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

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**ABSTRACT:** An equilibrium economic model for policy evaluation related to electricity generation 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. The non-renewable energy sources include three types of fossil fuels: coal, natural gas and petroleum, and renewable energy sources include nuclear, hydraulic, wind, solar photovoltaic, biomass wood, biomass waste and geothermal. Energy demand sectors include households, industrial manufacturing and non-manufacturing commercial enterprises. Energy supply takes into account the electricity delivered to the consumer by the utility companies at a certain price which maybe different for retail and wholesale customers. Environmental risks primarily take into account the $CO_2$ generation from fossil fuels. The model takes into account the employment in various sectors and labor supply and demand. Detailed electricity supply and demand data, electricity cost data, employment data in various sectors and $CO_2$ generation data are collected for a period of nineteen years from 1990 to 2009 in U.S. The model is employed for policy analysis experiments if a switch is made in sources of electricity generation, namely from fossil fuels to renewable energy sources. As an example, we consider a switch of 10% of electricity generation from coal to 5% from wind, 3% from solar photovoltaic, 1% from biomass wood and 1% from biomass waste. The model is also applied to a switch from 10% coal to 10% from clean coal technologies. It should be noted that the cost of electricity generation from different sources is different and is taken into account. 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.

**Keywords**: carbon dioxide sequestration and mitigation, renewable energy, electricity generation, economics
**JEL Classifications:** C54, C68, Q42, Q48

**NOMENCLATURE**

| | |
|---|---|
| $a$ | household asset |
| $c$ | consumption |
| $C$ | aggregate household consumption demand |
| $D$ | $CO_2$ emissions |
| $E$ | total electricity demand |
| $E^C$ | commercial electricity demand |
| $E^F$ | industrial electricity demand |
| $e^H$ | household electricity demand |

| | |
|---|---|
| $E^H$ | aggregate household electricity demand |
| $E(s)$ | electricity generated from sources $s$ |
| $K$ | capital input |
| $M(s)$ | 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, etc. |
| $V^H$ | household value function |
| $F^F$ | industrial value function |
| $w$ | wage |
| $x$ | consumption good |
| $X$ | aggregate household goods consumption demand |
| $Y$ | output |
| $z$ | investment |
| $Z$ | total investment |
| $\beta^H$ | household depreciation factor |
| $\beta^F$ | industrial depreciation factor |
| $\delta$ | capital depreciation rate |
| $\gamma(s)$ | unit pollution generation from source $s$ |
| $\eta$ | Cobb-Douglass parameter |
| $\mu(s)$ | unit cost of electricity from a given sources $s$ |
| $v$ | unit cost of other inputs (energy sources) |
| $\theta$ | source labor requirement parameter |
| $\sigma$ | constant growth rate for commercial electricity demand |
| $\zeta$ | employee-energy mix parameter |

## 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. It is therefore important to create economic models 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.

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 in the U.S. for two switches from conventional fossil fuel based energy sources. The first switch is made from non-renewable fossil fuel based energy sources to renewable energy sources. The second switch is made from non-renewable fossil fuel based energy sources (coal) to clean coal technologies (in particular CCS). For this purpose we develop an energy economic model, which is an optimization based equilibrium model where the economy is modeled in a top-down manner and the electricity generation sector is modeled using the bottom-up approach. Other significant energy economic models discussed in the literature are the MRN-NEEM model (CRA International, 2008) and the National Energy Model (Nakata, 2004). The MRN-NEEM model is a combination of the MRN (Multi-Region National) model which is a top-down general equilibrium model and the NEEM (North American Electricity and Environmental Model) model which is a bottom up model of the electricity generation sector. The MRN-NEEM model has been applied to the United States. The National Energy Model is a dynamic model that tracks the primary energy sources and how they are consumed by households and industry; this model has only been applied to Japan.

The motivation behind the development of an energy economic model for electricity generation in the U.S. has been to create a model that would forecast the effects on the United States economy of policy changes in the usage of energy sources from fossil fuels to renewables in order to achieve the target goals of greenhouse gas (GHG) emissions in the next 25 to 50 years. With a worldwide emphasis on sustainability, there is a great interest in switching electricity generation sources from predominantly coal based to more eco-friendly renewable sources. The goal then is to create a model that can determine the economically best mix of energy generation sources to achieve the environmental constraints on $CO_2$ emissions in 2025 and 2050. The model should also determine the impact of policy changes on electricity price, its supply and demand, and on employment. At present, there are very few models that address this goal in a comprehensive manner.

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 the 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 (CRA International, 2008). 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 (CRA International, 2008). 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:

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

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 $\beta$. 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:

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

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 (Bergin, 1998; Boileau, 2002):

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

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. PRESENT MODEL: OPTIMIZATION BASED GENERAL EQUILIBRIUM MODEL

*Operative Sectors of the Economy*

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 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 $\beta^H$ 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 $\delta$. 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 $\beta^F$ 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 (biomass wood), $s$ = 7 (biomass waste), $s$ = 8 (geothermal), $s$ = 9 (solar thermal and photovoltaic), $s$ = 10 (wind) and $s$ = 11 (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 $\theta$ 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 $M(2)$, $M(3)$, $M(4)$, $M(5)$, $M(6)$, $M(7)$, $M(8)$, $M(9)$, $M(10)$ and $M(11)$.

