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Economics of Carbon Dioxide Sequestration versus a Suite of Alternative Renewable Energy Sources for Electricity Generation in U.S., California and Illinois

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ABSTRACT: An equilibrium economic model for policy evaluation related to electricity generation at national and individual state level in U.S has been developed. The model takes into account the non-renewable and renewable energy sources, demand and supply factors and environmental constraints (CO_2 emissions). Economic policy analysis experiments are carried out to determine the consequences of switching the sources of electricity generation under two scenarios: in first scenario, a switch from coal to renewable sources is made for 10% of electricity generation; in the second scenario, the switch is made for 10% of electricity generation from coal to coal with clean coal technology by employing CO_2 capture and sequestration (CCS). The cost of electricity generation from various non-renewable and renewable sources is different and is taken into account in the model. The consequences of this switch on supply and demand, employment, wages, and emissions are obtained from the economic model under three scenarios: (1) energy prices are fully regulated, (2) energy prices are fully adjusted with electricity supply fixed, and (3) energy prices and electricity supply both are fully adjusted. The model is applied to the states of California and Illinois, and at national level.

Keywords: Carbon dioxide sequestration and mitigation; Electricity generation; Renewable energy; State-level analysis
JEL Classifications: C54; C68; Q42; Q48

1. Introduction

Modeling of CO_2 emissions and the economic factors related to the switch from fossil fuels to renewable energy sources for electricity generation has become very important with the recent trends of moving toward a more economically and environmentally sustainable society. The Brundland definition of sustainable development, 'the development that meets the needs of the present without compromising the ability of future generations to meet their own needs' is considered key to sustainability (Brudtland, 1987). The effects of global warming and its impact on climate change of the planet are making it apparent that the path humanity has taken so far, that is burning of excessive amounts of fossil fuels for meeting the energy needs, is not sustainable. We have created a national-level economic model that can be used by the policy makers to make informed decisions, which can lead to a sustainable path to meet the energy requirements in an economically and environmentally acceptable manner (Agarwal, et al, 2011). However, the national-level economic model is not suitable for policy making at state level since the economy and energy generation as well energy supply and demand profiles of each state are different. Therefore, the development of a state-level economic model is needed to make it possible to investigate the economic impact of carbon emission reduction policy on individual states rather than on national aggregated level.

Overall, the United States generates most of the electricity from coal-based power plants. The other power generation sources include: nuclear, hydroelectric, natural gas, biomass waste, biomass wood, geothermal, solar photovoltaic, solar thermal and wind. In 2006, coal (49.3%), nuclear (19.5%), hydroelectric (7.2%) and natural gas (20.0%) constituted the major sources for electric power generation compared to biomass waste (0.4%), biomass wood (1.0%), solar photovoltaic and solar thermal (0.01%), wind (0.6%) and geothermal (0.4%). During the past 15 years, wind power has become cheaper and competitive with fossil fuel based electricity generation, and therefore is increasingly deployed in the U.S. and around the world. Photovoltaic power generation is still very limited because at present it is not very efficient and is very expensive compared to other sources of electricity generation. Recently, there has been considerable emphasis by the Department of Energy (DOE) and electric utility companies on research in "Clean Coal Technologies." In particular, carbon capture and sequestration (CCS) is being considered as a viable technology that may make it possible the continued use of fossil fuels with CO_2 emissions being captured and then sequestered in geological formations. However, the CCS technology is yet to be tested for a medium to large scale power generation facility. It appears unlikely that carbon capture and sequestration (CCS) will be wide spread among power generation facilities within the next 15 years. It is therefore necessary to explore both the alternative renewable energy sources along with CCS for power generation and assess the relative economic viability of the two approaches in the near term horizon of twenty years.

In this paper, we consider the economics of electricity generation at state level in two states, California and Illinois which have very different energy generation mix as well as supply and demand. Illinois primarily generates energy from coal, while California is generally recognized as a "green" state since it generates a much larger portion of electricity from non-fossil fuel sources. Since the states have fairly distinct economies and energy generation profiles, national-level analysis presented in (Agarwal, et al., 2011) is inadequate to give satisfactory predictions of the economic consequences of a switch from coal to renewable or CCS under various regulatory scenarios. The goal of this paper is to create a state-level energy economic model that can determine the economic consequences of a switch from coal to a mix of renewable or CCS to achieve the environmental constraints on CO_2 emissions in 2025 and 2050. The model will also determine the impact of policy changes on electricity price, its supply and demand, and on employment for the particular state. At present, there are hardly any models in the literature that do the energy economic modeling at state level.

There are mainly four types of approaches currently employed in the majority of energy-economic models: top-down, bottom-up, optimization and equilibrium, and dynamic. The top-down and bottom-up models can be used together to create a more detailed model. The salient features of these models are briefly described below.

Top-Down/Bottom-Up Models

According to Nakata, "The top-down label comes from the way modelers apply macroeconomic theory and econometric techniques to historical data on consumption, prices, incomes, and factor costs to model the final demand for goods and services, and the supply from main sectors (energy sector, transportation, agriculture, and industry)" (Nakata, 2004). All of the agents in the model respond to changes in prices and allow for multiple regions to be linked by trade. Bottom-Up models model a given sector in detail, in the present case – electricity generation. These models use detailed costs for current and future technologies to model the effects of policy on the electricity generation sector. They, "capture technology in the engineering sense: a given technique related to energy consumption or supply, with a given technical performance and cost" (Nakata, 2004).

Optimization Based Models

Optimization based models are based on the concept of maximizing utility and minimizing the cost. The optimization takes place at a given point in time and is considered to be in steady state. The optimization based models employ either the top-down or bottom-up approach to modeling. The optimization equations used in this paper, for the most part, follow the format of the Bellman equation:

$$V(x_0) = \max_{a_0}\left[F(x_0, a_0) + \beta V(x_1)\right] \tag{1}$$

where V is the value function (Bellman, 1957). The value function is "the best possible value of the objective, written as a function of the state [variable]" (Bellman, 1957). The Bellman equation (1) gives the value function at a given time period as the maximum of some objective function (F) plus the value function of the next time period with a discounting factor β. This recursive format of the Bellman equation allows for the calculation of the value function at normalized time $t = 1$ if the value function and the objective function (F) are known at normalized time $t = 0$. The first-order conditions are the partial derivatives of the Bellman equation with respect to the variables over which the optimization is being preformed (not the state variables).

$$\frac{\partial}{\partial a_0}\left(V(x_0) = \max_{a_0}\left[F(x_0, a_0) + \beta V(x_1)\right]\right) \tag{2}$$

In this model, the states x_0 and x_1 are recursively defined as:

$$x_1 = G(x_0) \tag{3}$$

where G is a specified function. The Benveniste-Scheinkman condition, also known as the envelope condition, allows the calculation of the derivative of the value function with respect to the state variable (Boileau, 2002; Bergin, 1998):

$$\frac{\partial}{\partial x_0}\left(V(x_0) = \max_{a_0}\left[F(x_0, a_0) + \beta V(x_1)\right]\right) \tag{4}$$

Using the first-order necessary conditions and the Benveniste-Scheinkman condition, the value function can be calculated.

