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An energy Economic Model for Electricity Generation In the United States

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WASHINGTON UNIVERSITY IN ST. LOUIS

School of Engineering and Applied Science

Department of Mechanical, Aerospace and Structural Engineering

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AN ENERGY ECONOMIC MODEL FOR ELECTRICTY GENERATION IN THE UNITED STATES

by

Lee Chusak

A thesis presented to the School of Engineering
of Washington University in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE

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ABSTRACT OF THE THESIS

An Energy Economic Model for Electricity Generation In the United States

by

Lee Chusak

Master of Science in Mechanical Engineering

Washington University in St. Louis, 2009

Advisor: Professor R. K. Agarwal

Co-Advisor: Professor P. Wang

An equilibrium economic model for policy evaluation related to electricity generation in the 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 commercial enterprises (non-manufacturing businesses such as software firms, banks, restaurants, service organizations, universities etc.). Energy supply takes into account the electricity delivered to the consumer by the utility companies at a certain price which may be 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 seventeen years from 1990 to 2006 in the

U.S. The model is calibrated for the aggregate data. The calibrated model is then 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. 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. The U.S. model is modified to perform the state-level policy analysis for the same three scenarios stated above. Policy experiments are conducted for the states of California and Illinois.

CRA International has developed a top-down/bottom up model called the MRN-NEEM model which determines the percentage of electricity generation from various sources to meet the emission goals for CO_2 for 2020. To meet the same CO_2 goals for 2020, we employ our model to determine the mix of various electricity generation sources and then compare our results with those predicted by the MRN-NEEM model; both sets of results are in reasonably good agreement. In addition, an extrapolated dataset was used in our model to determine the mix of various electricity generation sources for meeting the Obama administration CO_2 goals for 2020 and 2050.

Acknowledgements

Thanks to Dr. Ramesh Agarwal and Dr. Ping Wang for their guidance, help and encouragement on the work presented in this thesis. Additionally, thanks to Dr. David Peters and Dr. Kenneth Jerina for being on my thesis defense committee. The financial support of the McDonnell Academy Global Energy and Environment Partnership (MAGEEP) grant and the Mechanical, Aerospace and Structural Engineering (MASE) department is gratefully acknowledged.

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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 source s
K	capital input
$M(s)$	material inputs for source s
MRN	Multi-Region National Model
NEEM	North American Electricity and Environmental Model
N	total labor demand
N^C	commercial sector labor
N^E	electricity sector labor
$N^E(s)$	electricity sector labor for source 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, ie. coal, nuclear, etc.
U	ratio of CO_2 emissions from a fossil fuel source to CO_2 emissions from coal for each 1 Btu of energy released
V^H	household value function
V^F	industrial value function
w	wage
x	consumption good
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 source s

ν	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
Ξ	CO_2 calculation calibration factor

Chapter 1

1.1 Introduction

Modeling of CO_2 emissions and the economic factors related to the switch from fossil fuels to renewable sources for electricity generation has become very important with the recent trends of moving toward a more economically and environmentally sustainable society. Using the, "Brundland definition…of sustainable development…. '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" [1]. It is therefore necessary 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 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 excessive amounts of fossil fuels for meeting the energy needs, is not sustainable.

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 is improbable 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 other alternative renewable energy sources for power generation.

In this thesis, we consider the economics of electricity generation in the U.S. as the switch is made from non-renewable fossil fuel based energy sources to renewable energy sources. 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 and the National Energy Model. 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) 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.

1.2 Motivation

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. Furthermore, since different fossil fuels produce different amounts of CO_2 emissions per unit of energy released, our energy-economic model also includes a detailed CO_2 emissions model in order to achieve the environmental constraints on CO_2 emissions in 2025 and 2050, while considering the mix of renewable and non-renewable energy sources for electricity generation in the U.S.

1.3 General Equilibrium Models

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. Figure 1.1 shows the flow of goods, services and payments normally seen in a computable general equilibrium model.

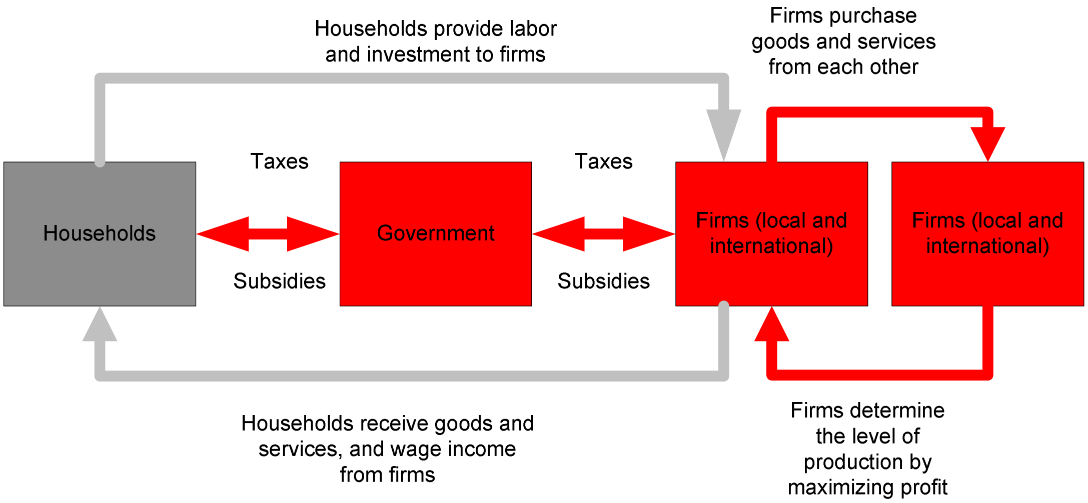


Figure 1.1: The flow of goods, services and payments in a computable general equilibrium model [2].

The household provides 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 also pay taxes to the government and receive 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.

1.3.1 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)"

[1]. All of the agents in the model respond to changes in prices and allow for multiple regions to be linked by trade [2].

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 [2]. They, “capture technology in the engineering sense: a given technique related to energy consumption or supply, with a given technical performance and cost” [1].

Table 1.1 describes the main differences between top-down and bottom up economic models.

Table 1.1: Comparison of top-down and bottom-up models, from Nakata [1].

Top-down models	**Bottom-up models**
Use an economic approach	Use an engineering approach
Cannot explicitly represent technologies	Allow for detailed description of technologies
Reflect available technologies adopted by the market	Reflect technical potential
Most efficient technologies are given by the production frontier (set by market behavior)	Efficient technologies can lie beyond the economic production frontier suggested by market behavior
Use aggregated data for predicting purposes	Use disaggregated data for exploring purposes
Based on observed market behavior	Independent of observed market behavior
Disregard the technically most efficient technologies available, thus underestimate potential for efficiency improvements	Disregard market thresholds (hidden costs and other constraints), thus overestimate the potential for efficiency improvements
Determine energy demand through aggregate economic indices (GNP, price elasticities), but vary in addressing energy supply	Represent supply technologies in detail using disaggregated data, but vary in addressing energy consumption
Endogenize behavioral relationships	Assess costs of technological options directly
Assumes no discontinuities in historical trends	Assumes interactions between energy sector and other sectors is negligible

1.3.2 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 thesis, for the most part, follow the format of the Bellman equation:

$$V(x_0) = \max_{a_0}\left[F(x_0, a_0) + \beta V(x_1)\right] \qquad (1.1)$$

where V is the value function [3]. The value function is, "the best possible value of the objective, written as a function of the state [variable]" [3]. The Bellman equation, (1.1), gives the value function at a given time period as the maximum of some objective, 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 variable).

$$\frac{\partial}{\partial a_0}\left(V(x_0) = \max_{a_0}\left[F(x_0, a_0) + \beta V(x_1)\right]\right) \qquad (1.2)$$

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

$$x_1 = G(x_0) \qquad (1.3)$$

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 [4, 5]:

$$\frac{\partial}{\partial x_0}\left(V(x_0) = \max_{a_0}\left[F(x_0, a_0) + \beta V(x_1)\right]\right) \tag{1.4}$$

Using the first-order necessary conditions and the Benveniste-Scheinkman condition, the value function can be calculated [3].

The present model, developed in this thesis, falls mostly 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.

1.3.3 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 Section 1.3.2. 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]" [1]. Unlike the present model developed in this thesis, the dynamic model results into a time series that can provide information as to how the current decisions affect the future outcomes.

1.4 Survey of Other Energy - Economic Models

1.4.1 National Energy Model

This model is a multi-period market equilibrium model which is a partial equilibrium dynamic model [1]. This model is called the "national energy model" that has been applied to Japan by Nakata [1]. Figures 1.2 - 1.7 show how all the sectors of the economy in this model are interconnected. The model includes petroleum, natural gas, coal, nuclear and renewable sources for electricity generation. The industrial sector has demand for heat and electricity as shown in Figure 1.2. The heat demand is obtained through the industrial heat market which is supplied from five different industrial heat sources - petroleum, gas, coal, gas (cogen) and electrical. Each of those five sources is fed from its respective market (e.g. petroleum market for petroleum heat). The electricity demand is obtained from the industrial electricity market which receives its electricity from the economy- wide electricity market and the electricity generated by the cogen gas industrial heat (cogen means that the excess industrial heat is used to generate electricity).

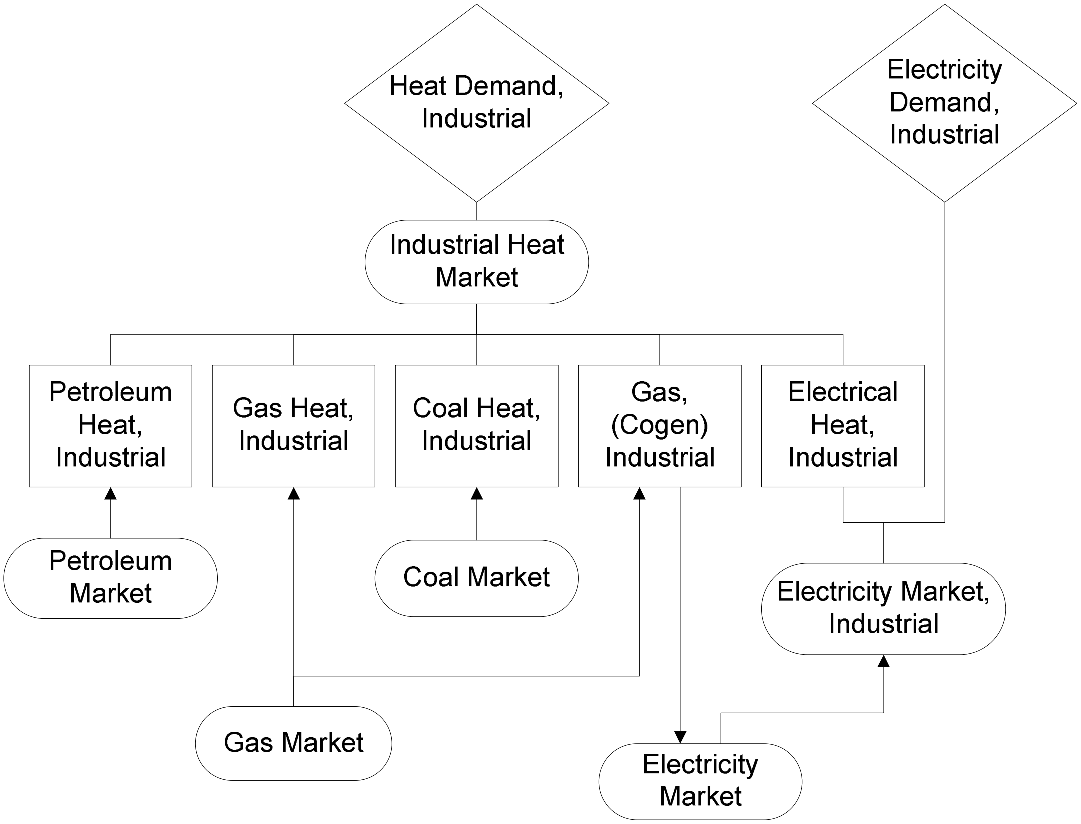


Figure 1.2: Industrial sector of the national energy model [1].

Figure 1.3 shows the commercial demand for electricity and heat. The system is similar to the industrial demand; however, it does not use gas (cogen) as a heat source.

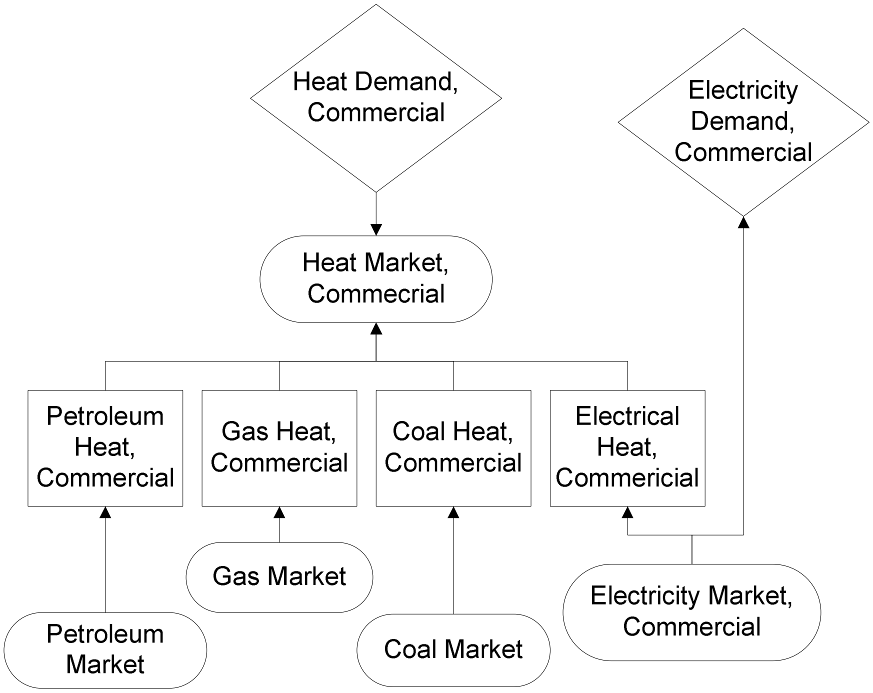


Figure 1.3: Commercial sector of the national energy model [1].