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:

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

Manufacturers 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:

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

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

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

*Model Calibration*

For the purpose of calibration analysis, we impose the following functional forms:

$$U = \ln(c) \tag{44}$$

$$h(x, e^H) = x^\eta (e^H)^{1-\eta} \tag{45}$$

$$f(K, N^F, E^F) = A \left\{ \varphi \left[ K^\alpha \left( N^F \right)^{1-\alpha} \right]^\rho + (1-\varphi)\left( E^F \right)^\rho \right\}^{1/\rho} \tag{46}$$

$$g(M(s)) = BM(s)^\psi \tag{47}$$

The model is calibrated based on the following steady-state relationships. In this paper, we use the 1990-2006 average values of $X$ , $Z$, $N^F$, $N^C$, $N^E$, $E^H$, $E^F$, $E^C$, $E(s)$, $\mu(s)$, $M(1)$, $w$, and $p$ as their steady-state values, where all values are in million dollars at 2000 constant prices. The calibration is conducted for each year on which the model is run. There are a few adjustments needed to fit the model. First, the total employment in our model economy is computed using (26):

$$N = N^F + N^C + N^E = 22{,}424{,}294 + 76{,}203{,}146 + 62{,}139 = 99.249 \times 10^6 \tag{48}$$

Since total employment of the U.S. is 123.035×106, we must scale down all the aggregates by a factor of 99.249/123.035 = 0.8067, yielding:

$$X = 5{,}019{,}207 \text{ , } Z = 759{,}482 \text{ , } E^H = 912{,}595 \text{ , } E^F = 814{,}054 \text{ , } E^C = 797{,}165 \tag{49}$$

Now the employee-energy mix parameter in the commercial sector can be derived using equation (14) as $\zeta$ = 95.5927. Second, aggregate electricity demand and supply are not identical in the data. We thus adjust *E(s)* so that the values in (15) and (17) are consistent. That is, call the raw data of electricity generation as *ES(s)*, define $ES = \sum_s ES(s)$ and set $E = E^H + E^F + E^C$. We must adjust electricity generation by the factor $E$ to have: $E(s) = (E/ES) \cdot ES(s)$. Accordingly, we obtain:

$$\begin{aligned}&E(1)=1{,}298{,}463,\ E(2)=496{,}095E(3)=204{,}693,\ E(5)=393{,}439\\&E(6)=26{,}208,\ E(7)=12{,}878,\ E(8)=10{,}581,\ E(9)=354,\ E(10)=5{,}181\end{aligned}\tag{50}$$

Third, material inputs of various forms of electricity generation are very different. To circumvent the problem, we choose to normalize the material inputs to generate *E(1)* as unity, that is, *M(1)* = 1. We can then use the cost data (million dollars per million megawatt-hours):

$$\begin{aligned}&\mu(1)=0.030509,\ \mu(2)=0.022675,\ \mu(3)=0.009513,\ \mu(4)=0.059974,\ \mu(5)=0.049816\\&\mu(6)=0.072496,\ \mu(7)=0.039934,\ \mu(8)=0.08,\ \mu(9)=0.348,\ \mu(10)=0.052359\end{aligned}\tag{51}$$

in conjunction with (24) to compute:

$$\begin{aligned}&v=29{,}270,\ M(2)=0.249303,\ M(3)=0.010817,\ M(4)=0.135025\\&M(5)=0.562525,\ M(6)=0.057777,\ M(7)=0.01065,\ M(8)=0.026039\\&M(9)=0.004115229,\ M(10)=0.007857166\end{aligned}\tag{52}$$

The total electricity cost is then computed as follows:

$$TC=\sum_s\left[wN^E(s)+vM(s)\right]=\sum_s\mu(s)E(s)\tag{53}$$

Next, we can use (8) and (9) to yield $x$ = 0.050572 and $e^H$ = 0.009195031. The average real interest rate is set at a commonly selected rate 5%, faced by all agents. Thus, (40) implies $\beta^H=\beta^F=1/(1+r)$ = 1/1.05. The capital depreciation rate usually falls in the range between 5% and 10%, which we set at 7.5%. The annual wage rate and the relative price of energy are given by $w$ = 0.03236 and $p$ = 0.06936, respectively. Then, from (41) and (42), we can compute:

$$a=\frac{x+pe^H-w}{r}=0.37694\tag{54}$$

$$K=\frac{Z}{\delta}=10{,}126{,}430\tag{55}$$

The Cobb-Douglass utility function simplifies (30) to:

$$\frac{1-\eta}{\eta}\frac{x}{e^H}=p\tag{56}$$

which gives the calibrated parameter value

$$\eta=\frac{x}{x+pe^H}=0.98755$$

The nested CES production function implies that (33), (34) and (43) can be rewritten as:

$$f_{N^F}=(1-\alpha)\Gamma\frac{Y}{N^F}=w\tag{57}$$

$$f_{E^F}=(1-\Gamma)\frac{Y}{E^F}=p\tag{58}$$

$$f_K=\alpha\Gamma\frac{Y}{K}=(r+\delta)q\tag{59}$$

where $\Gamma=\dfrac{\varphi\left[K^\alpha(N^F)^{1-\alpha}\right]^\rho}{\varphi\left[K^\alpha(N^F)^{1-\alpha}\right]^\rho+(1-\varphi)(E^F)^\rho}$. The last equation above can be combined with (11) to derive:

