conduct analyses on two distinct periods in addition to the whole sample period. One is the infancy period (2009–2011), which is the early stage when coal prices are relatively high and wood pellet prices are declining because of initial rapid supply expansion. The other is the substitution period, when cheap natural gas undermines coal's dominance as the fuel for US power plants. The null hypothesis is that both coal-only and cofiring are economically viable options for US power plants, which solely depends on contemporary market situations but not government involvement.[3]

2. Method

Based upon the classic real options approach proposed by Dixit and Pindyck (1994), Adkins and Paxson (2011) examine the reciprocal energy-switching options and provide a quasi-analytical solution for the case of two competing energy inputs. Extending their analysis, we adopt a general regime switching model, which incorporates price uncertainty of two alternative fuels to investigate a power plant's optimal choice of the fuel type. Consider an active, perpetual operating power plant that turns the chemical energy in coal into electricity and has an option to exchange the incumbent fuel (coal) with a substitute fuel (coal mixed with wood pellets). The switch is reciprocal and incurs a known sunk cost K_{ij}, $i, j \in \{c, m\}$ and $i \neq j$.[4] Gains from a switch include the net cost saving from using cheaper fuel and the option value of switching back.

Price for fuel X_i, $i \in \{c, m\}$, is assumed to follow a geometric Brownian motion,

$$dX_i = \alpha_i X_i dt + \sigma_i X_i dz_i \tag{1}$$

where α is the drift rate, σ is the volatility rate and dz is the increment of a standard Wiener process. Correlation between the two price variables is described by $\rho(|\rho| \leq 1)$, so that $\mathrm{cov}(dX_c, dX_m) = \rho\sigma_c\sigma_m dt$. To state the valuation relationship in terms of one unit of output, price for each fuel can be adjusted by a conversion factor.[5]

The function $F_i(X_c, X_m)$, $i \in \{c, m\}$, denotes the plant value from using fuel i and the embedded switch option, which depends on prices of both the incumbent and substitute fuels. Using the dynamic programming approach, the following partial differential equation can be

[2] Wood pellets are small nuggets of compressed, sawdust-sized wood fiber that have higher energy density and lower moisture content than their raw input. The sustainability of wood pellets as feedstock for energy is largely a matter of carbon cycle calculations, which depends on the origin and type of trees used for wood pellets. We believe that burning wood pellets locally for energy is more carbon efficient than burning coal, even after accounting for the emissions for collecting and processing biomass.

[3] The EU biomass market is driven by government mandates. The same has not been mirrored in the US.

[4] Letter c for coal and m for mixed fuel (coal mixed with wood pellets). K_c denotes the conversion cost from coal to mixed fuel and K_m denotes the conversion cost from mixed fuel to coal. For example, for a coal-burning power plant to burn wood and meet emission requirements, some accommodations to facility operation and physical structure are necessary, including ash and air emission control, hard coating cleaning, wood storage, and grinding and blowing systems.

[5] 1 kWh = 0.0034 mmbtu.

obtained

$$\frac{1}{2}\sigma_c^2X_c^2\frac{\partial^2 F_i}{\partial X_c^2}+\frac{1}{2}\sigma_m^2X_m^2\frac{\partial^2 F_i}{\partial X_m^2}+\rho\sigma_c\sigma_mX_cX_m\frac{\partial^2 F_i}{\partial X_cX_m} + \alpha_cX_c\frac{\partial F_i}{\partial X_c}+\alpha_mX_m\frac{\partial F_i}{\partial X_m}-\mu F_i+Y-X_i=0 \quad (2)$$

where μ is the discount rate, and Y is the output (electricity) price net of operating costs. The generic valuation function F_i takes the form

$$F_i(X_c,X_m)=A_iX_c^{\beta_i}X_m^{\eta_i}+\frac{Y}{\mu}-\frac{X_i}{\mu-\alpha_i} \quad (3)$$

where A ($A\geq 0$), β and η are unknown parameters of the product power function. The first term in Eq. (3) represents the option value of switching fuel inputs, and the last two terms represent the value of operation without any switch option. By applying the limiting boundary conditions, it can be shown that