Figure 1.4 shows the residential demand for heat and electricity. The method by which the residential sector is modeled is the same as the commercial sector.

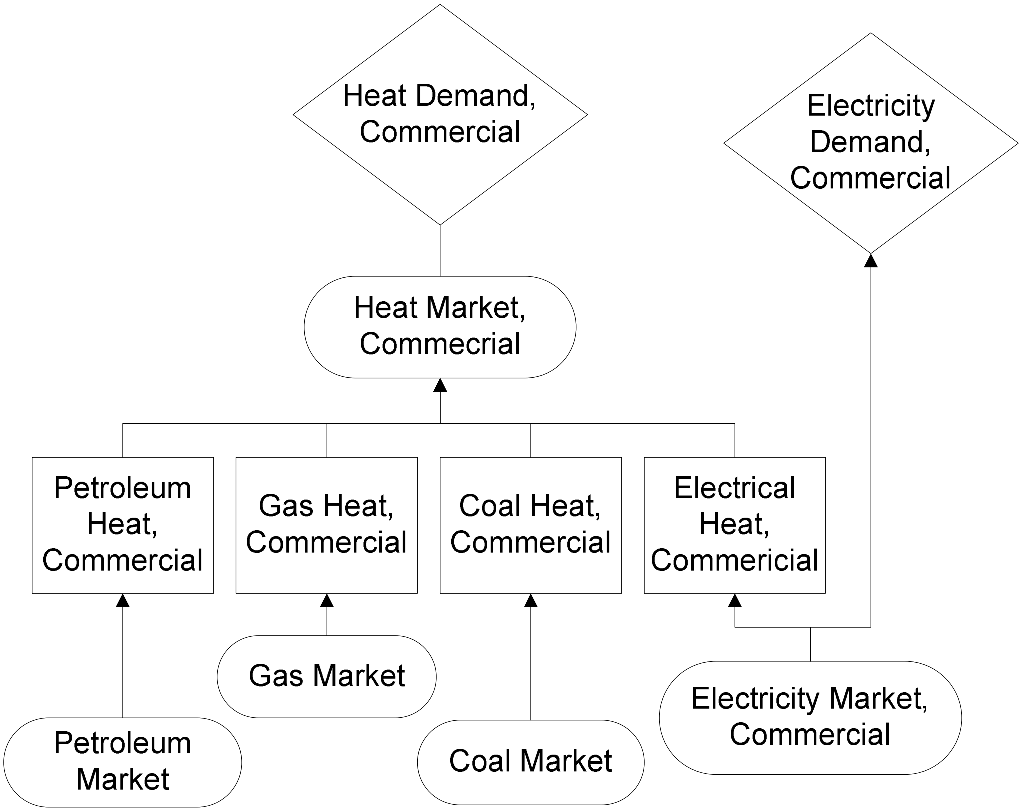


Figure 1.4: Residential sector of the national energy model [1].

Figure 1.5 shows the transportation sector of the model. There are two types of demand for transportation - truck and personal. Truck transportation and personal transportation satisfy those demands. Truck and personal transportation require fuel which comes from the petroleum market.

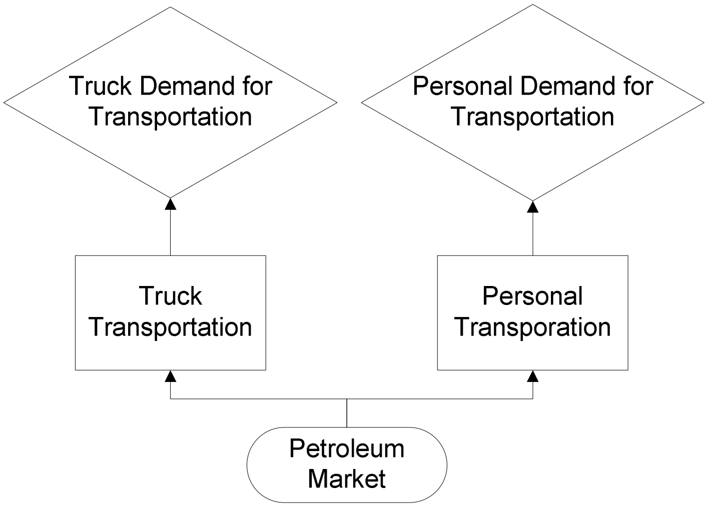


Figure 1.5: Transportation sector of the national energy model [1].

Figure 1.6 shows how the resources are brought to market and how the carbon taxes are applied. The model taxes the petroleum, natural gas and coal before it goes to the market place. There is a maximum amount of CO_2 that can be released and there is a tax associated with the release of a given unit of CO_2. There is a marketplace for emissions credits because the total amount of carbon emissions is limited.

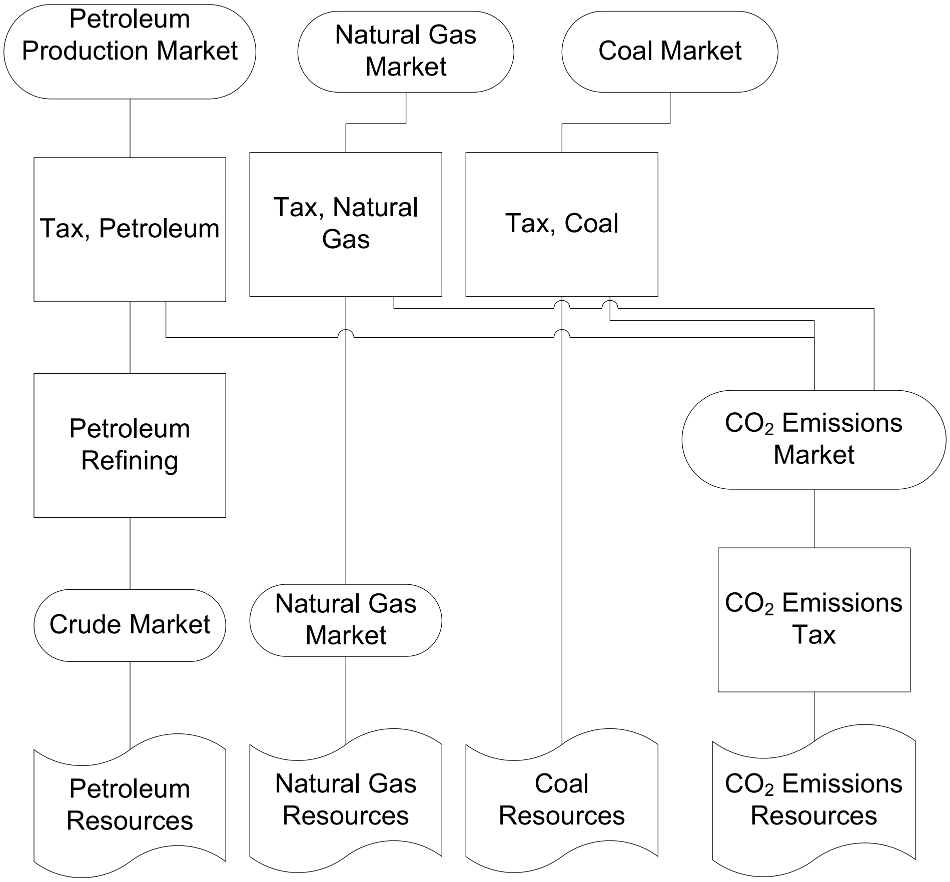


Figure 1.6: Fossil fuel resources of the national energy model [1].

Figure 1.7 shows the sources that contribute to the electricity market. The resources and taxes for the oil boiler, gas boiler, gas turbine, coal boiler, gas combined cycle and coal integrated gasification combine cycle have been omitted in this figure for clarity. If they were included, they would be from a resource that was taxed and then used in power generation (it would be similar to how the hydroelectric power is treated in

Figure 1.7). Hydroelectric resources are taxed before they are used in hydroelectric power generation; once the power is generated it is sold on the electricity market. For the nuclear boiler and the renewable sources, the resources are both taxed and subsidized. There is a tax on the resources while there is a subsidy on the power generation method. For example, for a nuclear reactor, there might be a subsidy to build the reactor itself; however, there is a tax on the nuclear fuel used in that reactor.

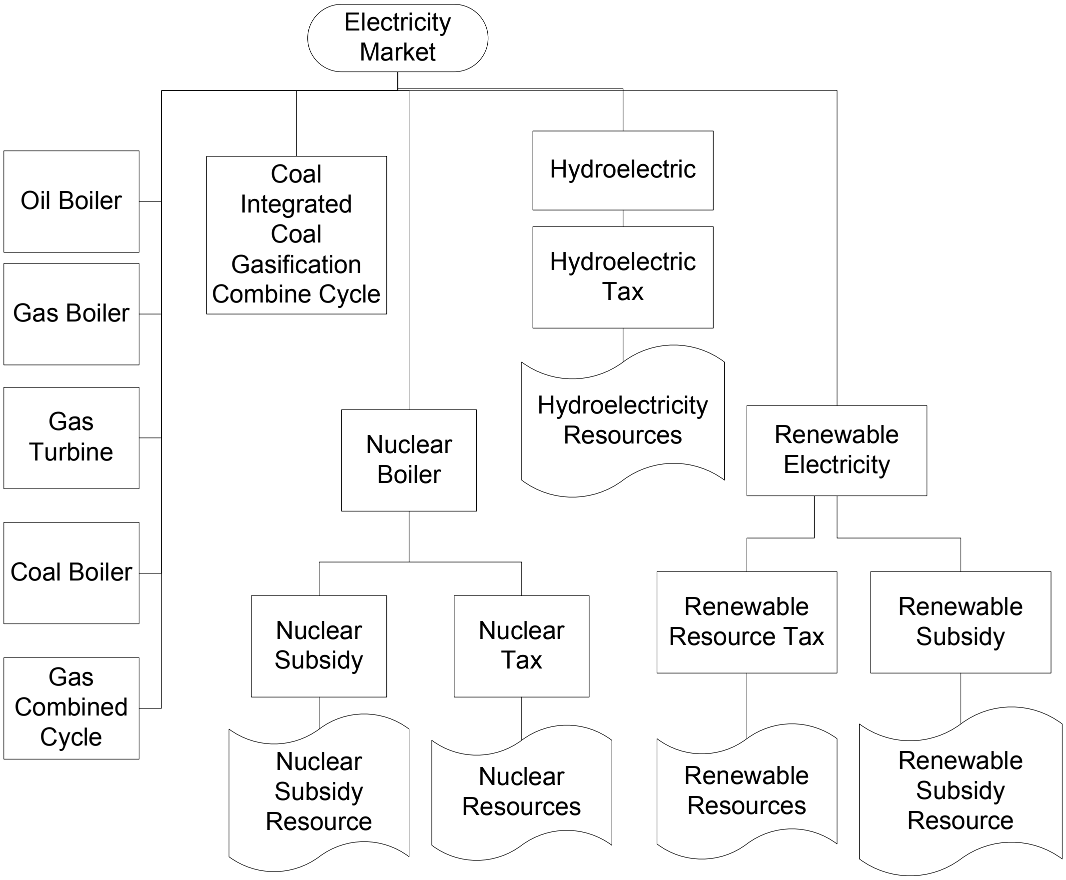


Figure 1.7: Electricity sector in the national energy model [1].

The model includes the implementation of a carbon tax and an energy tax. Carbon tax can be included on high carbon content fuels like coal, natural gas and petroleum (shown in Figure 1.6). Under a carbon tax, all firms that utilize these high carbon fuels, for example a power plant that generates electricity and a residential/commercial building that uses them for heating, would have to pay a tax per ton of CO_2 that is being emitted due to the combustion of fossil fuels. An energy tax is used in a manner similar to the carbon tax; however, it is applied to all sources of energy. In Figures 1.2 – 1.7, the energy tax is included where ever it shows …tax (for example "nuclear tax"). Sweden, Finland, Norway, Denmark and Holland have employed carbon taxes to reduce the amount of CO_2 emissions [1].

The model shows that both the carbon tax and the energy tax can cause a switch in the energy generation source from coal fired power plants to natural gas fired power plants [1]. The Figures 1.8 - 1.10 show the projected mix of electricity generation sources in Japan from 1995-2040 predicted by the national energy model [1].

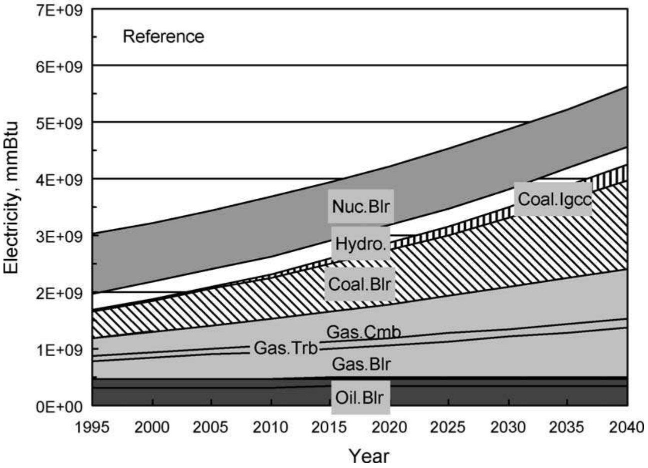


Figure 1.8: National Energy Model's analysis for energy generation mix based on using a carbon tax and an energy tax in the reference case of Japan [1].