The present model, developed in this paper, basically falls under this category; however it is only concerned with the steady state results. A bottom-up approach was applied to the electricity generation sector so that the effect of switching from one energy source to another could be analyzed; a top-down approach was also used to determine the economy wide effects of the policy changes.

Dynamic Models

Dynamic models are an extension of the optimization based models. They operate in a manner similar to the optimization models except that the optimization takes place on a time interval and does not assume the steady state. Dynamic models are based on the same mathematical background as described in the previous section. They "can also be termed partial equilibrium models. These technology-oriented models minimize the total costs of the [system], including all end-use sectors, over a 40-50 year horizon and thus compute a partial equilibrium for the [markets]" (CRA International, 2008). Unlike the present model developed in this paper, the dynamic model results into a time series that can provide information as to how the current decisions affect the future outcomes.

2. National Level Model

The state-level model is derived from the nation-level model described in (Agarwal, et al, 2011). Thus, it is helpful to first describe the construction of the national level model in order to develop the state level model. We consider a model economy with a continuum of households of mass N and three operative sectors: the industrial manufacturing sector, the commercial sector and the electricity generation sector. We omit the insignificant transportation sector because of relatively insignificant consumption of electricity compared to residential, manufacturing and commercial sectors. The government sector is also omitted because its behavior is different from the other sectors. The households provide the firms with labor and investment while the firms provide the households with goods, services and wages. The households pay the government taxes and the government grants the households subsidies. Firms can provide each other with goods and services. The optimum level of production by a firm is the point at which profit is maximized.

Household

Each household owns one unit of labor, whose consumption c is produced by the consumption good (x) and electricity (e^H):

$$c = h(x, e^H) \tag{5}$$

Set the consumption good x as the numeraire and denote the unit price of electricity as p. The optimization problem is given by:

$$V^H(a_t) = \max_{c_t, e_t^H} \left(U(c_t) + \beta^H V^H(a_{t+1}) \right)$$

$$s.t. \quad a_{t+1} = (1+r_t)a_t + w_t - x_t - p_t e_t^H \tag{6}$$

$$c_t = h(x_t, e_t^H)$$

where a denotes household asset, w the wage, r the real interest rate and β^H the subjective discount factor facing each household. The total population of households (N) is assumed to be fully employed in the three (industrial manufacturing, commercial and electricity generation) sectors of the model economy. Aggregate household demands are then defined by:

$$C_t = N_t c_t \tag{7}$$

$$X_t = N_t x_t \tag{8}$$

$$E_t^H = N_t e_t^H \tag{9}$$

Industrial Sector

There is a mass of producers normalized to one. Each producer hires labor (N^F), in conjunction with capital input (K) and electricity (E^F), to manufacture goods Y:

$$Y = f(K \ , N^F, E^F) \tag{10}$$

The output Y is used for consumption and capital investment:

$$Y = X + qZ \tag{11}$$

where q denotes the relative price of investment in units of the consumption good. Let capital depreciate at rate δ. The optimization problem is given by:

$$V^F(K_t) = \max_{N_t^F, E_t^F, Z_t} \left(Y_t - q_t Z_t - w_t N_t^F - p_t E_t^F + \beta^F V^F(K_{t+1}) \right)$$

$$s.t. \quad K_{t+1} = Z_t + (1-\delta)K_t \tag{12}$$

$$Y_t = f(K_t, N_t^F, E_t^F)$$

where β^F the subjective discount factor facing each producer.

The Commercial Sector

This is a sector with measuring difficulties. This sector includes not only commercial firms, but educational institutions and other nonprofit organizations. Its inputs and outputs are hard to measure. For simplicity, the commercial sector is modeled in a stylized manner with its demand for electricity given by:

$$E_{t+1}^C = (1+\sigma)E_t^C \tag{13}$$

where $\sigma > 0$ is assumed an exogenous constant. Under a Leontief production function specification, the demand for labor is given by:

$$N_t^C = \zeta \ E_t^C \tag{14}$$

where $\zeta > 0$ is the employee-energy mix parameter.

Aggregate Electricity Demand and Electricity Generation

Total electricity demand is therefore given by:

$$E = \sum_{i=H,F,C} E^i \tag{15}$$

Electricity can be generated via various sources s = 1 (coal), s = 2 (nuclear), s = 3 (hydro), s = 4 (petroleum), s = 5 (natural gas), s = 6 (renewable, including biomass wood/waste, geothermal, solar, etc), and s = 7 (clean coal). The generation function can be specified as follows:

$$E(s) = m(N^E(s), M(s), s) \tag{16}$$

depending on labor (N^E) and other inputs (M). Total electricity generated from all sources is:

$$E = \sum_s E(s) \tag{17}$$

while the labor demand by all sources of electricity generation is:

$$N^E = \sum_s N^E(s) \tag{18}$$

We assume fixed unit labor requirements θ across all sources:

$$N^E(s) = \theta E(s) \tag{19}$$

Thus, we have:

$$N^E(s) = \frac{E(s)}{E} N^E \tag{20}$$

and can rewrite (16) as:

$$E(s) = \min\left\{\frac{1}{\theta} N^E(s), g(M(s))\right\} \tag{21}$$

where $g(M(s)) = m(\theta E(s), M(s), s)$.

Denote the unit cost of other inputs as v. Utility firms using source s face the following optimization problem:

$$\begin{aligned} &\min\left\{wN^E(s) + vM(s)\right\} \\ &s.t. \quad E(s) = \min\left\{\frac{1}{\theta} N^E(s), g(M(s))\right\} \end{aligned} \tag{22}$$

Total cost incurred in electricity generation is:

$$\sum_s \left[wN^E(s) + vM(s) \right] \tag{23}$$

Let $\mu(s)$ denote the unit cost of electricity generation under source s. We can compute:

$$vM(s) = \mu(s)E(s) - wN^E(s) \tag{24}$$

Since we can measure $M(1)$, v can be backed out as well as $M(2)$, $M(3)$, $M(4)$, $M(5)$, $M(6)$, $M(7)$.