$$F_c=A_{c4}X_c^{\beta_{c4}}X_m^{\eta_{c4}}+\frac{Y}{\mu}-\frac{X_c}{\mu-\alpha_c} \quad (4)$$

$$F_m=A_{m2}X_c^{\beta_{m2}}X_m^{\eta_{m2}}+\frac{Y}{\mu}-\frac{X_m}{\mu-\alpha_m} \quad (5)$$

where $\beta_{c4}>0, \eta_{c4}\leq 0, \beta_{m2}\leq 0$, and $\eta_{m2}>0$. Using the value-matching conditions, smooth-pasting conditions, and the two characteristic root equations, a system of eight equations can be established and the switch timing boundaries can be determined numerically. The price ratios along the two discriminatory boundaries are given by

$$W_{cm}=\frac{X_c}{X_m}>1 \text{ and } W_{mc}=\frac{X_m}{X_c}>1 \quad (6)$$

where W_{ij} designates the price ratio when fuel i currently in use should be replaced by fuel j. Imposing the property of homogeneity of degree one on the value functions (i.e., $\beta_{c4}+\eta_{c4}=1$ and $\beta_{m2}+\eta_{m2}=1$) and the conversion cost function, the value-matching and the smooth-pasting conditions are

$$A_{c4}W_{cm}^{\beta_{c4}}-\frac{W_{cm}}{\mu-\alpha_c}=A_{m2}W_{cm}^{\beta_{m2}}-\frac{1}{\mu-\alpha_m}-k_cW_{cm}^{\phi_c} \quad (7)$$

$$A_{m2}W_{mc}^{1-\beta_{m2}}-\frac{W_{mc}}{\mu-\alpha_m}=A_{c4}W_{mc}^{1-\beta_{c4}}-\frac{1}{\mu-\alpha_c}-k_mW_{mc}^{\phi_m} \quad (8)$$

$$\beta_{c4}A_{c4}W_{cm}^{\beta_{c4}-1}-\frac{1}{\mu-\alpha_c}=\beta_{m2}A_{m2}W_{cm}^{\beta_{m2}-1}-\phi_ck_cW_{cm}^{\phi_c-1} \quad (9)$$

$$(1-\beta_{m2})A_{m2}W_{mc}^{-\beta_{m2}}-\frac{1}{\mu-\alpha_m}=(1-\beta_{c4})A_{c4}W_{mc}^{-\beta_{c4}}-\phi_mk_mW_{mc}^{\phi_m-1} \quad (10)$$

where k_i and ϕ_i are parameters in the conversion cost function $K_{ij}=k_iX_i^{\phi_i}X_j^{1-\phi_i}$, and the implied characteristic root equation has closed-form solutions for β_{c4} and β_{m2}

$$\beta_{c4}=\frac{1}{2}-\frac{\alpha_c-\alpha_m}{\sigma_H^2}+\sqrt{\left(\frac{1}{2}-\frac{\alpha_c-\alpha_m}{\sigma_H^2}\right)^2+\frac{2(\mu-\alpha_m)}{\sigma_H^2}}>0, \quad (11)$$

$$\beta_{m2}=\frac{1}{2}-\frac{\alpha_c-\alpha_m}{\sigma_H^2}-\sqrt{\left(\frac{1}{2}-\frac{\alpha_c-\alpha_m}{\sigma_H^2}\right)^2+\frac{2(\mu-\alpha_m)}{\sigma_H^2}}<0, \quad (12)$$

where $\sigma_H^2=\sigma_c^2-2\rho\sigma_c\sigma_m+\sigma_m^2$. Eqs. (7)–(10) can be solved numerically.

The conversion cost is an increasing function of ϕ_i, which indicates the relative importance of the two price levels in determining the converting cost ϕ_i. When ϕ_i approaches one, the conversion cost almost only depends on the price of the incumbent but not the substitute fuel. That is, when $\phi_i=1$ the conversion cost is proportional to the price of the incumbent, prevailing fuel but not the potential substitute because of the lack of production using the latter during the transition period.