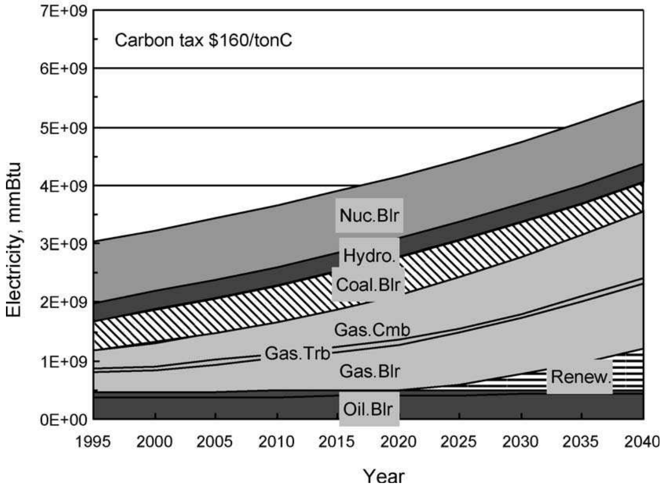


Figure 1.9: National Energy Model's analysis for energy generation mix with a carbon tax of $160/ton of CO_2 for the reference case of Japan [1].

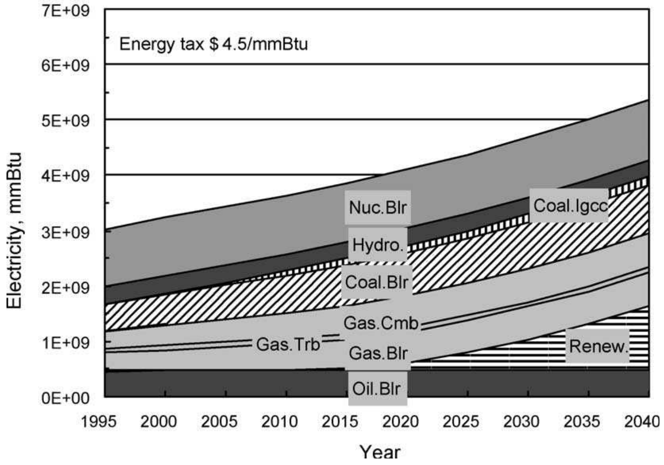


Figure 1.10: National Energy Model's analysis for energy generation mix with an energy tax of $4.5/mmBTU of primary energy consumed for the reference case of Japan [1].

The percentage of coal in the energy generation mix decreases in both cases with carbon tax (Figure 1.9) and with energy tax (Figure 1.10) with respect to the reference case (Figure 1.8) for Japan. When a carbon tax is implemented, the natural gas percentage in the energy generation mix increases; on the other hand, the percentage of natural gas in the energy generation mix decreases when the energy tax is implemented. The percentage of renewable sources of energy increases in the energy generation mix when the energy tax is implemented compared to the scenario when the carbon tax is implemented [1]. Nakata finds that, "the total cost [of electricity generation] with the energy tax is slightly less than the cost with the carbon tax. This [result may] appear to be [contrary to speculation] since the carbon tax is assumed to be more efficient. However, under the energy tax, part of the reduction in carbon is achieved through the reduction of energy services, presumably through greater efficiency in end uses, or by foregoing [the] services. The carbon tax also promotes the reduction in carbon through the energy shift from coal to petroleum and gas, and through the reduction of energy services" [1]. It was also noted by Nakata that it was not wise to quit using coal as an energy source due to the fact that Japan had very few fossil fuel resources. Restricting the types of fuel that could be used in power generation thus becomes a national security threat for Japan [1].

1.4.2 CRA International's MRN-NEEM Integrated Model for Analysis of US Greenhouse Gas Policies

The Ameren UE model created by CRA International called the Multi-Region National - North American Electricity and Environmental Model (MRN-NEEM) is a combination of the top-down MRN model and the bottom-up NEEM model. The top-down model represents the economy as a whole; however, it cannot model the electricity sector in the level of detail that is required for an analysis of the carbon emission policy. The level of detail for the electricity sector is used in the bottom-up model. The MRN and NEEM models are two separate models that are merged together to form the MRN-NEEM Integrated Model. The MRN and NEEM models divide the country into different sets of regions. The Figure 1.11 and Tables 1.2 and 1.3 show various regions for the MRN and NEEM models [2].

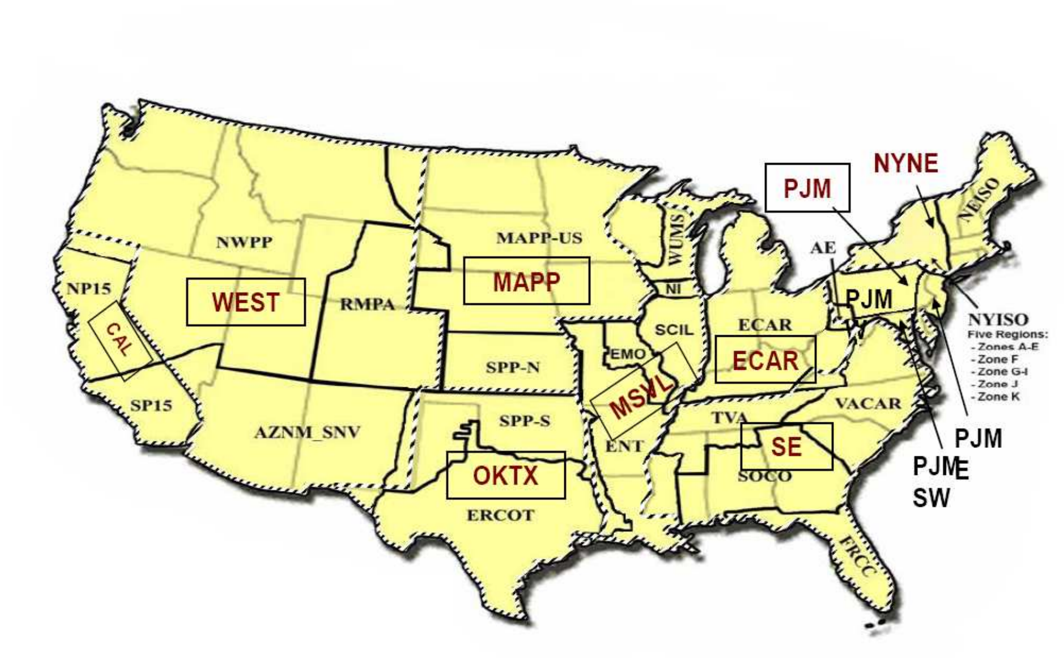


Figure 1.11: MRN and NEEM regions [2].

Table 1.2: MRN regions [2].

MRN Region	Description	State
ECAR	ECAR	MI, IN, OH, KY, WV
NYNE	NY and NEISO regions	MA, ME, NH, NY, RI, VT, CT
MAPP	MAPP-US	ND, SD, NE, KS, MN
PJM	PJM	PA, MD, DC, NJ, DE
CAL	California	CA
West	West except California	WA, OR, AK, HI, ID, MT, NV, UT, CO, WY, AZ, NM
SE	South East	MS, AL, TN, GA, SC, VA, NC, FL
OKTX	Oklahoma and Texas	TX, OK
MSVL	Mississippi Valley	IA, IL, MO, AR, LA, WI

Table 1.3: NEEM regions [2].

NEEM Regions
ECAR
NEISO, 5 NYISO regions
MAPP-US, SPP-N
AE, PJM
NP15, SP15
NWPP, RMPA, ASNM_SNV
SOCO, FRCC, TVA, VACAR
SPP-S, ERCOT
WUMS, NI, SCIL, EMO, ENT

The MRN model shows the total effect of a policy on the economy by tracking the money spent in reducing the CO_2 emissions, that is, the economic ramifications of spending money on reducing CO_2 emissions and the resulting changes in wealth caused by the new emission allowances [2]. The MRN model cannot deal with exports and imports of electricity; to fix this problem, the model uses a social accounting matrix. This social accounting matrix, "represents a 'snapshot' of the economy at the current point along a dynamic growth path" [2]. Since the model is dynamic, the simulation with this 'snapshot' of the economy without any policy scenarios represents the business as usual case. The MRN model uses three energy source sectors: oil and gas extraction, oil refining and distribution, and gas; five non-energy source sectors: agriculture, the three energy use-intensive sectors - manufacturing, transportation and services, and the household sector. CO_2 production is tracked via emission permits. The MRN and NEEM models use slightly different regions in Figure 1.1 in the analysis; when the models are combined, the MRN regions are used in the combined model [2].

The household in the MRN part of the MRN-NEEM model is, "represented as a single representative household that maximizes lifetime utility, subject to its lifetime budget constraint. Utility in a given time period is measured by the consumption of goods….Households optimally distribute wealth over the model horizon by choosing how much output in a given period to consume and how much to forgo for future investment" [2]. Households supply the factors of production: labor and capital. This model uses a variable depreciation rate for capital stock.

The role of government in the MRN part of the MRN-NEEM model assumes that the government sector maximizes its utility, subject to the constraint that it must maintain a balanced budget [2].

In the MRN part of the MRN-NEEM model, industrial firms utilize the labor and capital provided by the household sector and combine them with energy and other material inputs to create goods [2]. The model allows for substitution of inputs by using a nested CES (constant elasticity of substitution) structure [2].

The model builds-in energy efficiency improvements into its "business as usual" case. As an economy shifts from manufacturing to a service oriented economy, the amount of electricity required to generate each unit of gross domestic product decreases. The model calculates this change in electricity requirement using the historical data and trends. The model simulates technological breakthroughs by firms by substituting capital and labor in place of energy when electricity prices increase to produce a unit of output [2].

The NEEM part of the MRN-NEEM models the electricity market in the United States. The model, "solves for the optimal decisions by maximizing the present value of consumer and producer surplus subject to economic, technical and policy constraints. The economic constraint is that the supply and demand for electricity is balanced in each region" [2]. The NEEM model includes the following electricity generation sources: natural gas combined cycle, natural gas combustion turbine, nuclear, integrated gasification combined cycle, integrated gasification combined cycle with carbon sequestration, hydroelectric, pumped hydroelectric storage, wind, solar photovoltaic, solar thermal, landfill gas, biomass and geothermal [2]. The NEEM model allows for natural gas combined cycle, pulverized coal, nuclear, integrated gasification combined cycle, integrated gasification combined cycle with carbon sequestration, wind, solar photovoltaic, solar thermal, landfill gas, biomass and geothermal power generation plants to be built; however, the model limits the number of a single type of plant to be constructed in a given time period [2]. The model also allows for environmental retrofits for coal fired power plants like: flue gas desulphurization (reduces SO_2), selective catalytic reduction (reduces NO_x), selective non-catalytic reduction (reduces NO_x) and activated carbon injection (reduces mercury) [2]. The model also allows for unlimited transmission of power within a region but limited transmission of power between regions (based on data) [2].

The MRN and NEEM parts are solved using an iterative approach. Figure 1.12 shows the schematic of the iterative process.

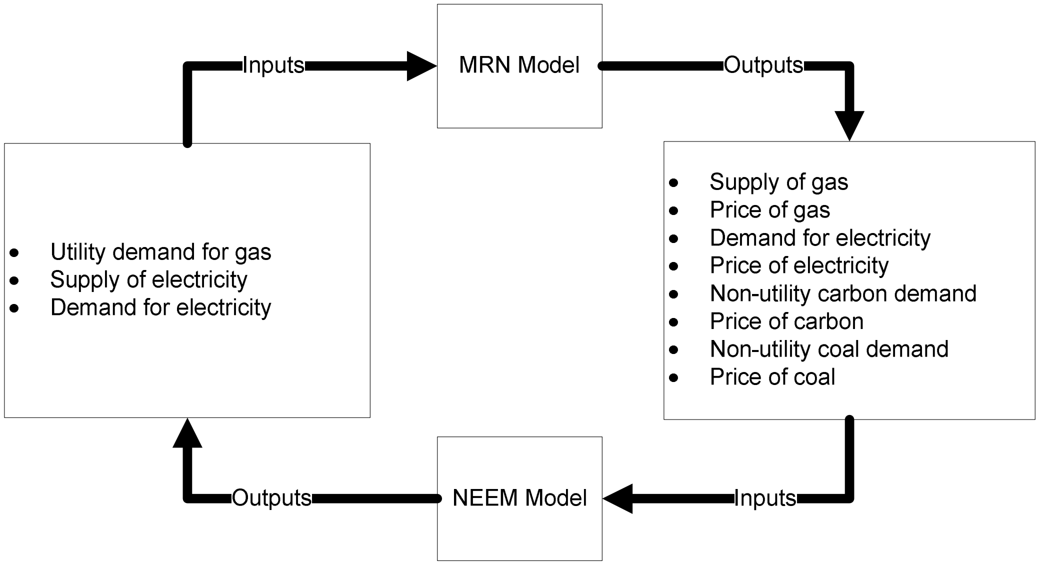


Figure 1.12: Flow of inputs and outputs for the MRN and NEEM parts of the MRN-NEEM model [2].

The NEEM model passes information about the utility's demand for gas, the supply of electricity and the demand of electricity to the MRN model. The MRN model takes these inputs and calculates the new supply of gas, price of gas, demand for electricity, non-utility carbon demand, price of carbon, non-utility coal demand and the price of coal, and feeds these parameters into the NEEM model. The NEEM model then calculates the inputs to the MRN. This process is repeated until the solution converges.