Denote unit pollution generation of source s as $\gamma(s)$. Total pollution generation in electricity generation is:

$$\sum_s \gamma(s)E(s) \tag{25}$$

Aggregate Labor Market

Total labor demand is:

$$\sum_{i=F,C,E} N^i = N \tag{26}$$

In equilibrium, labor supply equals labor demand.

Optimization and Equilibrium

Household's optimization can be rewritten as:

$$V^H(a_t) = \max_{x_t, e_t^H} \left(U(h(x_t, e_t^H)) + \beta^H V^H((r_t + 1)a_t + w_t - x_t - p_t e_t^H) \right) \tag{27}$$

The first-order necessary conditions are given by:

$$U_c h_x = \beta^H V^H_{a_{t+1}} \tag{28}$$

$$U_c h_{e^H} = \beta^H V^H_{a_{t+1}} \cdot p_t \tag{29}$$

Implying

$$\frac{h_{e^H}}{h_x} = p \tag{30}$$

where the time subscript is suppressed whenever it would not cause any confusion. The Benveniste-Scheinkman condition is given by:

$$V^H_{a_t} = \beta^H V^H_{a_{t+1}} \cdot (r_t + 1) \tag{31}$$

Manufacturer's optimization problem can be rewritten as:

$$V^F(K_t) = \max_{N_t^F, E_t^F, Z_t} \left(f(K_t, N_t^F, E_t^F) - q_t Z_t - w_t N_t^F - p_t E_t^F + \beta^F V^F(Z_t + (1-\delta)K_t) \right) \tag{32}$$

The first-order conditions are derived below:

$$f_{N_t^F} = w_t \tag{33}$$

$$f_{E_t^F} = p_t \tag{34}$$

$$\beta^F V_{K_{t+1}}^F = q_t \tag{35}$$

The Benveniste-Scheinkman condition is given by:

$$V_{K_t}^F = f_{K_t} + \beta^F V_{K_{t+1}}^F \cdot (1-\delta) \tag{36}$$

which can be combined with (35) to yield:

$$V_{K_t}^F = f_{K_t} + \beta^F V_{K_{t+1}}^F \cdot (1-\delta) \tag{37}$$

Under fixed labor requirements (19), utility firm's optimization leads to:

$$g_M(M(s)) = \frac{v}{w\theta} \tag{38}$$

$$E(s) = \frac{1}{\theta} N^E(s) = g(M(s)) \tag{39}$$

Steady-State Equilibrium

In steady-state equilibrium, all variables are constant. As a consequence, (31) implies:

$$1 + r = \frac{1}{\beta^H} \tag{40}$$

whereas (6), (12) and (37) yield the following steady-state relationships:

$$x + pe^H = w + \left(\frac{1}{\beta^H} - 1\right)a \tag{41}$$

$$Z = \delta K \tag{42}$$

$$f_K = \left(\frac{1}{\beta^F} - 1 + \delta\right)q \tag{43}$$

3. State Level Model

The energy-economic model for the U.S. described above is modified to conduct the state level policy analysis. Due to the unavailability of state-level consumption, investment and wage data, we adjust the model for state level analysis as follows. For each state j, we assume the wage to be proportional to the average product of labor and the capital stock to be proportional to output at the national level as:

$$\frac{w_j}{w} = \frac{Y_j / N_j}{Y / N} \tag{44}$$

$$\frac{K_j}{K} = \frac{Y_j}{Y} \tag{45}$$

where w is the wage, Y is the output, N is the total population of households (fully employed in the industrial manufacturing, commercial or electricity generating sectors) and K is the input capital. Thus, from the aggregate national data and the state-level Gross State Product (GSP) and employment data, we can determine the state-level wage and capital from equations (44) and (45) respectively.

In reality, electricity prices and interest rates are more or less constant across all states. Since households are fully mobile, it is reasonable to assume that their behavioral parameter η is the same for the residents in all states. Applying the equation for household electricity demand

$$e_j^H = \frac{1}{p}(1-\eta)\left(w_j + ra_j\right) \tag{46}$$

to state j, we obtain:

$$a_j = \frac{1}{r}\left(\frac{1}{1-\eta} pe_j^H - w_j\right) \tag{47}$$

where a_j is the household asset for state j, p is the price of electricity, r is the real interest rate and e_j^H is the household electricity demand for state j. Substituting equation (47) into the equation for household goods consumption demand x_j,

$$x_j = \eta\left(w_j + ra_j\right) \tag{48}$$

we obtain:

$$x_j = \frac{\eta}{1-\eta} pe_j^H \tag{49}$$

It should be noted that a_j must be nonnegative. Should the imputed value of a_j from equation (47) become negative it should be set $a_j = 0$ and the proportionality of wages assumption in equation (44) should be abandoned. Instead, one should use equation (46) with $a_j = 0$ to obtain:

$$w_j = \frac{1}{1-\eta} pe_j^H \tag{50}$$

The state-level electricity can be computed by:

$$ED_j = E_j^H + E_j^F + E_j^C \tag{51}$$

Then, the net export of electricity in state j is given by:

$$EX_j = E_j - ED_j \tag{52}$$

when $EX_j > 0$, the state j exports electricity to other states; when $EX_j < 0$, the state j imports electricity from other states. In aggregate, $\sum EX_j = 0$. Since emissions are tied to electricity generation, state-level CO_2 production and the effectiveness of energy policy will depend crucially on whether a state is an electricity exporter or importer. Substituting equations (44) - (49) in the national-level model to replace the corresponding equations completes development of state-level model.

4. Policy Analysis for the State of California and Illinois

California and Illinois were chosen to perform the state-level energy-economic analysis, since they have significantly different population, economy and the energy generation mix and energy supply and demand. California is an aggressively "green" state compared to many others, with very limited used of coal-based electricity, it larges uses natural gas and some renewable (primarily wind among others). In contrast, Illinois is considered relatively a "dirty" state with dominant use of coal-based electricity. We consider two scenarios. In the first scenario, we consider a switch from coal to renewable for 10% of electricity generation by 2030. In the second scenario, we consider a switch from coal to clean coal (using CCS) for 10% of electricity generation by 2030. For comparison purpose, similar analysis is also performed at national level. In the analysis for 10% switch in electricity generation from coal to renewables, we have lumped all major renewable sources together (wind, solar thermal and photovoltaic, geothermal, biomass waste and biomass wood) as a single source to work with. The average prices used for electricity from coal is 3.1 Cents/kWh, from renewables is 6.7 Cents/kWh and from clean coal with CCS is 5.1 Cents/kWh. Figures I-III respectively show the energy generation mix in 2030 for the business as usual (BAU) scenario and for the proposed scenarios with 10% switch from coal to renewables, and 10% switch from coal to clean coal with CCS.