$$Y=\frac{X}{1-\dfrac{\alpha\delta\Gamma}{r+\delta}K}\tag{60}$$

and $$q=\frac{\alpha\delta\Gamma}{r+\delta}\frac{Y}{Z}\tag{61}$$

which can be further substituted into the marginal product of labor and marginal product of energy expressions to solve jointly α and ρ as functions of $\varphi$. From the household side, we learn that the energy demand share is $1-\eta$ = 0.012454. It is reasonable to set the energy demand share by manufacturers twice as much $1-\varphi$ = 0.02491, or $\varphi$ = 0.975092. We can then calibrate $\alpha$ = 0.935881 and $\rho$ = 0.635049. Thus, manufactured output and the unit cost of capital investment are computed as: $Y$ = 11,374,760 and $q$ = 8.36827. These values together with the production function enable us to pin down the scaling parameter.

$$A = \frac{Y}{\left\{\varphi\left[K^{\alpha}(N^{F})^{1-\alpha}\right]^{\rho} + (1-\varphi)(E^{F})^{\rho}\right\}^{1/\rho}} = 1.102033 \tag{62}$$

Finally, we manipulate (20), (38) and (39), using the specific functional form, to calibrate:

$$\theta = \frac{N^{E}}{E} = 0.24615 \tag{63}$$

$$\psi = \frac{vM(s)}{wN^{E}}\frac{E}{E(s)} = 2.82979 \tag{64}$$

$$B = \frac{E(1)}{[M(1)]^{\psi}} = 1{,}298{,}463 \tag{65}$$

Given the $CO_2$ production of 2,229.756 million metric tons essentially from sources 1, 4 and 5, we can obtain an emission conversion ratio (per million megawatts of electricity generated) at $\gamma(\textit{fossil fuels})$ = 2,229.756/1,767,895 = 0.00126125, with $\gamma(2) = \gamma(3) = \gamma(6) = \gamma(7) = \gamma(8) = \gamma(9) = \gamma(10) = \gamma(11) = 0$, due to the fact that the majority of carbon emissions are coming from the combustion of fossil fuels. This completes the sample calibration procedure in the steady-state equilibrium.

## 3. POLICY ANALYSIS

In this section, we perform the policy analysis. In order to do this, we need to derive a few more useful steady-state equilibrium relationships. From (41) and (56), we can write household's goods consumption demand and electricity demand as:

$$x = \eta(w + ra) \tag{66}$$

$$e^{H} = \frac{1}{p}(1-\eta)(w+ra) \tag{67}$$

From (14), (18), and (26), manufacturing firm's labor demand is given by:

$$N^{F} = N_{\zeta}E^{C} - \theta\ E \tag{68}$$

Substituting this into the production function, (57) and (58) enable us to express $Y$, $w$ and $p$ all as functions of *(K, EF)*. Using (8), (10), (42) and (66), we can write household's asset as:

$$a = \frac{1}{r}\left(\frac{Y - \delta qK}{\eta N} - w\right) \tag{69}$$

which is a function of *(K, EF)* as well, as are $x$ and $e^{H}$, based on the demand relationships derived above. Aggregating each household's electricity demand with use of (69) and equating it with electricity supply, we obtain:

$$E^{H} = \frac{1-\eta}{\eta}\frac{Y - \delta qK}{p} = E - E^{C} - E^{F} \tag{70}$$

This together with (59) enables us to solve jointly *(K, EF)*. The solution can then be substituted into other functions to derive $Y$, $w$, $p$, $a$, $x$, $e^{H}$, and $E^{H}$. We are now ready for policy experiments.

We perform two experiments. In the first, we consider switching 10% of electricity generation from coal to 5% wind, 3% solar thermal and photovoltaic, 1% biomass waste and 1% biomass wood by 2030. In the second, we consider switching 10% electricity generation from coal to clean coal (using CCS) by 2030. Figures I-III respectively show the energy generation mix in 2030 for the business as usual (BAU) scenario and for proposed scenarios with 10% switch from coal to renewables, and 10% switch from coal to clean coal with CCS.