1.5 Scope of the Thesis

An equilibrium economic model for policy evaluation related to electricity generation in the 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 commercial enterprises (non-manufacturing businesses such as software firms, banks, restaurants, service organizations, universities etc.). Energy supply takes into account the electricity delivered to the consumer by the utility companies at a certain price which may be 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 seventeen years from 1990 to 2006 in the U.S. The model is calibrated for the aggregate data. The calibrated model is then 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. 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. The U.S. model is modified to perform the state-level policy analysis for the same three scenarios stated above. Policy experiments are conducted for the states of California and Illinois.

CRA International has developed a top-down/bottom up model called the MRN-NEEM model which determines the percentage of electricity generation from various sources to meet the emission goals for CO_2 for 2020. To meet the same CO_2 goals for 2020, we employ our model to determine the mix of various electricity generation sources and then compare our results with those predicted by the MRN-NEEM model; both sets of results are in reasonably good agreement. In addition, an extrapolated dataset was used in our model to determine the mix of various electricity generation sources for meeting the Obama administration CO_2 goals for 2020 and 2050.

Chapter 2: The Economic Model for Electricity Generation in the U.S.

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 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. In the United States the agriculture sector is also insignificant in terms of electricity consumption; therefore it is also omitted from this model.

2.1 Household

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

$$c = h(x, e^H) \tag{2.1}$$

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

$$V^H(a_t) = \max_{c_t, e_t^H} \left(U(c_t) + \beta^H V^H(a_{t+1}) \right) \tag{2.2}$$

such that

$$a_{t+1} = (1 + r_t)a_t + w_t - x_t - p_t e_t^H \tag{2.3}$$

$$c_t = h(x_t, e_t^H) \tag{2.4}$$

where a denotes the household asset, w the wage, r the real interest rate and β^H the subjective discount factor facing each household. V^H is the household value function; it describes the best possible value of the objective, in this case maximizing $U(c)$ which represents the utility from consumption of c as a function of the state variable a. Equation (2.2) states that the value function at time t is equal to the maximum utility that can come from consumption c_t plus the value function of the next year discounted back one year. Thus the current and the next year's utility is maximized.

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:

$$C_t = N_t c_t \tag{2.5}$$

$$X_t = N_t x_t \tag{2.6}$$

$$E_t^H = N_t e_t^H \tag{2.7}$$

2.2 The 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:

$$Y = f(K, N^F, E^F) \tag{2.8}$$

The output Y is used for consumption and capital investment:

$$Y = X + qZ \tag{2.9}$$

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:

$$V^F(K_t) = \max_{N_t^F, E_t^F, Z_t} \left(Y_t - q_t Z_t - w_t N_t^F - p_t E_t^F + \beta^F V^F(K_{t+1}) \right) \qquad (2.10)$$

such that

$$K_{t+1} = Z_t + (1-\delta)K_t \qquad (2.11)$$

$$Y_t = f(K_t, N_t^F, E_t^F) \qquad (2.12)$$

where β^F is the subjective discount factor facing each producer and V^F is the industrial value function. Equation (2.10) states that the value function at time t is equal to the maximum profits at t plus the value function at $t+1$ facing an industrial depreciation rate of β^F.

2.3 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:

$$E_{t+1}^C = (1+\sigma)E_t^C \qquad (2.13)$$

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

$$N_t^C = \zeta \; E_t^C \qquad (2.14)$$

where $\zeta > 0$ is the employee-energy mix parameter. The Leontief production function states that there is no substitutability between the two parameters (N_t^C and E_t^C) and that the ratio between the two is a constant, ζ [6].

2.4 Aggregate Electricity Demand and Electricity Generation

Total electricity demand is therefore given by a sum of demand from household, industrial manufacturing and commercial sectors:

$$E = \sum_{i=H,F,C} E^i \tag{2.15}$$

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) and $s = 10$ (wind). The electricity generation function can be specified as follows:

$$E(s) = m(N^E(s), M(s), s) \tag{2.16}$$

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

$$E = \sum_s E(s) \tag{2.17}$$

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

$$N^E = \sum_s N^E(s) \tag{2.18}$$

We assume fixed unit labor requirements θ across all sources:

$$N^E(s) = \theta E(s) \tag{2.19}$$

Thus, we have:

$$N^E(s) = \frac{E(s)}{E} N^E \tag{2.20}$$

meaning that the amount of labor required to generate one unit of electricity from a given source is equal to the amount of labor required to generate one unit of electricity from all sources. We can rewrite (2.16):

$$E(s) = \min\left\{\frac{1}{\theta} N^E(s), g(M(s))\right\} \tag{2.21}$$

where $g(M(s)) = m(\theta E(s), M(s), s)$. Equation (2.21) implies that the electricity generated can be limited by either the labor input $N^E(s)$ or the other inputs $M(s)$; the amount of electricity produced is the minimum of the two quantities.

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

$$\min\left\{wN^E(s) + vM(s)\right\} \tag{2.22}$$

such that

$$E(s) = \min\left\{\frac{1}{\theta} N^E(s), g(M(s))\right\} \tag{2.23}$$

Equation (2.22) states that for each source s the cost of electricity generation is minimized. The total cost incurred in electricity generation is the sum of the wages paid to the employees for all sources of electricity generation plus the cost of other inputs for these sources. It can be expressed as:

$$\sum_s \left[wN^E(s) + vM(s)\right] \tag{2.24}$$

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

$$vM(s) = \mu(s)E(s) - wN^{E}(s) \tag{2.25}$$

by setting the total cost of electricity generation from the given source to the unit cost of electricity generation from that source multiplied by the amount of electricity generated by that source and rearranging the equation (2.25). Since we can measure $M(1)$, v can be backed out as well as $M(2)$, $M(3)$, $M(4)$, $M(5)$, $M(6)$, $M(7)$, $M(8)$, $M(9)$ and $M(10)$.

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

$$\sum_{s} \gamma(s)E(s) \tag{2.26}$$

2.5 Aggregate Labor Market

Total labor demand is given by:

$$\sum_{i=F,C,E} N^{i} = N \tag{2.27}$$

In equilibrium, labor supply equals labor demand.

2.6 Optimization and Equilibrium

Household's optimization problem can be rewritten as:

$$V^{H}(a_t) = \max_{x_t, e_t^H} \left(U(h(x_t, e_t^H)) + \beta^{H} V^{H}((r_t + 1)a_t + w_t - x_t - p_t e_t^H) \right) \tag{2.28}$$

by substituting the expressions for c_t and a_{t+1} from equations (2.4) and (2.3) respectively into the household optimization equation (2.2). The first-order necessary conditions can be obtained as:

$$U_c h_x = \beta^H V^H_{a_{t+1}} \tag{2.29}$$

$$U_c h_{e^H} = \beta^H V^H_{a_{t+1}} \cdot p_t \tag{2.30}$$

by taking the partial derivatives of equation (2.28) with respect to x and e^H respectively. Dividing equation (2.30) by equation (2.29) yields:

$$\frac{h_{e^H}}{h_x} = p \tag{2.31}$$

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

$$V^H_{a_t} = \beta^H V^H_{a_{t+1}} \cdot (r_t + 1) \tag{2.32}$$

which is obtained by taking the partial derivative of equation (2.28) with respect to the state variable, a_t. Equations (2.29), (2.30) and (2.32) allow for the value function to be calculated.

Similarly, manufacturer's optimization problem can be rewritten as:

$$V^F(K_t) = \max_{N_t^F, E_t^F, Z_t} \left(f(K_t, N_t^F, E_t^F) - q_t Z_t - w_t N_t^F - p_t E_t^F + \beta^F V^F(Z_t + (1-\delta)K_t) \right) \tag{2.33}$$

by substituting the expressions for K_{t+1} and Y_t from equations (2.11) and (2.12) respectively into equation (2.10). The first-order conditions (partial derivatives of the optimization equation (2.33) with respect to N_t^F, E_t^F and Z_t^F) are obtained as:

$$f_{N_t^F} = w_t \tag{2.34}$$

$$f_{E_t^F} = p_t \tag{2.35}$$

$$\beta^F V^F_{K_{t+1}} = q_t \tag{2.36}$$

The Benveniste-Scheinkman condition (the partial derivative of the optimization equation (2.33) with respect to K_t) is given by:

$$V^F_{K_t} = f_{K_t} + \beta^F V^F_{K_{t+1}} \cdot (1-\delta) \tag{2.37}$$

which can be combined with equation (2.36) to yield:

$$q_{t-1} = \beta^F \left[f_{K_t} + (1-\delta) q_t \right] \tag{2.38}$$

The first order conditions, equations (2.34), (2.35) and (2.36) and the Benveniste-Scheinkman condition, equation (2.37), can be used to find the value function. Under fixed labor requirements, equation (2.19), utility firm's optimization leads to:

$$g_M(M(s)) = \frac{v}{w\theta} \tag{2.39}$$

$$E(s) = \frac{1}{\theta} N^E(s) = g(M(s)) \tag{2.40}$$

Equation (2.40) states that the utility company uses the optimal amount of labor and other inputs such that both N^E and $M(s)$ are limiting the amount of electricity being produced.

2.7 Steady-State Equilibrium

In steady-state equilibrium, all variables are constant. As a consequence, equation (2.32) implies:

$$1 + r = \frac{1}{\beta^H} \tag{2.41}$$

whereas equations (2.3), (2.11), (2.38) and (2.41) yield the following steady-state relationships:

$$x + pe^H = w + \left(\frac{1}{\beta^H} - 1 \right) a \tag{2.42}$$

$$Z = \delta K \tag{2.43}$$

$$f_K = \left(\frac{1}{\beta^F} - 1 + \delta \right) q \tag{2.44}$$

2.8 Calibration

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

$$U = \ln(c) \tag{2.45}$$

$$h(x, e^H) = x^\eta (e^H)^{1-\eta} \tag{2.46}$$

$$f(K, N^F, E^F) = A \left\{ \phi \left[K^\alpha \left(N^F \right)^{1-\alpha} \right]^\rho + (1-\phi)\left(E^F\right)^\rho \right\}^{1/\rho} \tag{2.47}$$

$$g(M(s)) = BM(s)^\psi \tag{2.48}$$

Equations (2.45), (2.46), (2.47) and (2.48) are standard equations used in economic modeling. Equation (2.46) is the Cobb-Douglass utility function. Equation (2.47) is the nested CES (Constant Elasticity of Substitution) production function.

We can calibrate the model based on steady-state relationships. All the data shown in this calibration section used the 1990-2006 average values (averaged for a period of 17 years from 1990 to 2006) 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 model must be recalibrated for each year by using the dataset for that particular year. There are a few adjustments needed to fit the dataset with the model described in sections 2.1 – 2.7.

First, the total employment in our model economy using the aggregate values (average values for the time period 1990 – 2006) is computed using the equation (2.27):

$$N = N^F + N^C + N^E = 22{,}424{,}294 + 76{,}203{,}146 + 62{,}139 = 99.249 \times 10^6 \quad (2.49)$$

Since total employment of the U.S. is 123.035×10^6, all the aggregates are scaled down by a factor of $\frac{99.249}{123.035} = 0.8067$, yielding:

$$\begin{aligned} X &= 5{,}019{,}207 \\ Z &= 759{,}482 \\ E^H &= 912{,}595 \\ E^F &= 814{,}054 \\ E^C &= 797{,}165 \end{aligned} \quad (2.50)$$

The employee-energy mix parameter in the commercial sector can be derived using equation (2.14): $\zeta = 95.5927$. Second, aggregate electricity demand and supply are not identical in the data. We thus adjust $E(s)$ so that the values in equations (2.15) and (2.17) are consistent. That is, if we call the raw data of electricity generation as $ES(s)$, define $ES = \sum_s ES(s)$ and set $E = EH + EF + EC$. We then adjust electricity generation by the factor $\frac{E}{ES}$ to get: $E(s) = \frac{E}{ES} ES(s)$. This conversion factor accounts for the sectors of the economy which are not included in our model (our model includes only households, manufacturing and commercial sectors). Accordingly, we obtain the scaled electricity supply for our three sectors from ten different sources $s = 1, 2, \ldots 10$ as given in Table 2.1:

Table 2.1: Scaled electricity supply for the model economy

$E(1) = 1{,}493{,}939 \quad E(2) = 416{,}955 \quad E(3) = 171{,}979$

$E(4) = 63{,}870 \quad E(5) = 330{,}674 \quad E(6) = 22{,}027$

$E(7) = 10{,}824 \quad E(8) = 9{,}893 \quad E(9) = 298$

$E(10) = 4{,}355$

Third, the material inputs for various forms of electricity generation are very different. To circumvent this problem, we normalize the material inputs to generate $E(1)$ to unity, that is $M(1) = 1$. We can then use the cost data (million dollars per million megawatt-hours) to determine the unit of cost of electricity generation $\mu(s)$, $s = 1$, $2, \ldots 10$ from various sources s as given in Table 2.2.

Table 2.2: Unit cost of electricity generation from various sources [7, 8, 9]

$\mu(1) = 0.030509 \quad \mu(2) = 0.022675 \quad \mu(3) = 0.009778$

$\mu(4) = 0.059974 \quad \mu(5) = 0.049816 \quad \mu(6) = 0.72496$

$\mu(7) = 0.039934 \quad \mu(8) = 0.08 \quad \mu(9) = 0.348$

$\mu(10) = 0.052359$

The results of Table 2.2 are then used in conjunction with equation (2.25) to compute $M(s)$, $s = 2, \ldots 10$. ν is computed for $s = 1$, since $\mu(1)$, $E(1)$, $N^E(1)$ and $M(1)$ are known: we obtain $\nu = 29{,}270$. This value of ν is used in determining $M(s)$, $s = 2, \ldots 10$ which are given in Table 2.3.