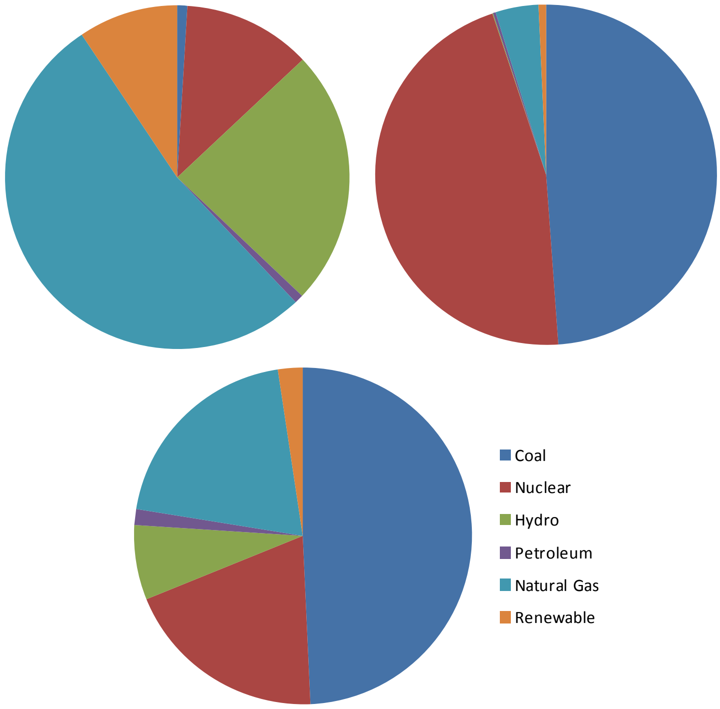


Figure I. Energy generation mix in 2030 in business as usual (left: California, middle: Illinois, right: U.S.)

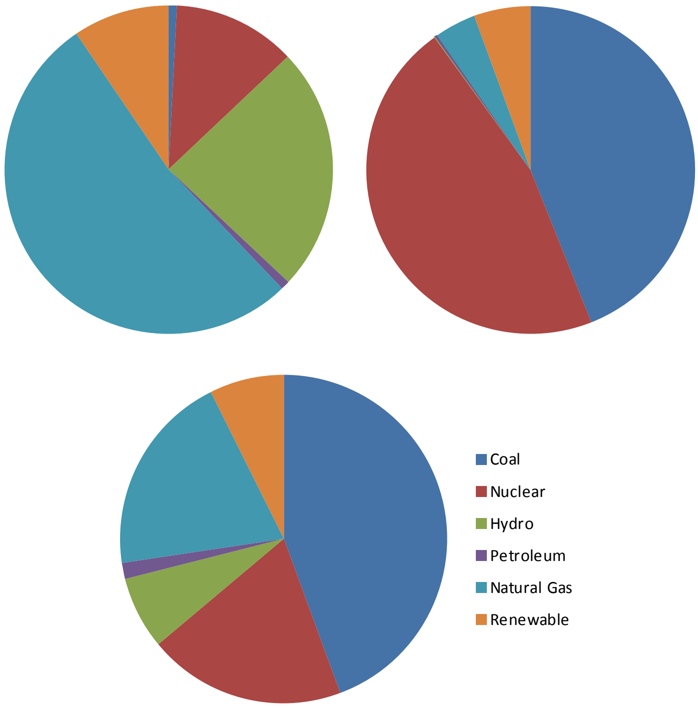


Figure II. Energy generation mix in 2030 for switch from coal to renewable sources for 10% of electricity generation (left: California, middle: Illinois, right: U.S.)

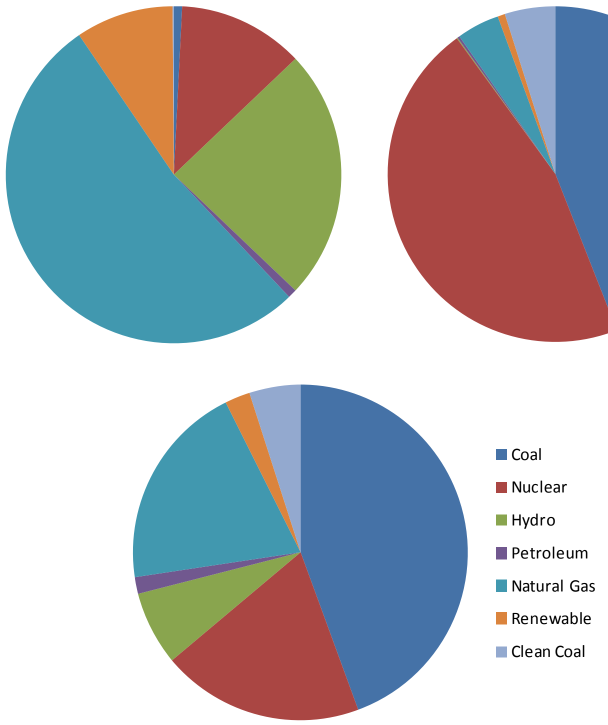
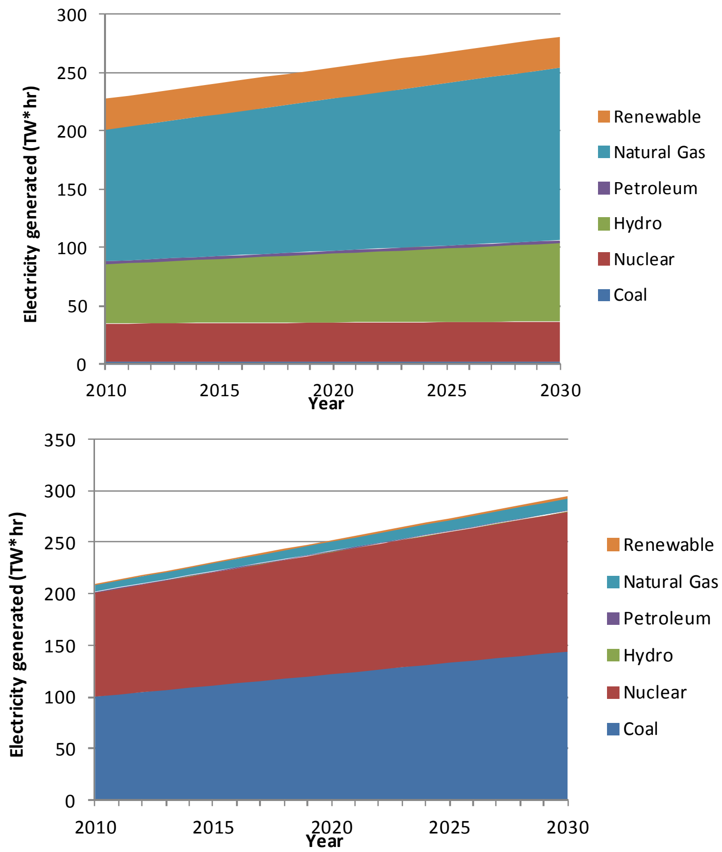


Figure III. Energy generation mix in 2030 for switch from coal to clean coal with CCS for 10% of electricity generation (left: California, middle: Illinois, right: U.S.)