**Figure I: Energy generation mix for 2030 in business as usual (BAU) case**

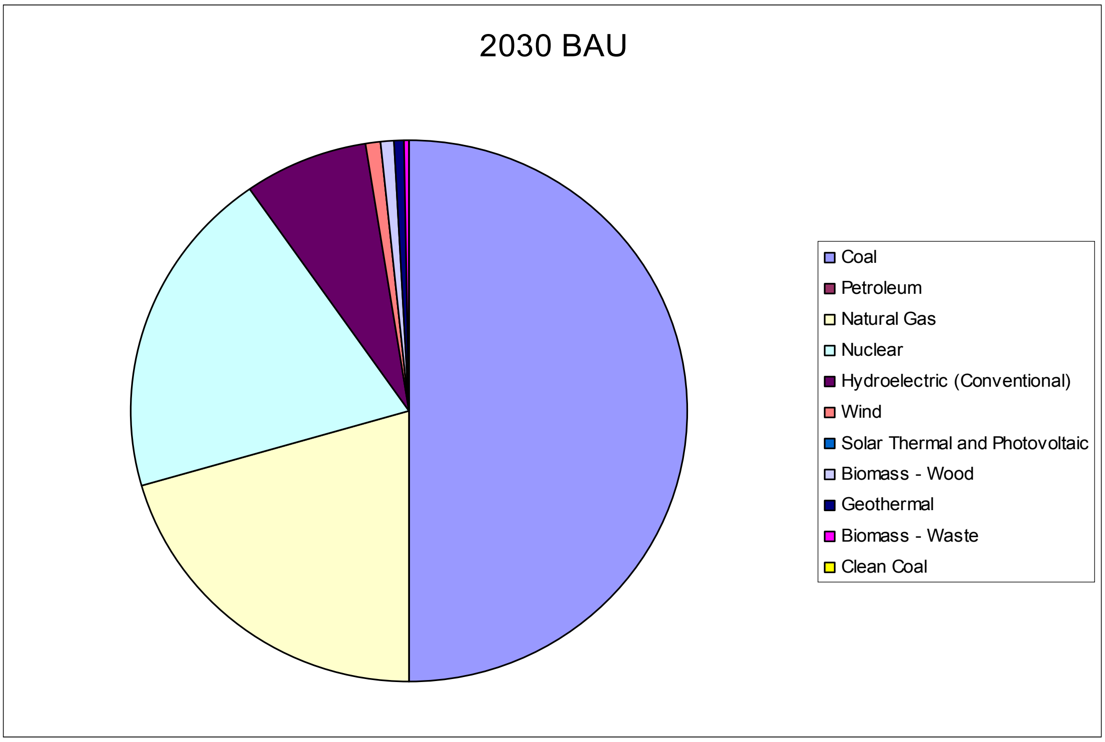



**Figure II: Energy generation mix for 2030 