Table 2.3: Calculated values of various material inputs $M(s)$.

$M(2) = 0.182116$ $M(3) = 0.00925301$ $M(4) = 0.098636$

$M(5) = 0.410924$ $M(6) = 0.042207$ $M(7) = 0.010275$

$M(8) = 0.019021$ $M(9) = 0.003006179$ $M(10) = 0.005739669$

The total cost of electricity generation is then computed as follows:

$$TC = \sum_{s} \left[wN^{E}(s) + vM(s) \right] = \sum_{s} \mu(s)E(s) \tag{2.51}$$

Next, we use equations (2.6) and (2.7) to yield $x = 0.050572$ and $e^{H} = 0.009195031$. The average real interest rate is set at a commonly selected rate of 5%, faced by all agents. Then using equation (2.41) we obtain $\beta^{H} = \beta^{F} = \frac{1}{1+r} = \frac{1}{1.05}$. The capital depreciation rate usually falls in the range between 5 and 10%, which we set at 7.5%. From the aggregate dataset for 1990 – 2006, the annual wage rate and the relative price of energy are given by $w = 0.03236$ and $p = 0.06936$ respectively. The annual wage rate was calculated using the average hourly wage (in millions of dollars) from the dataset and assuming the average person worked 2000 hours per year. The relative price of electricity, p, was the cost of electricity found in the dataset. Then using equations (2.42) and (2.43), we obtain:

$$a = \frac{x + pe^{H} - w}{r} = 0.37694 \tag{2.52}$$

$$K = \frac{Z}{\delta} = 10{,}126{,}430 \tag{2.53}$$

Using the Cobb-Douglass utility function, equation (2.46), equation (2.31) simplifies to:

$$\frac{1-\eta}{\eta}\frac{x}{e^{H}} = p \tag{2.54}$$

Rearranging equation (2.54) gives the calibration parameter value

$$\eta = \frac{x}{x + pe^{H}} = 0.98755 \tag{2.55}$$

Using the nested CES production function given by equation (2.47), equations (2.34), (2.35) and (2.44) can be rewritten as:

$$f_{N^F} = (1-\alpha)\Gamma\frac{Y}{N^F} = w \tag{2.56}$$

$$f_{E^F} = (1-\Gamma)\frac{Y}{E^F} = p \tag{2.57}$$

$$f_K = \alpha\Gamma\frac{Y}{K} = (r+\delta)q \tag{2.58}$$

where $\Gamma = \dfrac{\phi\left[K^{\alpha}(N^F)^{1-\alpha}\right]^{\rho}}{\phi\left[K^{\alpha}(N^F)^{1-\alpha}\right]^{\rho} + (1-\phi)(E^F)^{\rho}}$. Equation (2.56) is the marginal product of labor. Equation (2.57) gives the marginal product of energy. Equation (2.58) gives the marginal product of capital. The use of Γ simplifies the expressions to a more usable form. Equation (2.58) can be combined with equation (2.9) to obtain:

$$Y = \frac{X}{1 - \dfrac{\alpha\delta\Gamma}{r+\delta}K} \tag{2.59}$$

$$q = \frac{\alpha\delta\Gamma}{r+\delta}\frac{Y}{Z} \tag{2.60}$$

Equations (2.59) and (2.60) can be substituted into the marginal product of labor equation (2.56) and marginal product of energy equation (2.57) to solve for α and ρ as functions of ϕ. For the households, the energy demand share is given by

$1 - \eta = 0.012454$. This represents the portion of the total household budget going to electricity costs. It is reasonable to set the energy demand share by manufacturers twice that of households, i.e.,$1 - \varphi = 0.02490$ or $\varphi = 0.97510$. This represents the portion of the manufacturing firms' total budget going to electricity costs. We can then calibrate $\alpha = 0.935881$ and $\rho = 0.635049$ using equations (2.56), (2.57), (2.59) and (2.60) as described above. Now the manufactured output and the unit cost of capital investment can be 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,

$$A = \frac{Y}{\left\{\phi\left[K^{\alpha}(N^{F})^{1-\alpha}\right]^{\rho} + (1-\phi)(E^{F})^{\rho}\right\}^{1/\rho}} = 1.102033 \tag{2.61}$$

Finally, we manipulate equations (2.19), (2.20), (2.39), (2.40) and (2.48), using the specific functional forms, to calibrate:

$$\theta = \frac{N^{E}}{E} = 0.24615 \tag{2.62}$$

$$\psi = \frac{vM(s)}{wN^{E}}\frac{E}{E(s)} = 2.82979 \tag{2.63}$$

$$B = \frac{E(1)}{\left[M(1)\right]^{\psi}} = 1{,}298{,}463 \tag{2.64}$$

Equation (2.63) was derived by differentiating equation (2.48) with respect to M and equating it to equation (2.39). Equations (2.40) and (2.48) can be combined to yield $B\ M(s)^{\psi} = E(s)$ which can be combined with equation (2.19) and the previous result to yield the calibrated form of equation (2.63). Combining equations (2.40) and (2.48) and noting that we are calibrating for $s = 1$ yields the calibrated form of equation (2.64). Given the CO_2 production of 2,229.756 million metric tons essentially from fossil fuel sources 1,4 and 5, we can obtain an emission conversion ratio (per million megawatts of electricity generated) at $\gamma(1) = 0.00141152$, $\gamma(4) = 0.001112925$, $\gamma(5) = 0.000793973$ with $\gamma(2) = \gamma(3) = \gamma(6) = \gamma(7) = \gamma(8) = \gamma(9) = \gamma(10) = 0$, due to the fact that the majority of carbon emissions are coming from the combustion of fossil fuels ($s = 1,4$ and 5).

This completes the calibration procedure in steady-state equilibrium. Comparing the average values of each of the annual simulations on the time series (1990 – 2006) with the simulation on the average of the data, we find that most errors are very small, with a majority below 1% and only two imputed material input/investment cost data with errors above 10% (the two largest errors being 18.56% in calculating $N^E(10)$ and 11.52% in calculating $M(10)$). These errors can be attributed to the rapid (non-linear) increase in the amount of energy generated by wind power in the time sample. It is therefore concluded that our calibration over the entire sample period using steady-state approximation is fairly precise.

The above calibration applies to the average values for 1990-2006. This calibration would need to be conducted for each year or average of years on which the model is run. For future extrapolation it is unnecessary to calculate both the aggregate and the average of the annual time series. It was done above as an exercise in error analysis.

2.9 Policy Analysis

In this section, we proceed to perform the policy analysis. In order to do this, we need to derive a few more useful steady-state equilibrium relationships. From equations

(2.41), (2.42) and (2.54), we can write the households' goods consumption demand and electricity demand as:

$$x = \eta(w + ra) \tag{2.65}$$

$$e^H = \frac{1}{p}(1 - \eta)(w + ra) \tag{2.66}$$

Using (2.14), (2.18), and (2.19), manufacturing firm's labor demand is given by:

$$N^F = N - N^C - N^E \text{ or } N^F = N - \zeta\ E^C - \theta\ E \tag{2.67}$$

Substituting equation (2.67) into the production function, equations (2.56), (2.57) and (2.58) enable us to express Y, w and p all as functions of ($K,\ E^F$). Using equations (2.6), (2.9), (2.43) and (2.65), we can write household's asset as:

$$a = \frac{1}{r}\left(\frac{Y - \delta qK}{\eta N} - w\right) \tag{2.68}$$

which is again a function of ($K,\ E^F$) as are x and e^H, based on the demand relationships derived above. Aggregating each household's electricity demand with use of equations (2.7), (2.66) and (2.68) and equating it with electricity supply in equation (2.15), we obtain:

$$E^H = \frac{1 - \eta}{\eta}\frac{Y - \delta qK}{p} = E - E^C - E^F \tag{2.69}$$

Equation (2.69) together with equation (2.58) enables us to solve jointly for ($K,\ E^F$). The solution can then be substituted into other functions to derive Y, w, p, a, x, e^H, and E^H.

2.10 Method for Calculating CO_2 Production

CO_2 production was calculated using the data for the amount of CO_2 released to yield a certain amount of energy. It was calculated in terms of pounds of CO_2 released per billion BTU of energy input using Table 2.4.

Table 2.4: CO_2 emissions by primary fuel source per billion BTU of energy input [10].

Generation Source	Pounds of CO_2 Emissions per Billion BTUs of Energy
Natural Gas	117,000
Petroleum	164,000
Coal	208,000

Assuming that 1 Btu of energy coming from natural gas is equivalent to one Btu of energy coming from petroleum or coal, a ratio expressing the relative CO_2 production between the sources is constructed (assuming that this ratio = 1 for coal):

$$\begin{aligned} U_{NG} &= \frac{117{,}000}{208{,}000} = 0.5625 \\ U_{Petrol} &= \frac{164{,}000}{208{,}000} = 0.78846154 \\ U_{Coal} &= \frac{208{,}000}{208{,}000} = 1 \end{aligned} \tag{2.70}$$

Since the values U_{NG}, U_{Petrol} and U_{Coal} calculate the relative amounts of CO_2 released per unit amount of energy extracted, an additional calibration parameter is needed to relate the amount of energy used in the electricity generation process and the amount of electricity produced by the power plant. Using the data from 2006, the calibration factor Ξ is determined:

$$\Xi = \frac{D_{2006}}{E(coal)*U_{Coal} + E(NaturalGas)*U_{NG} + E(Petroleum)*U_{Petrol}} \qquad (2.71)$$

$$\Xi = 0.00141151$$

The year 2006 was chosen since it is the most recent available data in the dataset and therefore represents the latest technology. For other years (1990 – 2005) where CO_2 data is available, the scaling parameter Ξ is calculated such that the predicted value equals the value in the data.

Future CO_2 emissions can be calculated using:

$$D_{year} = \Xi*\left(E_{year}(coal)*U_{Coal} + E_{year}(NaturalGas)*U_{NG} + E_{year}(Petrol)*U_{Petrol}\right) \qquad (2.72)$$

The emission conversion ratios can be calculated as:

$$\gamma(1) = \Xi U_{coal} \quad \gamma(4) = \Xi U_{petrol} \quad \gamma(5) = \Xi U_{NaturalGas} \qquad (2.73)$$

The above calculations assume that all the CO_2 is generated from only three sources - coal, petroleum and natural gas. Biomass waste is not considered in this calculation; we assume that the amount of CO_2 produced by biomass waste is negligible in comparison to the amount of CO_2 produced by the combustion of fossil fuels. Biomass wood is also omitted from the calculation; we assume that the wood is a renewable resource and therefore the amount of wood being burned to generate electricity is equal to the amount grown, thus the net amount of CO_2 emitted by the biomass wood is zero.

2.11 Aggregate Policy Analysis

A computer program for the equilibrium economic model described in sections 2.1 – 2.10 is written in Mathcad; it is given in Appendix B. We now conduct a few policy experiments using the aggregate data for the period (1990 – 2006). We consider switching 10% of electricity generation from coal to 5% from wind, 3% from solar thermal and photovoltaics, 1% from biomass waste and 1% from biomass wood.

For all cases of the aggregate policy analysis the following variables are set as follows in the computer program: consumption = 6222.15, non-residential fixed investment = 941.51, total population = 123035471, factory employment = 22424294, commercial employment = 76203146, utility employment = 621239, average hourly wage = 16.18, average electricity price = 0.069358, electricity generation cost as shown in Table 2.2, interest rate = 0.05, depreciation rate = 0.075, household electricity demand = 1131315, factory electricity demand = 1009157, commercial electricity demand = 988220, $ES(1) = 1826291$, $ES(2) = 697759$, $ES(3) = 287800$, $ES(4) = 106885$, $ES(5) = 553373$, $ES(6) = 36861$, $ES(7) = 18113$, $ES(8) = 14882$, $ES(9) = 498$, $ES(10) = 7288$, CO_2 emissions = 2229.756 and $U(1)$, $U(4)$ and $U(5)$ as defined in equation (2.70). The policy change was calculated in the program with the policy inputs given above.

2.11.1 National Aggregate Policy Analysis: Energy Price and Electricity Supply Fully Regulated

When energy prices and electricity supply are fully regulated the source switch described above only causes the total electricity generation cost to go up by 17.93% and emissions to decrease by 8.230% without changing any other endogenous variables.

2.11.2 National Aggregate Policy Analysis: Energy Price Fully Adjusted and Electricity Supply Fully Regulated

When energy prices are fully adjusted with the electricity supply regulated, the source switch described above will then raise the energy price by 17.92% to beat par with the total electricity generation cost. Higher energy price lowers demand: household demand lowers by 16.38%, industrial demand lowers by 37.14% and total demand by 17.90%. In this scenario, electricity supply and the level of employment remains fixed. Both capital and market wages reduce by 1.11%, whereas the output is lowered by 1.23%. As a consequence, household asset and goods consumption are lowered by 1.87% and 1.39% respectively. Additionally, fixed electricity supply implies emissions decrease by exactly 10% of the emissions from coal. This represents an overall reduction of 8.230% in CO_2 emissions.

2.11.3 National Aggregate Policy Analysis: Energy Price Fully Adjusted with Electricity Supply Fully Adjusted

When energy prices and electricity supply are fully adjusted, the source switch described above will then raise the energy price by 17.92% to beat par with the total electricity generation cost. Higher energy price lowers demand: household demand lowers by 16.44%, industrial demand lowers by 37.14% and total demand by 17.90%. Both capital and market wages reduce by 1.219%, whereas the output is lowered by 1.231%. As a consequence, household asset and goods consumption are lowered by 1.865% and

1.457% respectively. Since demand is lowered less electricity is being produced, this causes 111,207 layoffs. Each household faces a layoff rate of 0.1121%.