Utilizing a series of curve fits to the data from 1990-2009, the projected business as usual energy generation mix from 2010 to 2030 is obtained as shown in Figure IV.



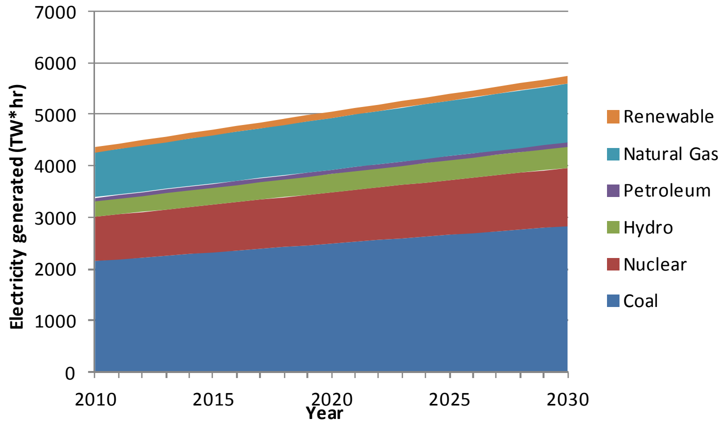


Figure IV. Projected electricity generation mix from 2010 to 2030 for business as usual scenario (top left: California, top right: Illinois, bottom: U.S.)

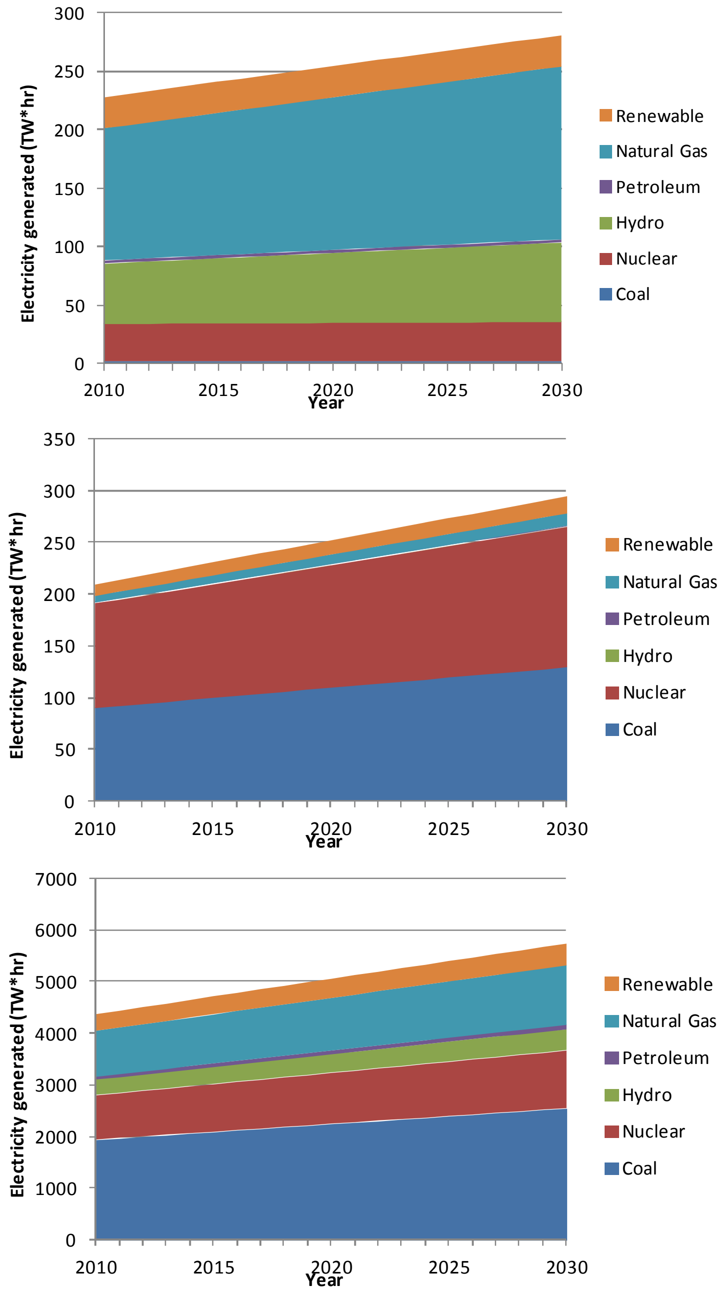


Figure V. Projected electricity generation mix from 2010 to 2030 for scenario 1, that is switching 10% of electricity generation from coal to renewable sources (top left: California, top right: Illinois, bottom: U.S.)

Under the first scenario, that is switching 10% of electricity generation from coal to renewable energy sources, the business as usual energy generation mix in Figure IV changes to the energy generation mix shown in Figure V.

Under the second scenario, that is switching 10% of electricity generation from coal to clean coal technology with CCS, the business as usual energy generation mix in Figure IV changes to the energy generation mix shown in Figure VI.