for 10% switch from coal to renewables**

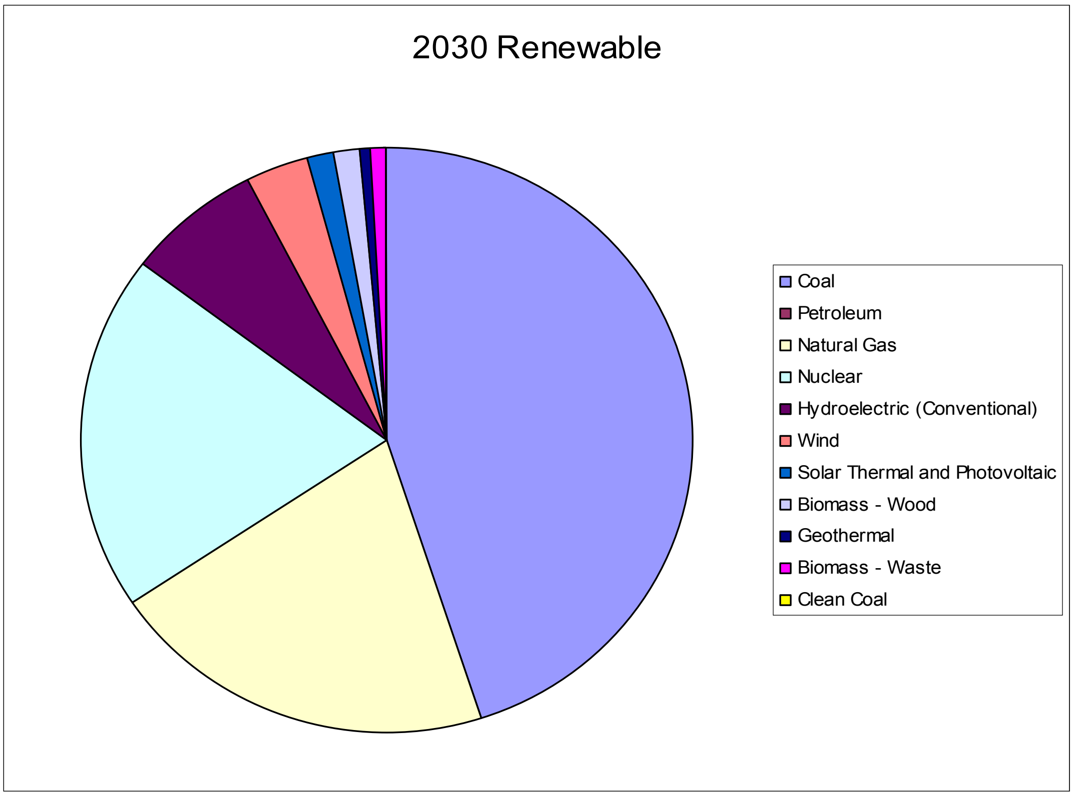
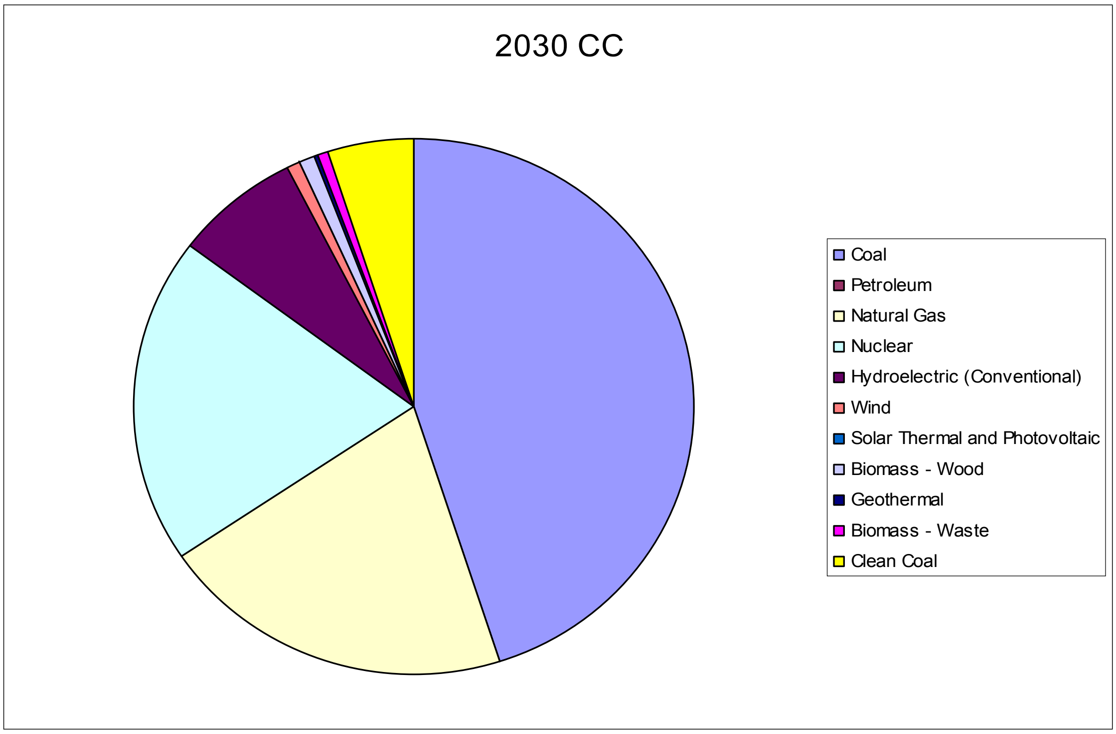
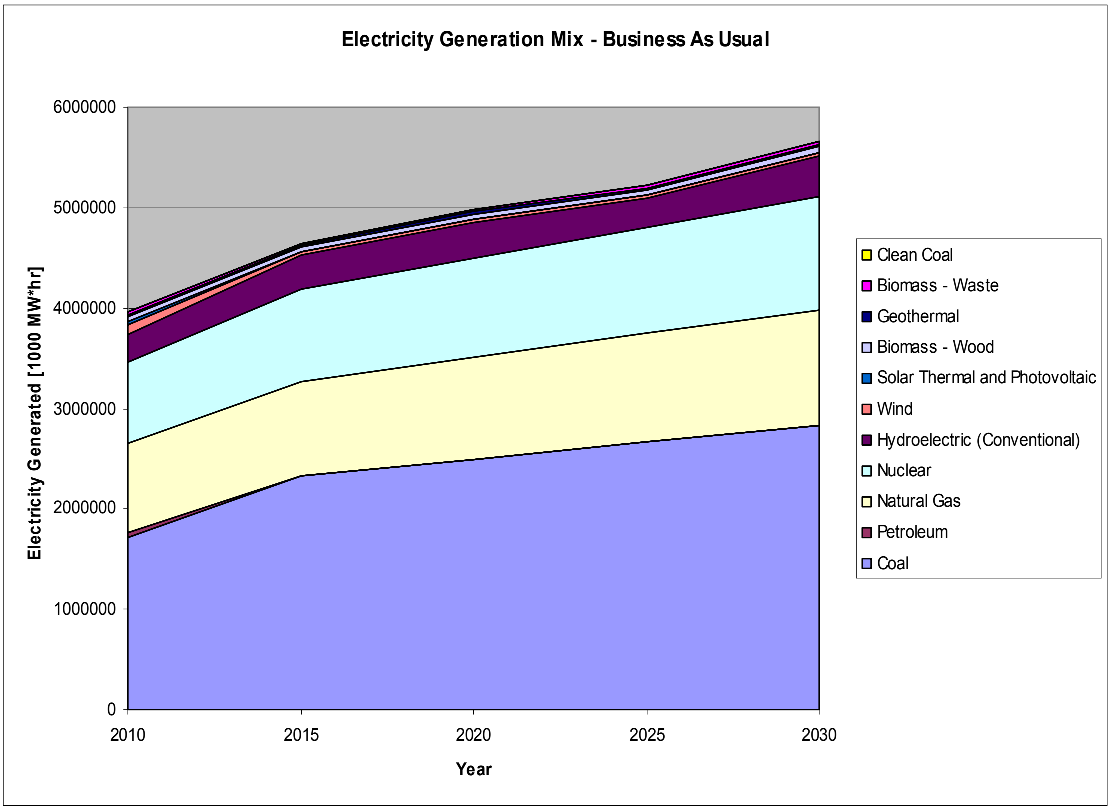