2.11.4 National Aggregate Policy Analysis: Additional Notes

The policy simulations in sections 2.11.1 – 2.11.3 have only been conducted on the aggregate values for the time period (1990 – 2006) considered.

It is assumed that when supply is scaled back to meet the lower demand and the price is fully adjusted that all electricity generation sources are scaled back equally. For example, if the price of electricity were to increase, all electricity sources would scale back by a given percentage to meet the lower demand.

2.11.5 National Aggregate Policy Analysis: Conclusions

1. An equilibrium economic model for electricity generation in the U.S. has been developed. The policy simulations on the aggregate data for the U.S. from 1990 to 2006 have been conducted under three policy scenarios: (a) both the energy supply and the electricity price are fully regulated, (b) the energy supply is fully regulated and the energy price is fully adjusted and (c) both the energy price and the electricity cost are fully adjusted. The results of these three different policy scenarios are given in sections 2.11.1-2.11.3.

2. The national model predicts that without government subsidy there will be a decrease in the number of utility workers due to the decrease in demand of electricity with increasing prices. In reality this might not be the case. The model assumes that the utility workers are evenly distributed throughout the power generation sector based on the amount of energy produced. However, newer and less developed technologies are most likely to need more workers than older highly developed technologies used, for example, in coal fired power plants. It is therefore possible that a shift of 10% of coal generated electricity to 5% wind power, 3% geothermal, 1% biomass waste and 1% biomass wood based electricity may result in an increase in employment.

Chapter 3

3.1 The State Level Economic Model for Electricity Generation

The energy/economic model for the U.S. presented in section 2 is modified to conduct the state level policy analysis. Due to the unavailability of state-level consumption, investment and wage data, we adjust the calibration procedure 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:

$$\frac{w_j}{w} = \frac{Y_j / N_j}{Y / N} \tag{3.1}$$

$$\frac{K_j}{K} = \frac{Y_j}{Y} \tag{3.2}$$

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 (3.1) and (3.2) 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 equation (2.66) to state j, we obtain:

$$a_j = \frac{1}{r}\left(\frac{1}{1-\eta} pe_j^H - w_j\right) \tag{3.3}$$

Substituting equation (3.3) into equation (2.65), we obtain:

$$x_j = \frac{\eta}{1-\eta} pe_j^H \tag{3.4}$$

It should be noted that a_j must be nonnegative. Should the imputed value of a_j from equation (3.3) become negative it should be set $a_j = 0$ and the proportionality assumption of wages in equation (3.1) should be abandoned. Instead, one should use equation (2.66) with $a_j = 0$ to obtain: $w_j = \frac{1}{1-\eta} pe_j^H$.

The state-level electricity can be computed by:

$$ED_j = E_j^H + E_j^F + E_j^C \tag{3.5}$$

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

$$EX_j = E_j - ED_j \tag{3.6}$$

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, $\sum_j EX_j = 0$. 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. The computer code described in Appendix B is modified to perform the state-level analysis using the equations (3.1) – (3.6) in conjunction with appropriate equations from section 2.

3.2 Aggregate Policy Analysis for California

We consider switching 7.345% of electricity generation from fossil fuels (lumped together) to renewable (lumped together) energy sources due to lack of detailed state level data. This was done to match the switch analyzed in section 2.11 (the national aggregate policy analysis was conducted on 10 energy sources where as the state level aggregate policy analysis is conducted on 4 energy sources, 7.345% is the reduction in fossil fuel based electricity generation in the national aggregate model once coal, natural gas and petroleum based power generation are lumped together).

3.2.1 California Aggregate Policy Analysis: Energy Price and Electricity Supply Fully Regulated

If the energy prices and electricity supply were fully regulated, the total cost of electricity generation would increase by 1.453% and there would be a decrease in CO_2 emissions of 7.345%.

3.2.2 California Aggregate Policy Analysis: Electricity Supply Fully Regulated and Energy Price Fully Adjusted

Table 3.1 shows the effects of this policy when the energy price is fully adjusted but the electricity supply is fully regulated.

Table 3.1: California aggregate policy analysis: energy price fully adjusted and electricity supply fully regulated.

Total Cost of Generation	1.453%
Household Demand	-1.524%
Industrial Demand	-2.926%
Total Demand	-1.316%
Electricity Price	1.453%
Wages	-0.07451%
Output	-0.08378%
Household Assets	-1.817%
CO_2 Emissions	-7.345%
Jobs Lost	0

3.2.3 California Aggregate Policy Analysis: Energy Price Fully Adjusted and Electricity Supply Fully Adjusted

Table 3.2 shows the effects of the policy when both the energy supply and electricity price are fully adjusted. Each household faces a layoff rate of 0.00589%. This represents the percentages of households that will have a member laid off.

Table 3.2: California aggregate policy analysis: energy price fully adjusted and electricity supply fully adjusted.

CO_2 Emissions	-8.564%
Total Cost of Generation	0.0118%
Electricity Prices	1.453%
Household Asset	-1.820%
Household Demand	-1.524%
Industrial Demand	-2.926%
Consumption	-0.100%
Wages	-0.080%
Jobs Lost	702

3.3 Illinois Aggregate Policy Analysis

We consider switching 7.345% of electricity generation from fossil fuels (lumped together) to renewable (lumped together) energy sources due to lack of detailed state level data. This was done to match the switch analyzed in section 2.11 (the national aggregate policy analysis was conducted on 10 energy sources where the state level aggregate policy analysis is conducted on 4 energy sources, 7.345% is the reduction in fossil fuel based electricity generation in the national aggregate model once coal, natural gas and petroleum based power generation are lumped together).

3.3.1 Illinois Aggregate Policy Analysis: Energy Price and Electricity Supply Fully Regulated

If prices were fully regulated, CO_2 emissions would decrease by 7.345% and the total cost of electricity generation would increase by 4.710%.

3.3.2 Illinois Aggregate Policy Analysis: Electricity Supply Fully Regulated and Energy Price Fully Adjusted

Table 3.3 shows the results of the aggregate policy analysis when supply is fully regulated and price is fully adjusted. The total cost of electricity generation and the total CO_2 emissions remain the same as when supply and price are fully regulated.

Table 3.3: Illinois aggregate policy analysis: electricity supply fully regulated and energy price fully adjusted.

Total Cost of Electricity Generation	4.710%
Household Demand	-4.682%
Industrial Demand	-8.952%
Total Demand	-4.347%
Wages	-0.150%
Electricity Price	4.710%
Output	-0.171%
CO2 Emissions	-7.345
Jobs Lost	0

3.3.3 Illinois Aggregate Policy Analysis: Energy Price Fully Adjusted and Electricity Supply Fully Adjusted

Table 3.4 shows the results of Illinois's aggregate policy analysis when electricity supply and energy price are fully adjusted.

Table 3.4: Illinois aggregate policy analysis: electricity supply and energy price fully adjusted.

CO_2 Emissions	-11.37%
Total Cost of Electricity Generation	0.159%
Electricity Price	4.710%
Wages	-0.180%
Consumption	-0.222%
Household Demand	-4.710%
Industrial Demand	-8.952%
Output	-0.171%
Jobs lost	1499

The corresponding layoff rate to the 1,499 jobs lost is 0.02955%. The model for Illinois required that the asset "a" be set to zero because when it was calculated by equation (3.3) it was found to be negative.

3.4 Conclusions

The state level model is applied to two states – California and Illinois with two very different mixes of energy generation sources. Illinois primarily generates energy from coal while California generates a much larger portion of electricity from non-fossil fuel sources. As a result of this difference in energy sources for electricity generation, the same percentage switch in energy sources from fossil fuels to renewables causes a much larger drop in output in Illinois than in California. This is apparent by the layoff rate shown in sections 3.2.3 and 3.3.3 for California and Illinois respectively, Illinois's layoff rate is 3 times greater than that of California. Despite the greater economic effects (especially on employment) of the switch in Illinois, the switch results in a much greater percentage decrease in CO_2 emissions.

It should be noted that the state level analyses have only been conducted on the aggregate data for the time period from 1990 to 2006. For a more in-depth analysis of how the endogenous variables react to policy changes, the simulations must be run for each year in the time period.

Chapter 4: Application of National Economic Model to Evaluate Future Policy Goals

Three future policy simulations are analyzed in this chapter. The first two scenarios address the recently enunciated Obama administration's goals to reduce the CO_2 emissions by switching from the fossil fuel based electricity generation to nuclear or renewable based electricity generation. In the third scenario, we consider the CO_2 reduction goal used in Ameren UE's model, developed by CRA International using the top-down/bottom-up (MRN-NEEM) approach [11]. To evaluate these scenarios using our economic model described in section 2, we consider four energy sources: fossil fuels, nuclear, hydro-electric and renewable. Furthermore, we assume that the hydro-electric power generation remains constant in the future years.

4.1 The Obama Administration's CO_2 Reduction Goals

In January 2009, the Obama administration enunciated the goals for CO_2 emission reduction from electric power generation. In Figure 4.1, the magenta line represents the projected CO_2 emissions in future years for the business as usual (BAU) case. The blue line represents the desired goal of the Obama administration for the level of CO_2 emissions in future years with the target of achieving the level of CO_2 emissions in 2020 to the 1990 level and in 2050 to 20% of the 1990 level [11]. Figure 4.1 shows the time span from 1990 to 2030 because we applied our model to this time period (and not beyond).

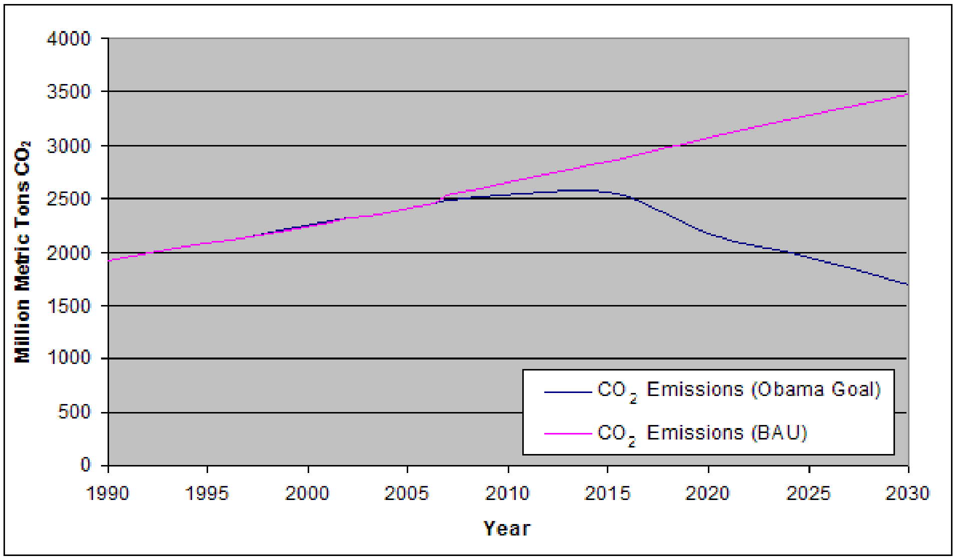


Figure 4.1: Business as usual (BAU) CO_2 emissions and CO_2 emission reduction goal as enunciated by the Obama administration [11].

The BAU case in Figure 4.1 for 2000 – 2030 was calculated by extrapolating the trend for annual net electricity generation for 1990 – 2006 as shown in Figure 4.2. A linear fit was used for the net electricity generation in the U.S. from 1990 to 2006 as shown in Figure 4.2; this curve fit was then used to determine the net electricity generation for the years 2007 – 2030.

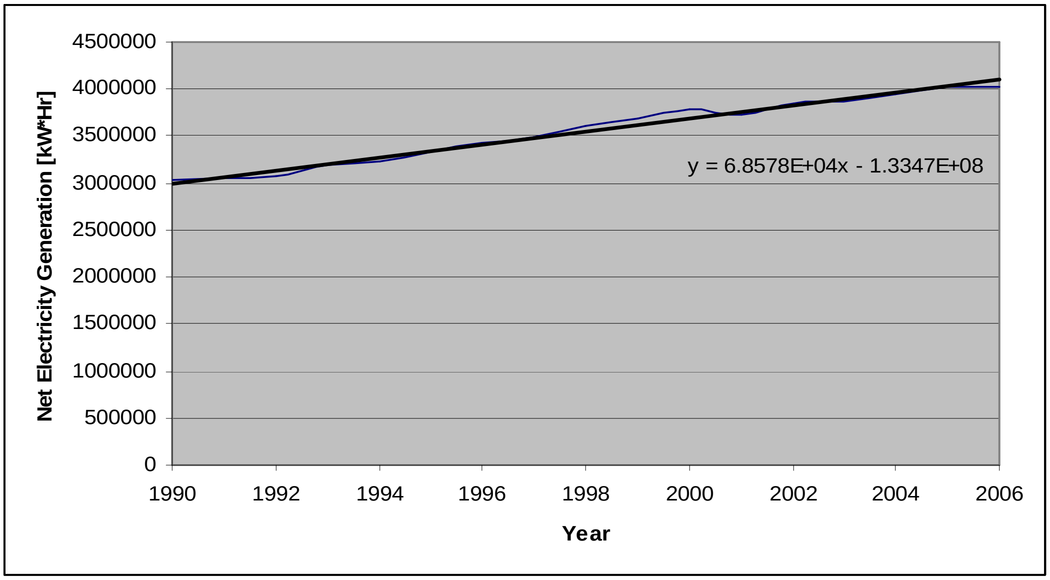


Figure 4.2: Net electricity generation in the US for 1990-2006 [12].

In the BAU case, the mix of electricity generation sources was kept constant for 2006 – 2030 to meet the increased demand for electricity generation as determined by extrapolating the curve in Figure 4.2. Figure 4.3 shows that the mix of electricity generation sources remains constant in the BAU case. The net CO_2 production is calculated for each year from 1990 to 2030 by employing the method for CO_2 emissions calculation described in section 2.10.