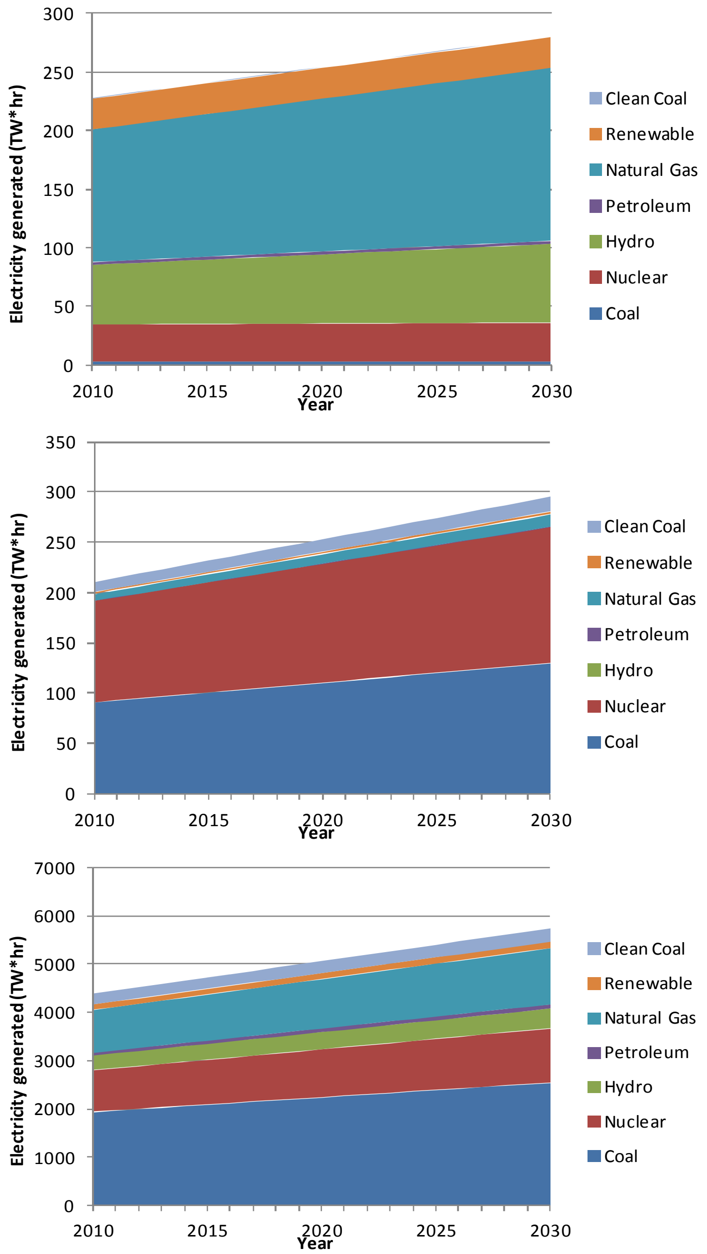


Figure VI. Projected electricity generation mix from 2010 to 2030 for scenario 1, that is switching 10% of electricity generation from coal to clean coal with CCS (top left: California, top right: Illinois, bottom: U.S.)

For the three scenarios: (1) BAU, (2) 10% switch in electricity generation from coal to renewables, and (3) 10% switch in electricity generation from coal to clean coal using CCS, the policy implications are examined under the following conditions: (a) both the energy supply and price are regulated, (b) energy price is fully adjusted with electricity supply fixed, and (c) both the energy price and electricity supply are fully adjusted. The results of policy simulations using our national and state level economic model for the three scenarios under the three types of price and supply conditions are summarized in Tables I, II and III respectively.

Table I. Policy simulation results for the three scenarios under the condition – both the energy supply and price are regulated. All values in the table are percentage change from the business as usual case

Energy Supply and Price Regulated – **U.S.**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
K - Capital Input	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E^F - Industrial Electricity Demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Y - Output	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
p - Price	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
w - Wage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
a - Household Asset	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
x - Consumption	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
e^H - Household Electricity Demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
D - Emission	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%
TCV - Total Cost of Generation	8.8%	3.0%	7.7%	2.6%	6.9%	2.2%	6.3%	2.0%

Energy Supply and Price Regulated - **California**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
K - Capital Input	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E^F-Industrial Electricity Demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Y - Output	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
p - Price	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
w - Wage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
a - Household Asset	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
x - Consumption	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
e^H-Household Electricity Demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
D - Emission	-0.20%	-0.20%	-0.19%	-0.19%	-0.18%	-0.18%	-0.17%	-0.17%
TCV - Total Cost of Generation	0.10%	0.05%	0.10%	0.05%	0.09%	0.05%	0.09%	0.05%

Energy Supply and Price Regulated - **Illinois**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
K - Capital Input	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
E^F-Industrial Electricity Demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Y - Output	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
p - Price	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
w - Wage	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
a - Household Asset	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
x - Consumption	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
e^H-Household Electricity Demand	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
D - Emission	-9.3%	-9.3%	-9.3%	-9.3%	-9.2%	-9.2%	-9.2%	-9.2%
TCV - Total Cost of Generation	6.4%	3.5%	6.4%	3.5%	6.4 %	3.5%	6.4%	3.5%

Table II. Policy simulation results for the three scenarios under the condition – the energy supply is regulated and the energy price is adjusted. All values in the table are percentage change from the business as usual case

Energy Supply Regulated and Energy Price Adjusted – **U.S.**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
K - Capital Input	-0.2%	-0.2%	-0.6%	-0.2%	-0.6%	-0.2%	-0.5%	-0.2%
E^F - Industrial Electricity Demand	-21.0%	-8.0%	-18.9%	-6.9%	-17.3%	-6.0%	-16.1%	-5.4%
E - Total Electricity Demand	-8.5%	-2.3%	-7.4%	-2.7%	-6.5%	-2.2%	-5.9%	-2.0%
Y - Output	-0.7%	-0.3%	-0.6%	-0.2%	-0.6%	-0.2%	-0.6%	-0.2%
p - Price	8.8%	3.0%	7.7%	2.6%	6.9%	2.2%	6.3%	2.0%
w - Wage	-0.7%	-0.2%	-0.6%	-0.2%	-0.6%	-0.2%	-0.5%	-0.2%
a - Household Asset	-0.9%	-0.3%	-0.8%	-0.3%	-0.7%	-0.2%	-0.7%	-0.2%
x - Consumption	-0.8%	-0.3%	-0.7%	-0.2%	-0.6%	-0.2%	-0.6%	-0.2%
e^H - Household Electricity Demand	-8.8%	-3.2%	-7.8%	-2.7%	-7.1%	-2.4%	-6.5%	-2.1%
D - Emission	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%	-8.1%
TCV - Total Cost of Generation	8.8%	3.0%	7.7%	2.6%	6.9%	2.2%	6.3%	2.0%