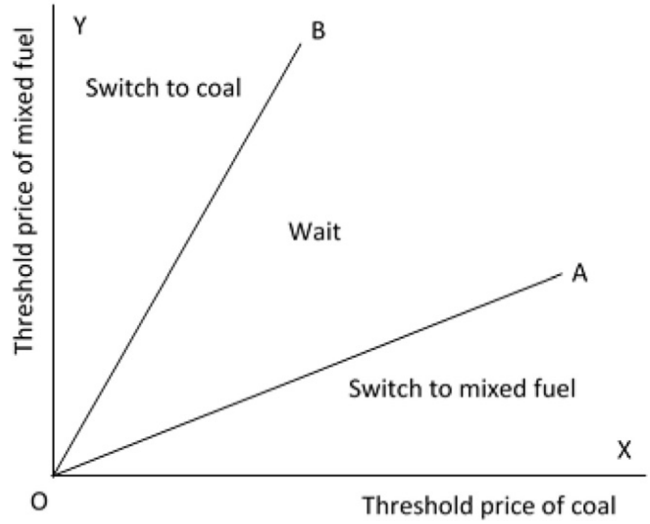

Fig. 2. Switching boundaries between two fuel types for a power plant.

The optimal switch decisions can be illustrated in Fig. 2. The locus OA denotes the optimal switching boundary from coal as the current fuel to mixed fuel as the substitute, whereas the locus OB denotes that from mixed fuel as the current fuel to coal as the substitute. If a price pair falls into the region OAX and the incumbent fuel is coal, it is optimal to switch to mixed fuel. Instead, if a price pair falls into the region OBY and the incumbent fuel is mixed fuel, it is optimal to switch to coal. Therefore, the continuance region is OAY if the incumbent is coal and OBX if the incumbent is mixed fuel.

3. Data and variable description

All energy prices, expressed as of \$/mmbtu, are of weekly frequency and range from June 5, 2009 to April 25, 2014. Coal prices of US Central Appalachian are used because >33% of total coal burned by power plants in the Southeast is supplied by this region. Natural gas prices of the Henry Hub are used because of its importance to the North American natural gas market. Both coal and natural gas prices are obtained from US Energy Information Administration (EIA, 2016). Wood pellet prices (energy density 17 GJ/ton and free on board US southeast) are from Argusmedia (2015). All prices are deflated by the Producer Price Index (PPI) for crude material and stated in January 2013 dollars. A transportation cost of \$1.15/mmbtu, which is the average railway cost from Central Appalachian to Atlanta, Georgia in 2013 (EIA, 2016),

Table 1
Summary statistics of real energy prices in \$/mmbtu.

Fuel type	Whole period		Infancy period		Substitution period	
	2009–2014		2009–2011		2012–2014	
	Mean	SD	Mean	SD	Mean	SD
Coal	4.01	0.29	4.22	0.21	3.77	0.15
Natural gas	3.54	0.88	3.61	0.76	3.45	0.99
Wood pellet	9.89	1.09	10.47	1.18	9.23	0.40
WP10	4.67	0.31	4.92	0.17	4.38	0.14
WP15	5.01	0.34	5.28	0.19	4.70	0.15
WP25	5.70	0.41	6.01	0.28	5.34	0.16

Note: Price deflator is PPI for crude material with January 2013 as the base. WP10, WP15, and WP25 represent 10%, 15%, and 25% wood pellet cofiring with coal, respectively.

Table 2
Parameter estimates of the geometric Brownian motion for real energy prices in \$/mmbtu.

Fuel type	Whole period			Infancy period			Substitution period		
	2009–2014			2009–2011			2012–2014		
	α	σ	ρ	α	σ	ρ	α	σ	ρ
Coal	−0.009	0.103	1.000	0.050	0.100	1.000	−0.075	0.105	1.000
Wood pellet	−0.011	0.123	0.327	−0.001	0.149	0.348	−0.019	0.085	0.329
WP10	−0.013	0.093	0.959	0.035	0.095	0.942	−0.065	0.090	0.981
WP15	−0.014	0.091	0.915	0.029	0.096	0.886	−0.061	0.085	0.957
WP25	−0.015	0.092	0.808	0.021	0.102	0.765	−0.053	0.079	0.886

Note: WP10, WP15, and WP25 represent 10%, 15%, and 25% wood pellet cofiring with coal, respectively.