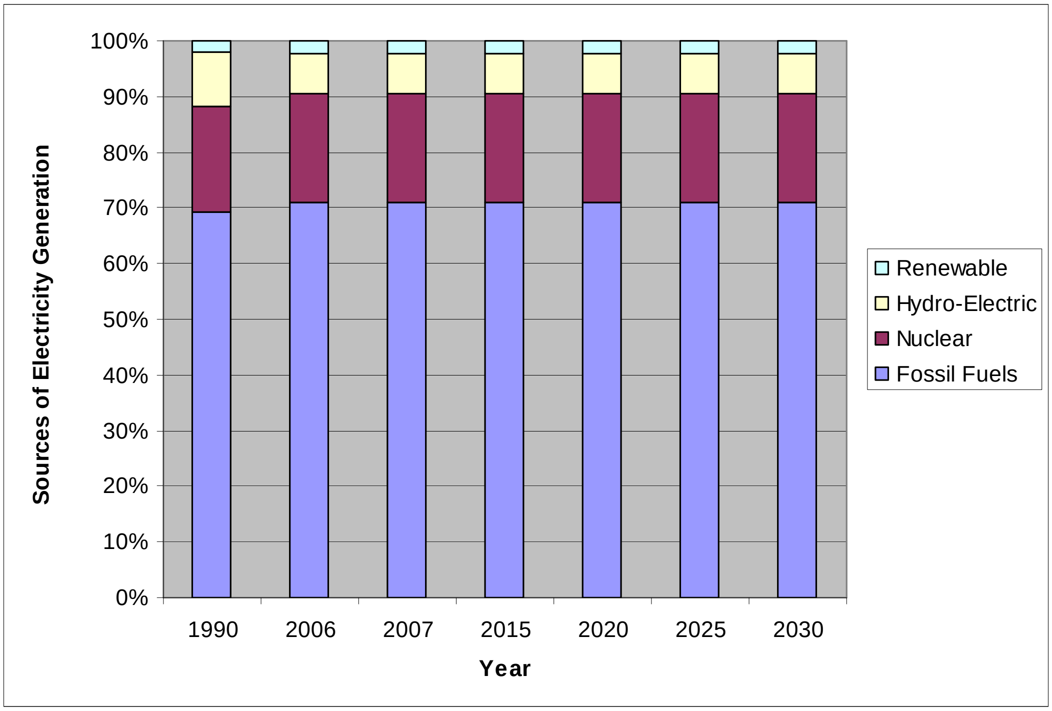


Figure 4.3: Energy generation mix for Business as Usual (BAU) case for 1990 - 2030.

It should be noted from Figure 4.2 that the total amount of electricity generated increases linearly at a rate of 68,578.36kW*hr/yr. This value was obtained from a linear fit for the data series of 1990-2006 shown in Figure 4.2.

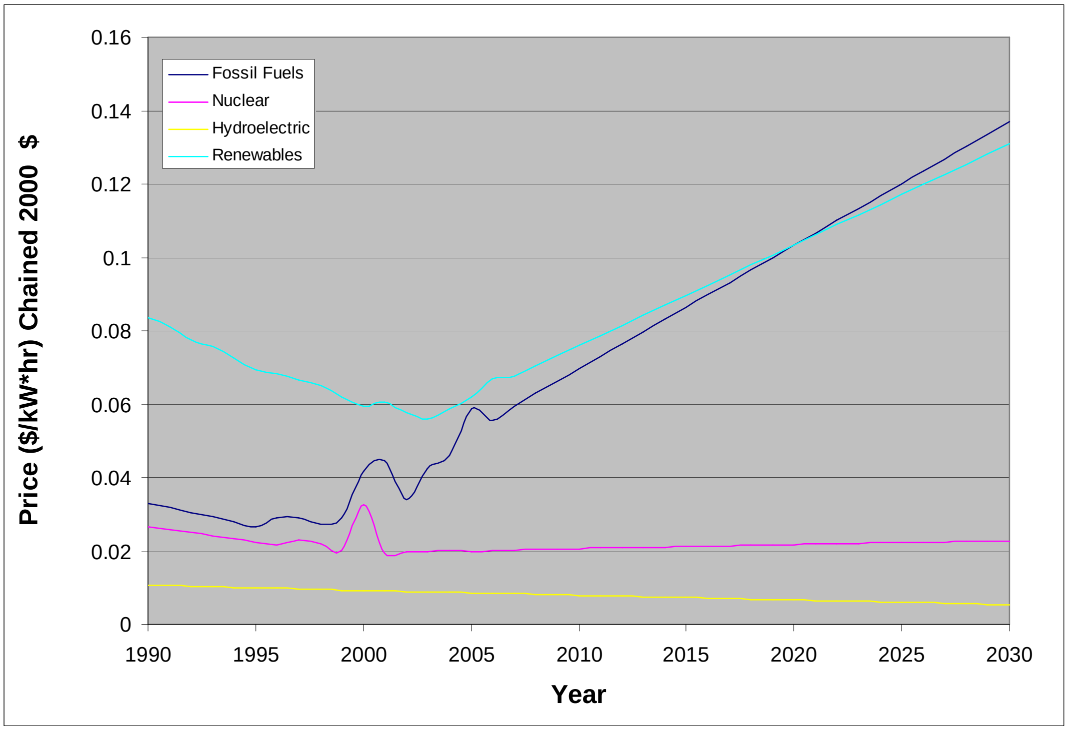


Figure 4.4: Electricity generation costs for 1990 – 2030 [7, 8, 9].

The extrapolated trends for 2006 - 2030 (Figure 4.4) for nuclear, hydroelectric and renewable energy costs as well as the fossil fuel energy costs show that they continue to increase. In the period 2006 – 2030 where the costs have been determined by extrapolation, fossil fuel energy costs are increasing faster than the renewable energy costs. Fossil fuels become more expensive compared to renewable energy sources around 2021. The primary reason for this change is that the projected prices of natural gas and petroleum are increasing rapidly although the coal prices remain low. The portion of the time series used in the linear fit for a given energy source depends on the general trend of the time series. The linear fit was used for the known cost of electricity generation from coal, petroleum and natural gas for 1990 – 2006. This curve-fit was then extrapolated to determine the cost of electricity generation from these sources as shown in Figure 4.4.

Figure 4.5 shows the cost of electricity generation from various fossil fuels (coal, clean coal and natural gas) and hydroelectric, nuclear and renewable sources. This figure shows that the cost of electricity generation from natural gas is increasing faster than the cost from other sources.

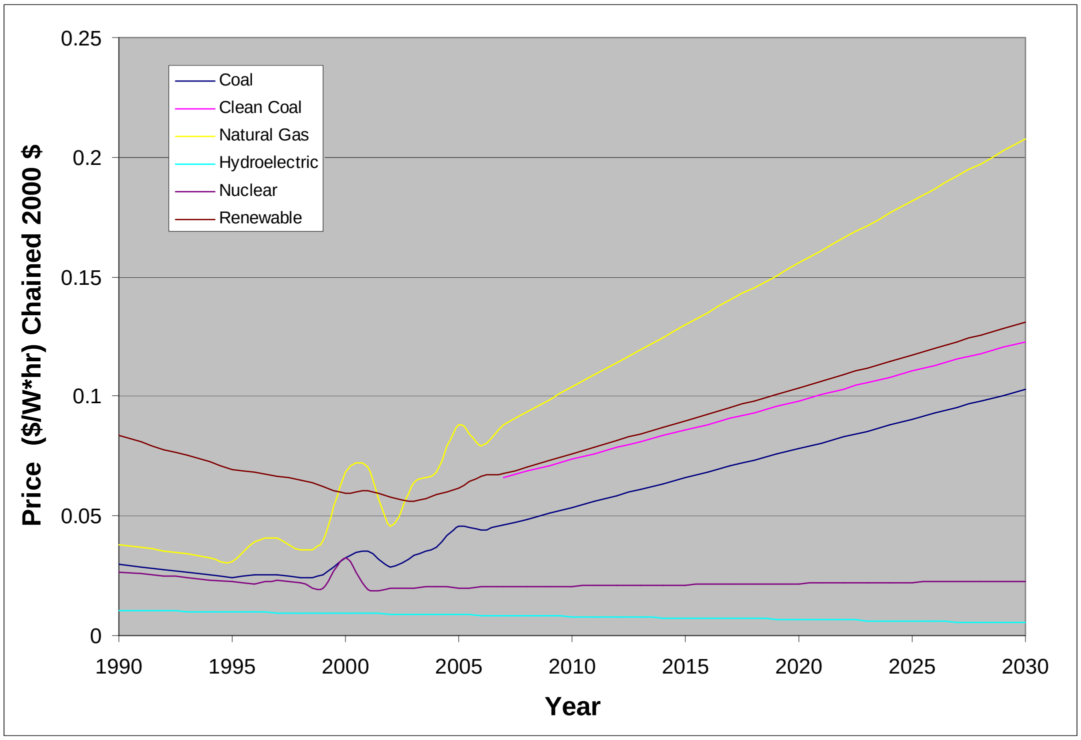


Figure 4.5: Electricity generation costs for 1990-2006 [7, 8, 9, 13]. The curves beyond 2006 are based on extrapolations.

Figure 4.6 shows the electricity generation costs from various types of renewable energy sources for 1990 - 2006.

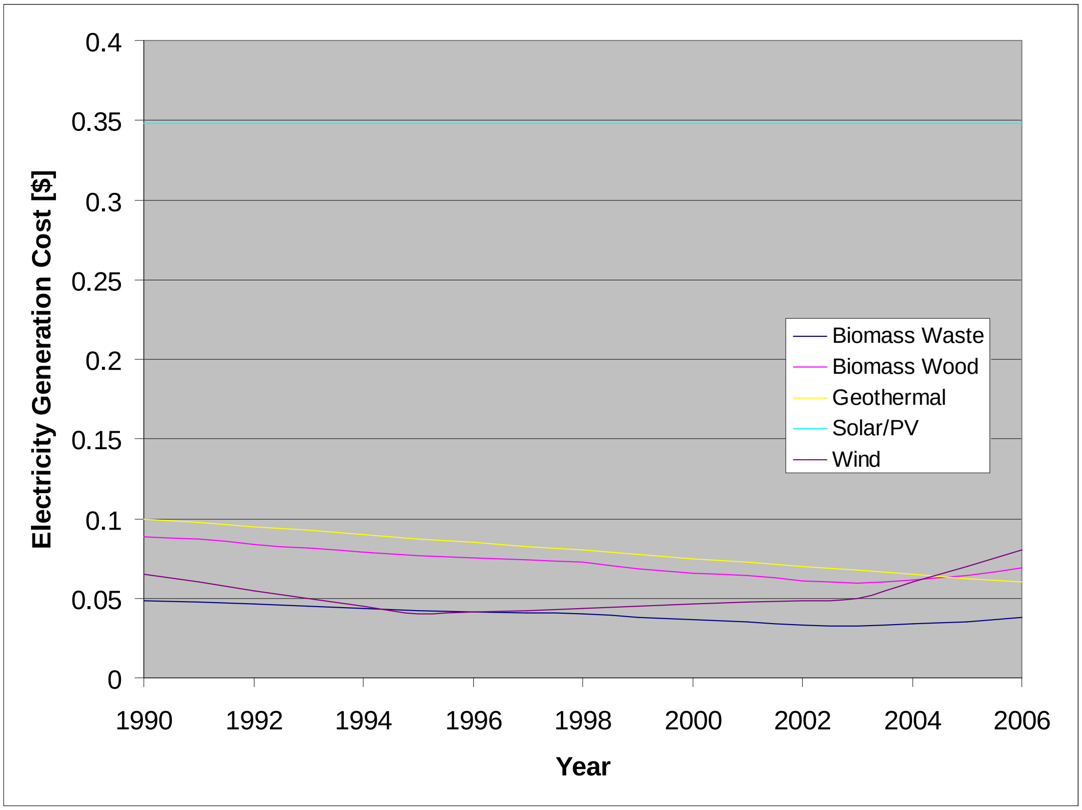


Figure 4.6: Electricity generation cost from various renewable energy sources for 1990-2006 [7, 9].

4.1.1 Impact of Switch from Fossil Fuels to Nuclear Energy

The CO_2 emissions reduction goals enunciated by the Obama administration can be achieved by switching the electricity generation capacity from fossil fuels to nuclear. Figure 4.7 shows the calculated mix of energy generation sources to achieve the Obama administration's goals for CO_2 emissions reductions for 2020 and 2050.