Energy Supply Regulated and Price Adjusted - **California**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
K - Capital Input	-0.03%	-0.02%	-0.04%	-0.02%	-0.04%	-0.02%	-0.04%	-0.02%
E^F-Industrial Electricity Demand	-0.23%	-0.13%	-0.20%	-0.1%	-0.2%	-0.1%	-0.2%	-0.1%
E - Total Electricity Demand	-0.11%	-0.06%	-0.12%	-0.06%	-0.11%	-0.06%	-0.10%	-0.06%
Y - Output	-0.03%	-0.02%	-0.04%	-0.02%	-0.05%	-0.02%	-0.05 %	-0.03%
p - Price	0.10%	0.05%	0.09%	0.05%	0.09%	0.05%	0.09%	0.05%
w - Wage	-0.03%	-0.02%	-0.04%	-0.02%	-0.04%	-0.02%	-0.04%	-0.02%
a - Household Asset	-0.09%	-0.05%	-0.10%	-0.05%	-0.08%	-0.05%	-0.08%	-0.04%
x - Consumption	-0.03%	-0.02%	-0.05%	-0.02%	-0.05%	-0.03%	-0.05%	-0.03%
e^H-Household Electricity Demand	-0.13%	-0.07%	-0.14%	-0.08%	-0.14%	-0.08%	-0.14%	-0.07%
D - Emission	-0.20%	-0.20%	-0.19%	-0.19%	-0.18%	-0.18%	-0.17%	-0.17%
TCV - Total Cost of Generation	0.10%	0.05%	0.09%	0.05%	0.09%	0.05%	0.09%	0.04%

Energy Supply Regulated and Price Adjusted - **Illinois**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
K - Capital Input	-3.6%	-3.6%	-9.0%	-5.4%	-14.8%	-8.9%	-21.6%	-13.2%
E^F-Industrial Electricity Demand	-27.7%	-16.5%	-32.9%	-20.1%	-35.9%	-22.1%	-41.4%	-26.1%
E - Total Electricity Demand	-11.9%	-7.1%	-15.0%	-9.1%	-16.6%	-10.2%	-19.3%	-12.1%
Y - Output	-4.2%	-2.6%	-10.4%	-6.2%	-16.3%	-9.8%	-23.4%	-14.4%
p - Price	6.4%	3.5%	6.4%	3.5%	6.4%	3.5%	6.4%	3.5%
w - Wage	-3.6%	-3.6%	-9.0%	-5.4%	-14.8%	-14.8%	-21.6%	-13.2%
a - Household Asset	-6.6%	-3.9%	-14.3%	-8.6%	-20.3%	-12.3%	-27.5%	-17.0%
x - Consumption	-5.0%	-2.9%	-11.9%	-7.1%	-18.0%	-10.9%	-25.4%	-15.6%
e^H-Household Electricity Demand	-10.7%	-6.2%	-17.2%	-10.2%	-23.0%	-13.9%	-29.9%	-18.5%
D - Emission	-9.3%	-9.3%	-9.3%	-9.3%	-9.2%	-9.2%	-9.2%	-9.2%
TCV - Total Cost of Generation	6.4%	3.5%	6.4%	3.5%	6.4%	3.5%	6.4%	3.5%

Table III. Policy simulation results for the three scenarios under the condition – both the energy supply and price are fully adjusted. All values in the table are percentage change from the business as usual case

Energy Supply and Price Fully Adjusted – **U.S**.	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
D - Emission	-16.0%	-11.1%	-14.9%	-10.6%	-14.2%	-10.2%	-13.6%	-9.9%
TCV - Total Cost of Generation	-0.5%	-0.3%	-0.2%	-0.2%	-0.1%	0.0%	0.1%	0.0%
Layoff [people]	38000	14000	29000	11000	23000	7800	17000	5700
w - Wage	-0.7%	-0.3%	-0.6%	-0.2%	-0.6%	-0.2%	-0.5%	-0.2%
x - Consumption	-0.8%	-0.3%	-0.7%	-0.3%	-0.7%	-0.2%	-0.6%	-0.2%
e^H - Household Electricity Demand	-8.8%	-3.2%	-7.8%	-2.7%	-7.1%	-2.4%	-6.5%	-2.1%

Energy Supply and Price Fully Adjusted - **California**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
D - Emission	-0.31%	-0.26%	-0.30%	-0.25%	-0.29%	-0.24%	-0.27%	-0.22%
TCV - Total Cost of Generation	-0.01%	-0.006%	-0.21%	-0.01%	-0.02%	-0.01%	-0.02%	-0.01%
Layoff [people]	67	36	72	39	78	38	83	39
w - Wage	-0.03%	-0.016%	-0.04%	-0.021%	-0.04%	-0.023%	-0.05%	-0.024%
x - Consumption	-0.03%	-0.019%	-0.05%	-0.025%	-0.05%	-0.027%	-0.05%	-0.027%
e^H- Household Electricity Demand	-0.13%	-0.07%	-0.14%	-0.08%	-0.14%	-0.08%	-0.14%	-0.07%

Energy Supply and Price Fully Adjusted - **Illinois**	*2015 - Renewables*	*2015 - Clean Coal*	*2020 - Renewables*	*2020 - Clean Coal*	*2025 - Renewables*	*2025 - Clean Coal*	*2030 - Renewables*	*2030 - Clean Coal*
D - Emission	-20.1%	-15.7%	-22.9%	-17.5%	-24.3%	-3.5%	-26.7%	-20.2%
TCV - Total Cost of Generation	-6.3%	-3.9%	-9.6%	-6.0%	-11.2%	-18.5%	-14.1%	-9.1%
Layoff [people]	1117	1081	1810	1101	1588	979	1464	923
w - Wage	-3.6%	-2.1%	-5.4%	-5.4%	-14.8%	-14.8%	-21.7%	-13.2%
x - Consumption	-5.0%	-2.9%	-11.9%	-7.1%	-18.0%	-10.9%	-25.4%	-15.6%
e^H - Household Electricity Demand	-10.7%	-6.2%	-17.2%	-10.2%	-23.0%	-13.9%	-29.9%	-18.5%

The results in Tables I, II and III under three types of regulatory conditions are summarized below for years 2015, 2020, 2025 and 2030.

Condition 1: Energy Price Fully Regulated

When energy prices are fully regulated, the source switch under scenario 2 (renewables) causes total electricity generation cost to go up by 0.1% for CA and 6.4% for IL through 2030 and emissions to decrease by 0.2% for CA and 9.2% for IL through 2030 without changing any other endogenous variables. However, the source switch under scenario 3 (clean coal) causes total electricity generation cost to go up only by 0.05% for CA and by 3.5% for IL and emissions to decrease by 0.2% for CA and 9.3% for IL through 2030. This type of regulatory environment is undesirable at this time because the government would have to pay for the increase in total cost of electricity generation. If at some future time fossil fuel based electricity became equal priced or more expensive than renewables or clean coal then the government would either not lose money or make a profit.