Table 3
Description of the variables used in the regime switch analysis.

Symbol	Definition	Value
μ	Discount rate for US power plants	0.08
k_c	Parameter of the conversion cost function from coal to mixed fuel	0.5
k_m	Parameter of the conversion cost function from mixed fuel to coal	0.5
ϕ_c	Parameter of the conversion cost function from coal to mixed fuel	1
ϕ_m	Parameter of the conversion cost function from mixed fuel to coal	1
Y	Electricity price net of operating costs	0.050
X_c	Coal price	0.014
X_m	Mixed fuel price (10% wood pellets)	0.016
	Mixed fuel price (15% wood pellets)	0.017
	Mixed fuel price (25% wood pellets)	0.019

Note: Real prices are in \$/kWh.

is added to the real price of coal to make it comparable to wood pellet price.

Mixed fuels are defined as 10%, 15%, and 25% of wood pellets cofiring with coal. Their price series (X_{mi}) are weighted averages of wood pellet (X_w) and coal (X_c) prices, and adjusted for fuel efficiency

$$X_{mi} = \lambda_i[w_{wi}X_w + (1-w_{wi})X_c] \tag{13}$$

where w_{wi} is the share of wood pellets in the cofiring and λ_i is the efficiency multiple defined as the ratio of coal-to-electricity efficiency over mixed-fuel-to-electricity efficiency. The net efficiency of coal-to-electricity is 32.67% based on the average heat rate of 10,444 btu/kWh of a coal power plant (EIA, 2016). The efficiency loss for low level cofiring is about 0.5% per each 10% of wood pellet input (Robinson et al., 2003). Therefore, the efficiency multiples for 10%, 15%, and 25% wood pellet cofiring are 1.016, 1.024, and 1.040, respectively.

Summary statistics of energy prices are reported in Table 1. Over the whole sample period, wood pellet has the highest average price and volatility, and natural gas has the lowest average price but a relative moderate volatility. Blending more wood pellets with coal increases the mixed fuel cost and volatility. Note that the impact on volatility is less than proportional, given wood pellet prices are not perfectly correlated with coal prices. Considering the overall evolvement of the energy market, two sub-sample periods are investigated. In the infancy period, 2009–2011, US wood pellet production was primarily consumed domestically for home heating (EIA, 2016). In contrast, during the substitution period, 2012–2014, wood pellet exports from the United States to the EU increased dramatically and relatively cheap natural gas began to substitute coal in US power plants. Energy prices in the substitution period are lower than those in the infancy period resulting from a more intense competition of alternative fuels in the energy market. In addition, the volatility of mixed fuel in the two sub-samples is comparable or even lower than that of coal due to the low correlations between these two price series.

Parameters in Eq. (1) are estimated and calibrated as follows.[6] Let $r_t = d\ln(X_t) = \ln(X_t) - \ln(X_{t-1})$ be the continuously compounded return in the tth time interval, then $\hat{\alpha} = \bar{r}/\Delta + s^2/2\Delta$ and $\hat{\sigma}_1 = s/\sqrt{\Delta}$, where $\bar{r}$ and s are the sample mean and standard deviation of the series r_t and Δ is the equally spaced time interval measured in years (i.e., $\Delta = 1/52$ year for weekly data). As indicated by the magnitudes of the drift parameters (Table 2), all energy price series show a declining trend during the whole sample and the substitution periods. In contrast, for the infancy period, all energy price series except for wood pellets exhibit a rising trend. Regarding the variation, coal prices have a fairly constant volatility, whereas wood pellet prices stabilize over time and become less volatile than coal prices during the substitution period. The correlation coefficient estimates remain low at 0.327–0.348 and therefore volatilities of mixed fuel prices are generally lower than those of wood pellets and coal. Because of the portfolio effect, the correlation coefficient decreases as the percentage of wood pellets in the mixed fuels increases. Finally, the values of parameters k's and ϕ's in the conversion cost function are based on Adkins and Paxson (2011), where $k_c = k_m = 0.5$ means switch options are equally reciprocal and $\phi_c = \phi_m = 1$ means the conversion cost merely depends on the price of the incumbent fuel. Other key variables and their adopted values are presented in Table 3, including a discount rate of 8% for US power plants, an average retail electricity price of \$0.050/kWh net of operating costs, an average coal price of \$0.014/kWh, and average mixed fuel prices of \$0.016/kWh, \$0.017/kWh, and \$0.019/kWh with 10%, 15%, and 25% wood pellets, respectively.