**Figure III: Energy generation mix for 2030 for 10% switch from coal to clean coal with CCS**



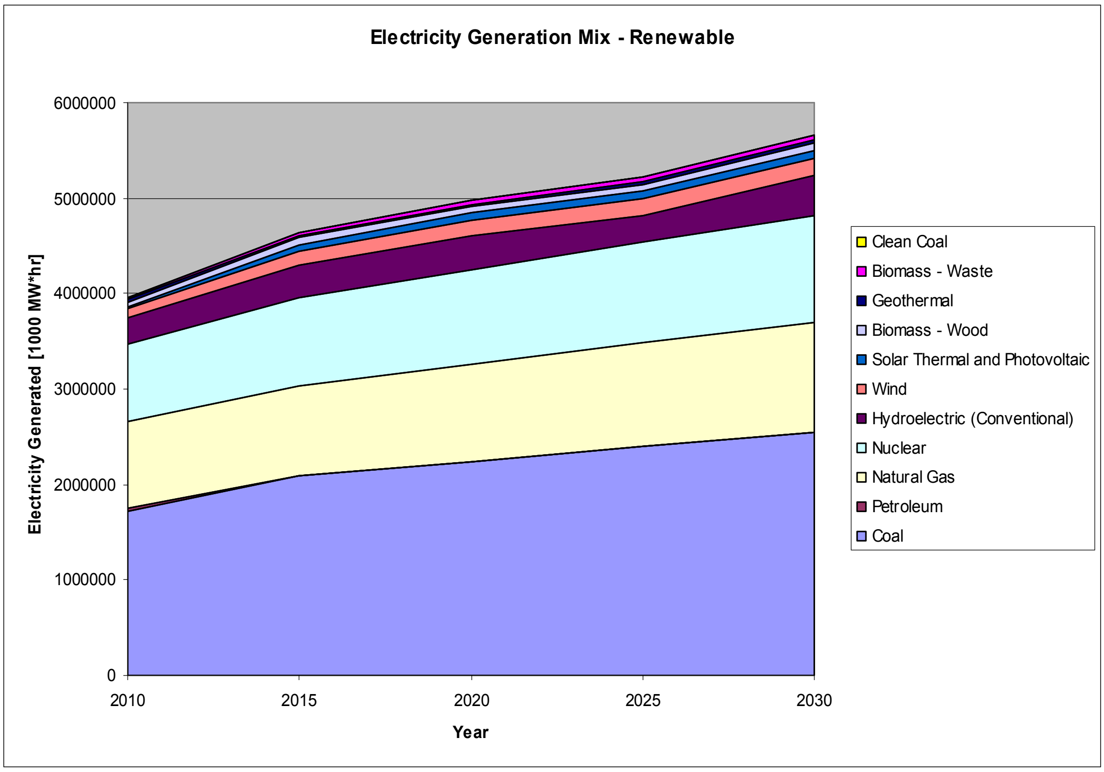

Utilizing a series of curve fits to the data from 1990-2009, the projected business as usual energy generation mix from 2010 to 2030 is obtained as shown in Figure IV.

**Figure IV: Projected electricity generation mix from 2010 to 2030 for business as usual scenario**



The first policy scenario, that is switching 10% coal to 5% wind, 3% solar, 1% biomass waste and 1% biomass wood was applied to the business as usual energy generation mix in Figure IV to yield the renewable energy generation mix shown in Figure V.

**Figure V: Projected electricity generation mix from 2010 to 2030 for policy scenario 1, that is switching 10% coal to renewables (5% wind, 3% solar, 1% biomass waste and 1% biomass wood)**




The second policy scenario, that is switching 10% coal to clean coal technologies using CCS, was applied to the business as usual energy generation mix in Figure IV to yield the energy generation mix with clean coal as shown in Figure VI.

For the three scenarios: (1) BAU, (2) 10% switch from coal to renewables, and (3) 10% switch 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 economic model for the three scenarios under the three types of price and supply conditions are summarized in Tables 1, 2 and 3 respectively.

**Figure VI: Projected electricity generation mix from 2010 to 2030 for policy scenario 2, that is switching 10% coal to clean coal using CCS**