Condition 2: Energy Price Fully Adjusted with Electricity Supply Fixed

Under this condition, electricity supply and the level of employment remains fixed. When energy prices are fully adjusted, the source switch described above under scenarios 2 and 3 will raise the energy price by the same amount as under condition 1 and reduce the emissions by the same amount. However, higher energy price lowers demand: under scenario 2 (renewables) through 2030, the household demand lowers by 0.14% for CA and by 10.7%~30% for IL, the industrial demand lowers by 0.2% for CA and 27.7%~41.4% for IL, total demand by 0.11% for CA and 11.9%~19.3% for IL. The capital input decreases by 0.03% for CA and by 3.6%~21.6% for IL. The wages reduce by 0.04% for CA and by 3.6%~21.6% for IL. The output is lowered by 0.04% for CA and 4.2%~23.4% for IL. As a consequence, the household assets are lowered by 0.09% for CA and 6.6%~27.5% for IL, household consumption decreases by 0.05% for CA and 5%~25.4% for IL through 2030. Under scenario 3 (clean coal) through 2030, household demand lowers by 0.08% for CA and by 6.2%~18.5% for IL, industrial demand lowers by 0.13% for CA and 16.5%~26.1% for IL, total demand also decreases by 0.06% for CA and by 7.1%~12.1% for IL. The capital input decreases by 0.02% for CA and 3.6%~13.2% for IL. The wages reduce by 0.02% for CA and 3.6%~13.2% for IL. The output is lowered by 0.02% for CA and by 2.5%~14.4% for IL. As a consequence, the household assets are lowered by 0.05% for CA and 3.9%~17% for IL. Finally, household consumption decreases by 0.03% for CA and 2.9%~15.6% for IL through 2030. Additionally, fixed electricity supply implies emissions from coal decrease by 0.2% for CA and 9.2% for IL.

Condition 3: Energy Price and Electricity Supply Both Fully Adjusted

Under this condition, the source switch under both scenarios 2 and 3 will raise the energy price and lower the electricity demand in the same manner as under condition 2. However, in contrast with condition 2, electricity supply is now fully adjusted to meet the demand, which causes a layoff of workers. Under scenario 2, it will result in a layoff of 67 workers for CA and 1117 workers for IL in 2015 and of 83 workers for CA and 1464 workers for IL in 2030. So the expected market wages reduce by 0.04% for CA and by 3.6%~21.7% for IL is now fully adjusted downward, the total electricity generation cost goes down by 0.02% for CA and by 6.3%~14.1% for IL through 2030 and emissions decrease by 0.3% for CA and by 24% for IL through 2030. Under scenario 3, it will result in layoff of 36 workers for CA and 1084 workers for IL in 2015, and 39 workers for CA and 923 workers for IL in 2030. So the expected market wages reduce by 0.02% for CA and 2.1%~13.2% for IL. Goods consumption decreases by 0.03% for CA and 2.9%~15.6% for IL. Because electricity supply is now fully adjusted downward, the total electricity generation cost goes down by 0.01% for CA and 3.9%~9.1% for IL through 2030 and emissions decrease by 0.25% for CA and by 15.7%~20.2% for IL through 2030.

The above analysis shows that scenario 3 (switch to clean coal) is a better policy option than the scenario 2 (switch to renewables) for both states. Furthermore, policy condition 3 yields the largest CO_2 reduction for the given energy generation mix. Allowing the free market to adjust price and supply will lead to the largest decreases in CO_2 emissions for a given energy generation mix for the near future (since the fossil fuel based electricity generation is cheaper than renewable sources and clean coal with CCS).

5. Conclusions

1. An economic model for state-level electricity generation in the U.S has been created and the policy simulations have been run for 2010-2030 for the three scenarios: (1) BAU, (2) 10% switch in electricity generation from coal to renewables, and (3) 10% switch in electricity generation from coal to clean coal using CCS; the policy implications have been examined under the following conditions: (a) both the energy supply and price are regulated, (b) energy price is fully adjusted with electricity supply fixed, and (c) both the energy price and electricity supply are fully adjusted.
2. The switch from fossil fuel based electricity generation to renewables or clean coal technology with CCS is always associated with some negative economic impact in the near term because the fossil fuel based electricity is cheaper. For states that primarily generate energy from fossil fuel, switch in energy sources from fossil fuel to renewables or clean coal with CCS causes a much larger drop in economic output than in states which generate greater part of energy from non-fossil fuel sources.
3. The model predicts that utilizing clean coal technologies such as CCS will affect the economy less than utilizing the renewable energy sources by almost a factor of one-half, regardless of the states' current primary sources of electricity generation. This is due to clean coal

technologies being cheaper than renewable energy technologies based on the current price estimates.

4. While fossil fuel based electricity generation is cheaper than renewables based electricity generation, government regulation will be necessary to achieve any sort of CO_2 emissions reduction. Clean coal technologies could be used to bridge the gap until renewables based electricity becomes less expensive than fossil fuel based electricity.

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Nomenclature

a	household asset, national-level
a_j	household asset, state-level
c	consumption
C	aggregate household consumption demand
D	CO_2 emissions
E	total electricity demand, national-level
ED_j	total electricity demand, state-level
E^C	commercial electricity demand, national-level
E_j^C	commercial electricity demand, state -level
E^F	industrial electricity demand, national-level
E_j^F	industrial electricity demand, state-level
E^H	aggregate household electricity demand, national-level
E_j^H	aggregate household electricity demand, state-level
$E(s)$	electricity generated from sources s
EX_j	net export of electricity in state j
e^H	household electricity demand, national-level
e_j^H	household electricity demand, state-level
K	capital input, nation-level
K_j	capital input, state-level
$M(s)$	material inputs for source s
N	total labor demand
N^C	commercial sector labor
N^E	electricity sector labor

$N^E(s)$	electricity sector labor for sources s
N^F	industrial labor
p	price of electricity
q	relative price of an investment in units of the consumption good
r	real interest rate
s	source of electricity, i.e. coal, nuclear, wind etc.
V^H	household value function
F^F	industrial value function
w	wage, nation-level
w_j	wage, state-level
x	consumption good, national-level
x_j	consumption good, state-level
X	aggregate household goods consumption demand
Y	output
z	investment
Z	total investment
β^H	household depreciation factor
β^F	industrial depreciation factor
δ	capital depreciation rate
$\gamma(s)$	unit pollution generation from source s
η	Cobb-Douglass parameter
$\mu(s)$	unit cost of electricity from a given sources s
v	unit cost of other inputs (energy sources)
θ	source labor requirement parameter
σ	constant growth rate for commercial electricity demand
ζ	employee-energy mix parameter