[6] For completeness, we conducted unit root tests on the energy price series and find mixed results for or against the null hypothesis of unit roots. An alternative stochastic model for price series is the geometric Ornstein-Uhlenbeck process. We also estimate the parameters for the geometric Ornstein-Uhlenbeck process and find low rates of mean reversion and similar volatility estimates. Therefore, we conclude that the geometric Brownian motion well captures the short-run stochastic nature of the energy price series.

4. Empirical results and discussion

4.1. Base case results

Numerical solutions based on the system of four nonlinear equations, Eqs. (7)–(10), are presented in Table 4. Parameters β's and A's are of expected signs and all price ratios are greater than one. The total value per kWh of a coal power plant and a mixed fuel power plant can be calculated according to Eqs. (4) and (5) for a given coal and mixed fuel price pairs. For example, the total value of a coal (mixed fuel with 10% wood pellets) power plant using the whole sample parameter values and average energy prices is \$0.7837/kWh (\$0.8052/kWh) and the option value to switch to mixed fuel with 10% wood pellets (coal) is \$0.0014/kWh (\$0.0081/kWh).

The threshold price ratios W_{cm} and W_{mc} define the optimal switching boundaries between coal and mixed fuel as fuel options for a power plant for nine different scenarios. The boundaries together with historical mixed fuel and coal price ratios are plotted in Fig. 3. In most cases, the price pairs fall into the switch-to-coal region, meaning that it is not economical to cofire wood pellets with coal because the mixed fuel cost increases with the share of wood pellets. Exceptions are 10% and 15% cofiring during the infancy period, where some portion of the price pairs fall into the continuation region. In these two exceptions, a power plant should continue to use whichever is its incumbent fuel. Consequently, a cofiring power plant could have operated efficiently during that time period. In general, Fig. 3 suggests that cofiring wood pellets with coal is not economically feasible in the United States over the 2009–2014 period with high wood pellet prices.

Next, we consider the impact of potential government interventions on the renewable resource energy market (Fig. 4). First, we include a direct subsidy of \$1.40/mmbtu to the mixed fuel with 10% wood pellets, which essentially cuts the input cost of a cofiring power plant. As

Table 4
Results of the regime switching model.

Symbol	WP10			WP15			WP25		
	Whole period	Infancy period	Substitution period	Whole period	Infancy period	Substitution period	Whole period	Infancy period	Substitution period
	2009–2014	2009–2011	2012–2014	2009–2014	2009–2011	2012–2014	2009–2014	2009–2011	2012–2014
β_{c4}	11.022	2.809	46.028	8.293	2.276	32.430	6.097	1.894	22.703
β_{m2}	−19.057	−28.428	−10.787	−13.048	−20.325	−7.448	−8.289	−12.983	−4.564
A_{c4}	0.372	10.684	0.0001	0.550	13.310	0.004	0.804	16.007	0.0013
W_{cm}	1.100	1.051	1.178	1.121	1.064	1.211	1.157	1.090	1.268
A_{m2}	0.040	0.002	0.190	0.088	0.005	0.359	0.205	0.018	0.750
W_{mc}	1.138	1.199	1.102	1.164	1.244	1.110	1.201	1.302	1.121

Note: WP10, WP15, and WP25 represent 10%, 15%, and 25% wood pellet cofiring with coal.