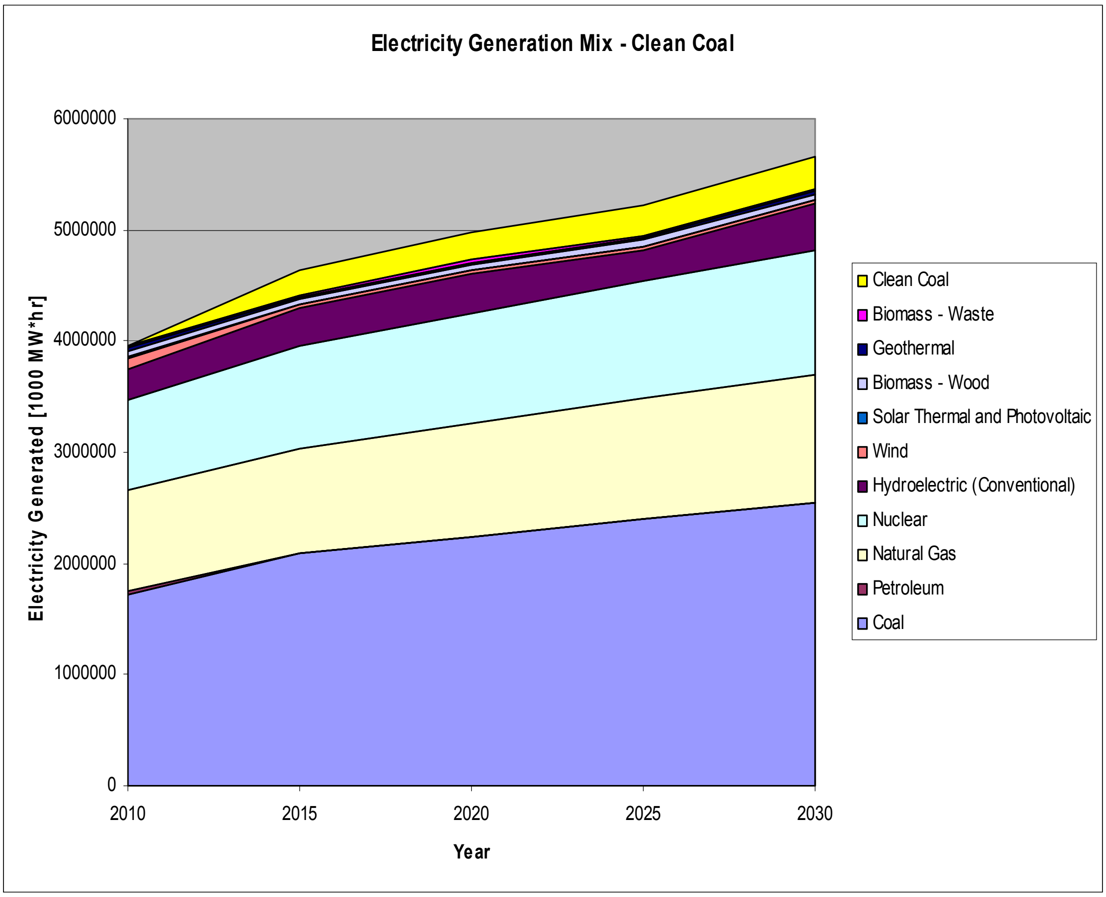



**Table 1. Policy simulation results for the three scenarios under the condition – both the energy supply and price are regulated. All values in the table are percentage change from the business as usual case**

| Energy Supply and Price Regulated | 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% |

**Table 2. 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 | 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% |

**Table 3. 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 | 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 ] | 3.8E+04 | 1.4E+04 | 2.9E+04 | 1.1E+04 | 2.3E+04 | 7.8E+03 | 1.7E+04 | 5.7E+03 |
| *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% |

The results in Tables 1, 2 and 3 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 8.8% in 2015 and by 6.3% in 2030 and emissions to decrease by 8.1% 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 3.0% in 2015 and by 2% in 2030 and emissions to decrease by 8.1%. 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) the household demand lowers by 8.8% in 2015 and by 6.5% in 2030, the industrial demand lowers by 21% in 2015 and by 16.1% in 2030 and total demand by 8.5% in 2015 and by 5.9% in 2030. The capital input decreases by 0.2% in 2015 and by 0.5% in 2030. The wages reduce by 0.7% in 2015 and by 0.5% in 2030. The output is lowered by 0.7% in 2015 and by 0.6% in 2030. As a consequence, the household assets are lowered by 0.9% in 2015 and by 0.7% in 2030 and the household consumption decreases by 0.8% in 2015 and by 0.6% in 2030. Under scenario 3 (clean coal) the household demand lowers by 3.2% in 2015 and by 2.1% in 2030, the industrial demand lowers by 8% in 2015 and by 5.4% in 2030 and total demand by 2.3% in 2015 and by 2% in 2030. The capital input decreases by 0.2% in 2015 and by 0.2% in 2030. The wages reduce by 0.2% in 2015 and by 0.2% in 2030.The output is lowered by 0.3% in 2015 and by 0.2% in 2030. As a consequence, the household assets are lowered by 0.3% in 2015 and by 0.2% in 2030 and the household consumption decreases by 0.3% in 2015 and by 0.2% in 2030. Additionally, fixed electricity supply implies emissions decrease by exactly 10% of the emissions from coal. This represents an overall reduction of 8.1% in $CO_2$ emissions.

*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 38,000 workers in 2015 and of 17,000 workers in 2030. So the expected market wages reduce by 0.7% in 2015 and by 0.5% in 2030 and goods consumption decreases by 0.8% in 2015 and by 0.6% in 2030. Because electricity supply is now fully adjusted downward, the total electricity generation cost goes down by 0.5% in 2015 and by 0.1% in 2030 and emissions decrease by 16% in 2015 and by 13.6% in 2030. Under scenario 3, it will result in layoff of 14,000 workers in 2015 and of 5,700 workers in 2030. So the expected market wages reduce by 0.3% in 2015 and by 0.2% in 2030 and goods consumption decreases by 0.3% in 2015 and by 0.2% in 2030. Because electricity supply is now fully adjusted downward, the total electricity generation cost goes down by 0.3% in 2015 and by 0.0% in 2030 and emissions decrease by 11.1% in 2015 and by 9.9% in 2030.

The above analysis shows that scenario 3 (switch to clean coal) is a better policy option than the scenario 2 (switch to renewable). 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 (while fossil fuel based electricity generation is cheaper than renewable sources and clean coal with CCS).

## 4. CONCLUSIONS

1. An economic model for electricity generation in the U.S has been created that runs policy simulations for 2010-2030.
2. The model predicts that utilizing clean coal technologies such as CCS will affect the economy less than utilizing the renewable energy sources. This is due to clean coal technologies being cheaper than renewable energy technologies based on the current estimates.
3. 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.

## FUTURE WORK

1. The model should be applied to the major emerging economies of India and China. The agriculture sector is important in these countries. The agriculture sector can be modeled in a manner similar to the commercial sector in the present model.

2. The non-fixed labor requirements should be added to the model. It is likely that the older and more developed power generation methods will become increasingly more automated and therefore less labor intensive compared to the power plants employing newer less-traditional renewable power generation sources; thus, the value of $\theta$ is likely to be larger for the newer technologies than the older established technologies.
3. The provision for carbon tax should be included in the model. Carbon tax is a way to encourage the electricity generation companies to reduce the carbon emissions by either switching to alternative renewable energy generation sources or by developing the $CO_2$ capture and sequestration (CCS) technologies.
4. The current model does not take into account the cost associated with switching from one energy source to another. A cost function should be included which can model this cost.
5. The current model is a steady state model. It should be extended to conduct the dynamic analysis using the tools of dynamic programming. This will allow for the ongoing growth of households and firms over time; it will also capture shifts in supply and demand factors over time.

**DATA COLLECTION SOURCES**

1. Employment for each state by sector for 2001-2006. Sectors: Agriculture, forestry, fishing and hunting, Mining; Utilities, Construction, Manufacturing, Transportation and Warehousing (excluding Postal Service), Government and Other as well as the total employment; Source: Bureau of Labor Statistics.
2. US electricity retail sales by sector in thousand megawatt hours for each state for 1990-2006. Sectors: Residential, Commercial, Industrial and Other, as well as total sales. Source: Energy Information Administration (EIA), 2008.
3. US energy generation data for 1980-2009 by source. Electricity generation sources: coal, petroleum, natural gas, other gases, total fossil fuels, nuclear, hydro (conventional), biomass wood, biomass waste, geothermal, solar/PV, wind, total renewables, other; as well as total for all sources. Source: EIA, Annual Energy Review, 2008.
4. Total coal usage in power generation for 1990-2006 in thousands of tons of coal. Source: EIA, 2008.
5. US $CO_2$ emissions from the electric power industry for each state by source for 2003-2006. Sources: coal, petroleum, natural gas, geothermal and other renewables as well as the total. Source EIA, 2008.
6. US average electricity retail price in cents per kilowatt hour for 1998-2006. Source: EIA, 2007.
7. US electricity generation costs in cents per kilowatt hour.
8. A full data set is available for 2006. Additional years of data are available for some of the sources so that a curve fit could be made to fill in the gaps in the data for other years. Sources: coal, natural gas, nuclear, petroleum, wind, residential photovoltaics, commercial photovoltaics, industrial photovoltaics, solar thermal, geothermal, hydroelectric small and hydroelectric large. Sources: Nuclear Energy Institute, U. S. Electricity Production Costs and Components (1995-2008); Energy Information Administration, Annual Energy Review 2008; Table 8.2a Electricity Net Generation: Total (All Sectors), Selected Years, 1949-2008; World Energy Assessment; Overview: 2004 Update. Solarbuzz.com, Solar Electricity Price Index verses US Electricity tariff Price Index; Facts About Hydropower, Wisconsin Valley Improvement Company.
9. US electricity generation for each state by source in megawatt hours for 1990-2006. Sources: coal, petroleum, natural gas, other gases, nuclear, hydroelectric, other renewables, pumped storage and other as well as the total. Source EIA, 2008.
10. US $CO_2$ emissions from energy consumption for each sector from 1980 to 2005. Sectors: residential, commercial, transportation, electric power. Source: EIA, 2008.
11. US electricity demand from 1980 to 2006 for each sector.
12. Sectors: residential, commercial, industrial, transportation as well as total. Source: EIA, 2008.
13. State level $CO_2$ emissions from fossil fuel combustion for electricity generation from 1990 to 2004 in million metric tons of $CO_2$. Source: EIA, 2008.

14. Cost of living statistics (consumer price index) for the Northeast Urban, Midwest Urban, South Urban, and West Urban, as well as US total for 1985-2006. Source: Bureau of Economic Analysis, 2008.
15. State level population data for 1970-2007. Source: US Census Bureau, 2008.
16. State level average number of people per household for 2007. Source: Bureau of Labor Statistics, 2008.
17. US Gross State Product (GSP) for each state for each industry in non-chained dollars for 1997-2006. Industries: agriculture, forestry, fishing and hunting, mining, utilities, construction, manufacturing, transportation and warehousing (excluding postal service), government and other; as well as the total. Source: Bureau of Economic Analysis, 2008.
18. State level motor-vehicle registration for 2003-2005. Sectors: automobiles, motorcycles, busses and trucks. Source: Bureau of Transportation Statistics, 2008.

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