such, all the energy price pairs move just under the coal-to-mixed-fuel switch boundary. Second, we impose a tax of \$1.50/mmbtu on a coal-only power plant, which is equivalent to increasing the cost of coal. Accordingly, all the energy price pairs fall just below the coal-to-mixed-fuel switch boundary. In both scenarios, a coal power plant should convert to wood pellets and coal cofiring. Therefore, a minimum tax of \$1.50/mmbtu on coal has a similar effect as a minimum subsidy of \$1.40/mmbtu on mixed fuel in triggering the investment in cofiring power plants. Given an average cost of \$0.12/kWh (\$35/mmbtu) in the United States, the mixed fuel subsidy or coal tax represents about 4% of the electricity rate. Alternatively, a minimum subsidy of \$0.45/mmbtu on the mixed fuel or a minimum tax of \$0.50/mmbtu on the coal could maintain existing cofiring power plants in the status quo, which represents about 1.3% of the electricity rate.

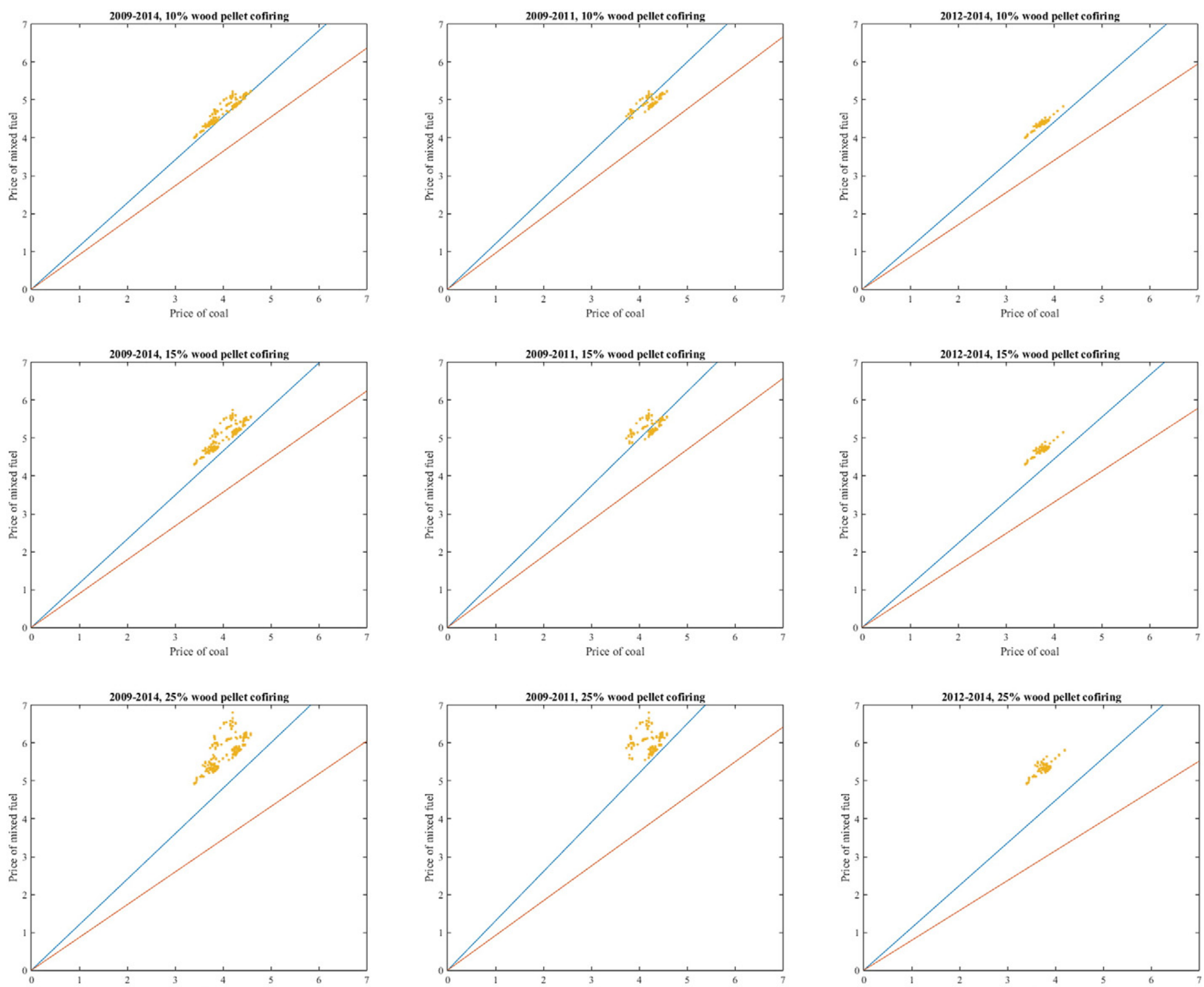

Fig. 3. Optimal switching boundaries for nine different wood pellet and coal cofiring scenarios for electricity generation. All prices are in \$/mmbtu.

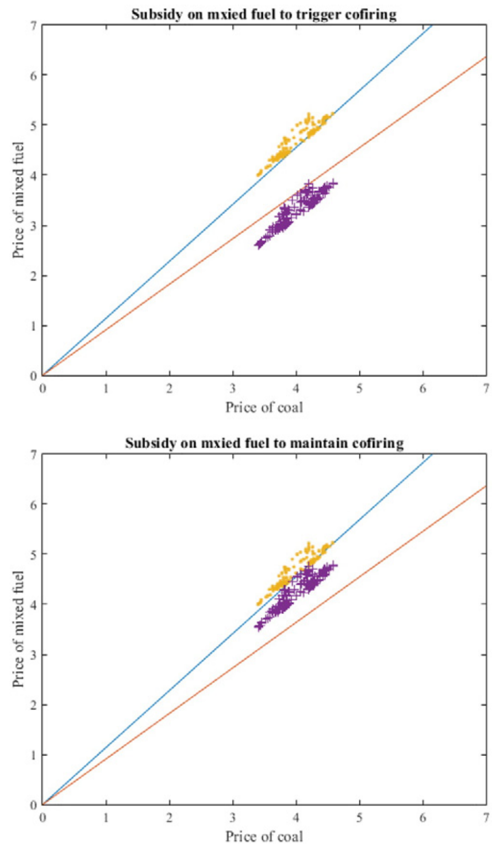

Fig. 4. Impact of the subsidy on mixed fuel and the tax on coal on optimal switch decisions. A subsidy of $1.40/mmbtu to the 10% mixed fuel or a coal tax of $1.50/mmbtu would trigger the conversions of coal-only power plants to cofiring ones, and a subsidy of $0.45/mmbtu to the 10% mixed fuel or a tax of $0.50/mmbtu on coal would maintain existing cofiring power plants in the status quo.

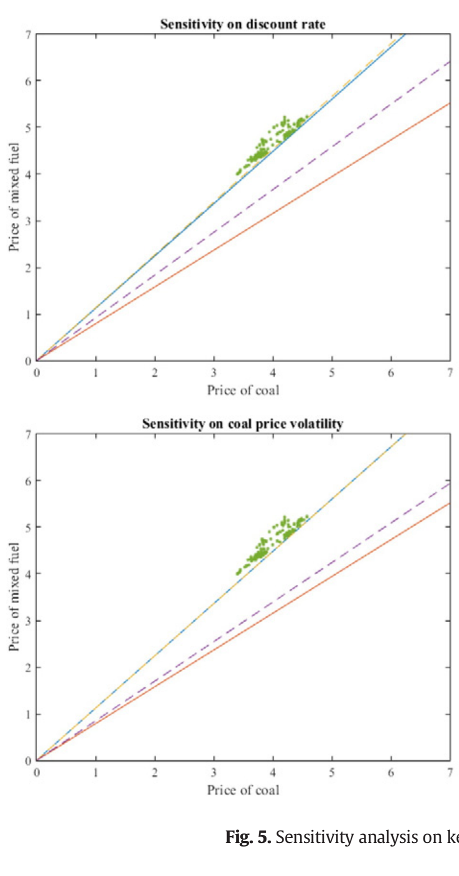

Fig. 5. Sensitivity analysis on key variables in the regime switch model.

4.2. Sensitivity analysis

Sensitivity analysis is conducted on the discount rate, drift and volatility parameters of coal price, correlation coefficient, and wood pellet price for the whole sample period and the case of 10% wood pellet cofiring (Fig. 5). When the discount rate is reduced from 8% to 6%, the major impact is on the switch boundary from coal to mixed fuels. A lower discount rate yields higher cost mixed fuels more affordable and thus shifts the switch boundary up. When the drift parameter of coal price is reduced from −0.009 to −0.020, both coal price and mixed fuel price tend to fall over time, so that the wait region narrows and both switches are more likely to occur. When the volatility parameter of coal is lowered from 0.103 to 0.050, the volatility of mixed fuel decreases as well. With less uncertainty in the mixed fuel cost, a coal power plant is more willing to switch to mixed fuel. When the correlation coefficient is reduced from 0.959 to 0.800, the portfolio effect becomes more significant. Hence, the impact is quite similar to that of a reduction in the volatility of mixed fuel. In summary, when values of the key variables in the switch regime model change by a significant amount, the optimal decision for a power plant does not change appreciably. Specifically, cofiring wood pellets with coal is not an economically viable option.

At the plant level, heat rates and delivered fuel prices can deviate from the industry averages. A lower heat rate implies higher operation efficiency and thus reduces fuel input cost, all else equal. This means that the price pairs in Fig. 3 fall more into the “switch to coal” region. Similarly, the same would occur if a plant can negotiate a lower coal delivered price. In other words, plants with lower heat rates or better control of delivered coal prices are less willing to switch to wood pellets cofiring and larger incentives are needed to induce the conversion.

5. Conclusions

Using the regime switching model under the theoretic framework of real options, we examine the optimal timing boundaries for coal and mixed fuel as two alternative fuels for a US power plant. Results indicate that cofiring wood pellets with coal is not a commercially viable option in most cases. However, lower-level (with wood pellets < 15%) cofiring could have been feasible during the infancy period when wood pellet price is declining. Sensitivity analysis indicates that our conclusions are robust and the most important factors are relative prices of coal and mixed fuel. Therefore, we reject the null hypothesis that cofiring is economically feasible and suggest using policy vehicles to stimulate the bioenergy market and meet the GHG emission reduction target.

Specifically, a subsidy of \$1.40/mmbtu to the 10% mixed fuel[7] or a coal tax of \$1.50/mmbtu would trigger the conversions of coal-only power plants to cofiring ones, and a subsidy of \$0.45/mmbtu to the 10% mixed fuel or a tax of \$0.50/mmbtu on coal would maintain existing cofiring power plants in the status quo. Given the total electricity of 1596 billion kWh generated from coal (EIA, 2016), the estimated government spending is about \$8 billion to prompt the conversion to mixed fuel and \$2.7 billion to retain current cofiring power plants. This spending will increase as the share of wood pellets in the mixed fuel enlarges. These numbers are roughly comparable to the subsidy levels of \$0.03–0.20/kWh or \$8.82–58.82/mmbtu to solar energy (Fthenakis et al., 2009), and the production tax credit of \$0.019/kWh or \$5.59/mmbtu toward wind energy (Greenblatt et al., 2007). Therefore, renewable energy policies should give equal priorities to wood pellets cofiring as to solar and wind energy in the US.

Unlike most countries in Europe, where domestic cost of manufacturing wood pellets is not competitive with the import price, the US Southeast has a productive forest industry and well-established infrastructure. Hence, producing wood pellets from intensively managed timberland in this region is likely to increase local employment as well as GDP. For example, a 500-megawatt coal power plant takes about 2540 jobs, whereas a same-sized power plant with mixed fuel is estimated to take 3480 jobs, or a 37% increase in employment (Strauss, 2014). In addition, a long-term demand for wood pellets can help preserve existing working forests and attract more investments in commercial forests, which in turn increases carbon sequestration. Thus, the government expenditure on boosting wood pellet usage by power plants does not simply represent a cost but has some benefits and can potentially improve the rural economy.

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[7] On a hypothetical 100% carbon reduction basis, a multiple of 10 should be applied. So, roughly speaking, the corresponding subsidy should be \$14/mmbtu to trigger the switch from coal to 100% wood pellets burning.

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