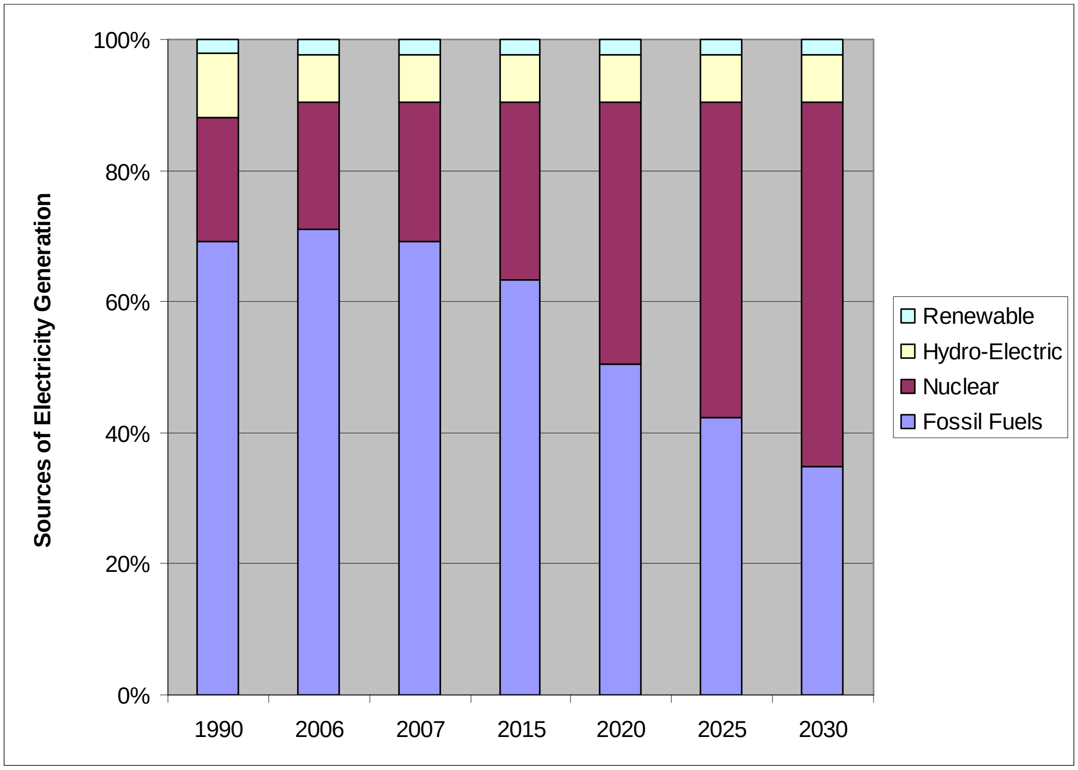


Figure 4.7: Switch from fossil fuels to nuclear as energy generation source for 1990 – 2030 to meet the Obama administration's CO_2 reduction goal with energy price and electricity supply fully regulated.

When energy price and supply are fully regulated, the Obama administration's CO_2 emission reduction goal is met for the time period 1990 - 2030. By 2030, the total cost of electricity generation decreases by 39.3%.

If the energy price was adjusted and the electricity supply was regulated, the Obama administration's CO_2 emission reduction goal can be met for the time period 1990 - 2030. By 2030, our economic model predicts that the total demand for electricity would increase by 100% due to the 39.2% decrease in electricity prices. Output would increase by 8.11%. Wages would increase by 7.61%. Household assets would increase by 9.83%. Consumption would increase by 8.78%. The level of employment would remain the same.

If the energy price and electricity supply are not fully regulated, then the usage of electricity would increase by 43.09% by 2030 causing a 2.08% decrease in CO_2 emissions from the BAU case. This increase causes the simulation under this policy scenario not to be able to meet the Obama administration's CO_2 emission reduction goal. Since nuclear power generation becomes cheaper than the fossil fuel based power generation in the future years, there is a significant increase in electricity usage due to reduction in electricity prices as a result of the switch from fossil fuel to nuclear energy which reduces the cost of electricity generation. In this particular case, the total cost of electricity generation decreases by 11.72% causing the price of electricity to decrease by an equal amount in 2030.

The above scenario does not take into account the capital cost associated with switching from fossil fuel to nuclear energy power plants. It is quite likely that the cost of electricity may increase with this switch in energy generation sources because the cost of building the new power plant may be very high and its cost is likely to be passed on to the consumer by the utility company unless it is subsidized by the government (again very unlikely).

4.1.2 Impact of Switch from Fossil Fuels to Renewable Energy Sources

In this section, we consider achieving Obama administration's CO_2 emissions reduction goals by switching the energy generation sources from fossil fuels to renewables. Figure 4.8 shows the calculated mix of energy generation sources to achieve the Obama administration's goals for CO_2 emissions reductions for 2020 and 2050. For this mix of energy generation sources we apply our economic model described in section 2 to determine its economic impact under various policy scenarios.

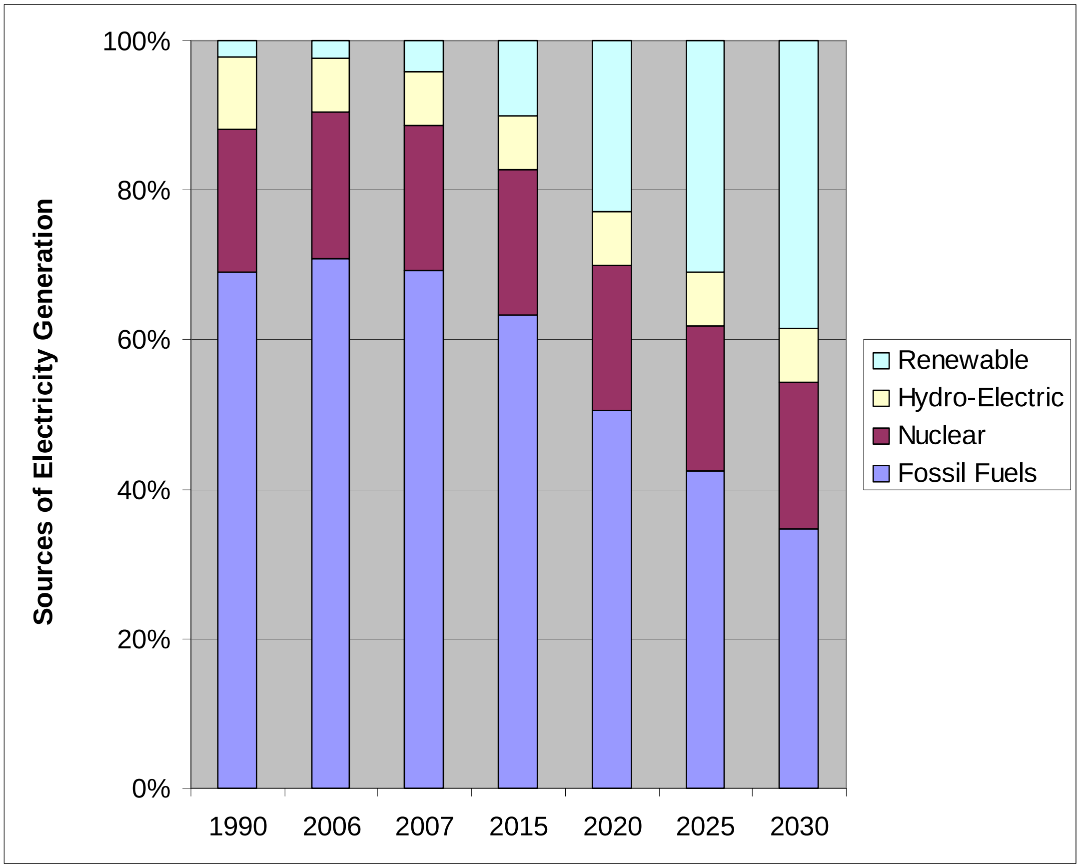


Figure 4.8: Switch from fossil fuels to renewable sources for 1990 – 2030 to meet the Obama administration's CO_2 reduction goals with the energy price and electricity supply fully regulated.

If the energy price and electricity supply are fully regulated, by 2030 the CO_2 emissions will decrease by 51.35% compared to the BAU case to meet the Obama administration's CO_2 emission reduction goals. The total cost of electricity generation will decrease by 2.11% in 2030 over the BAU case. The manufacturers demand for electricity will increase by 6.289%. The households demand for electricity will increase by 2.385%. The total demand for electricity will increase by 2.238%. The production or output will increase by 0.211%. The electricity price will decrease by 2.107%. The market wages will increase by 0.198%. The household assets will increase by 0.254%. The consumption will increase by 0.228%. There will not be any change in the level of employment.

If the energy price and electricity supply is fully adjusted, by 2030 electricity consumption will increase by 22.38% compared to the business as usual case. The price of electricity will decrease by 2.107%. The market wages will increase by 0.2038%. The household asset will increase by 0.2542%. The consumption will increase by 0.2303%. The total cost of electricity generation will increase by 0.08455%. The household's electricity demand will increase by 2.387%. 6,546 new jobs will be created. The cause for increase in the electricity usage is that the price of electricity decreases. This is due to the price of renewable energy sources becoming cheaper compared to the fossil fuels as shown in Figure 4.4.

When energy prices and electricity supply are adjusted, the Obama administration CO_2 emission goals are not met. Since electricity prices decrease in this policy scenario, there will be an increased demand for electricity. When supply increases to meet the new increased demand, more electricity is produced and consequently CO_2 emissions increase. This increase in CO_2 emissions makes this policy scenario exceed the CO_2 emission goals enunciated by the Obama administration.

The analysis presented in sections 4.1.1 and 4.1.2 shows that in the future, more aggressive CO_2 emission reduction goals can be met by assuming that the renewable sources of energy will become cheaper than the fossil fuels (in particular the natural gas). Electricity prices would then need to be established so that the people do not increase their consumption due to decrease in electricity prices. From the present (2008) until 2021 (when fossil fuel prices are expected to be greater than the renewable energy prices as shown in Figure 4.4), a combination of switching from fossil fuels to nuclear and renewable energy sources could be employed to reduce CO_2 emissions without changing the price of electricity. After 2021 any switch away from fossil fuel to nuclear or renewable source based electricity generation will decrease the total cost of electricity generation. It should be noted that in the above analysis, we have lumped all types of fossil fuels together; in reality in 2021, coal will still be cheaper than most of the renewable resources, but the natural gas will become more expensive than most of the renewable sources. If the fossil fuel based energy generation mix shifts more towards coal and clean coal and away from natural gas, it is likely that the fossil fuel based energy prices will still be cheaper than the renewable energy based prices in 2021 and beyond.

4.2 Comparison of Present Economic Model with Ameren UE MRN/NEEM Model

CRA International has developed a top-down/bottom-up MRN/NEEM model (described in section 1.4.2) for Ameren UE which determines the mix of energy sources for electricity generation to achieve its CO_2 emission reduction goals in the future by

2025 as shown in Figure 4.10 by the magenta line. To achieve this reduction in CO_2 emissions by 2025, the required mix of energy generation sources predicted by the MRN/NEEM model is shown in Figure 4.9. We apply our model described in section 2 to compare the results with the MRN/NEEM model. It should be noted that the petroleum based electricity generation is not included in this comparison in either of the models.

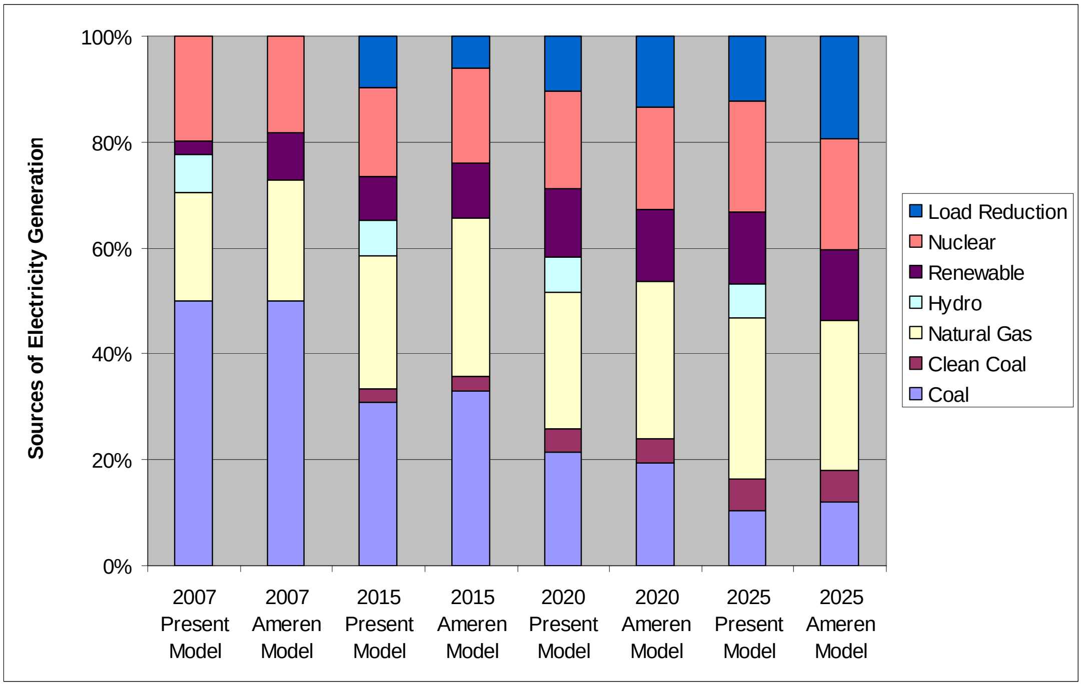


Figure 4.9: Mix of Energy Sources for Electricity Generation: Comparison of present model's predictions with Ameren UE model [14].

In 2015, 2020 and 2025, the mix of energy generation sources similar to that used by Ameren UE was employed as the input to our model. The starting year (no policy changes) for the MRN/NEEM model was 2007; extrapolations were used for our model because the dataset ended in 2006. The load reduction component was omitted in the input data since our economic model calculates the load reduction when the energy price and electricity supply are fully adjusted. Figure 4.9 shows the resulting mix of energy generation sources with load reduction calculated by our model for the years 2007 - 2025. Our calculations show the same trend as the Ameren UE model (load reduction increases as the electricity generation sources are switched from coal to clean coal, natural gas, renewables and nuclear); however, the calculated load reduction from our model is less than that predicted by the Ameren UE model. There are some differences in our model and the Ameren UE model. The Ameren UE model includes the hydroelectric component in the renewable category which was included in our model as a separate component because it is a source of a significant amount of electricity generation (it is considered to be constant over the years). In addition, the differences between the two models can be attributed to different approaches to economic modeling as well as to variations in the methods of data extrapolation in the BAU case.

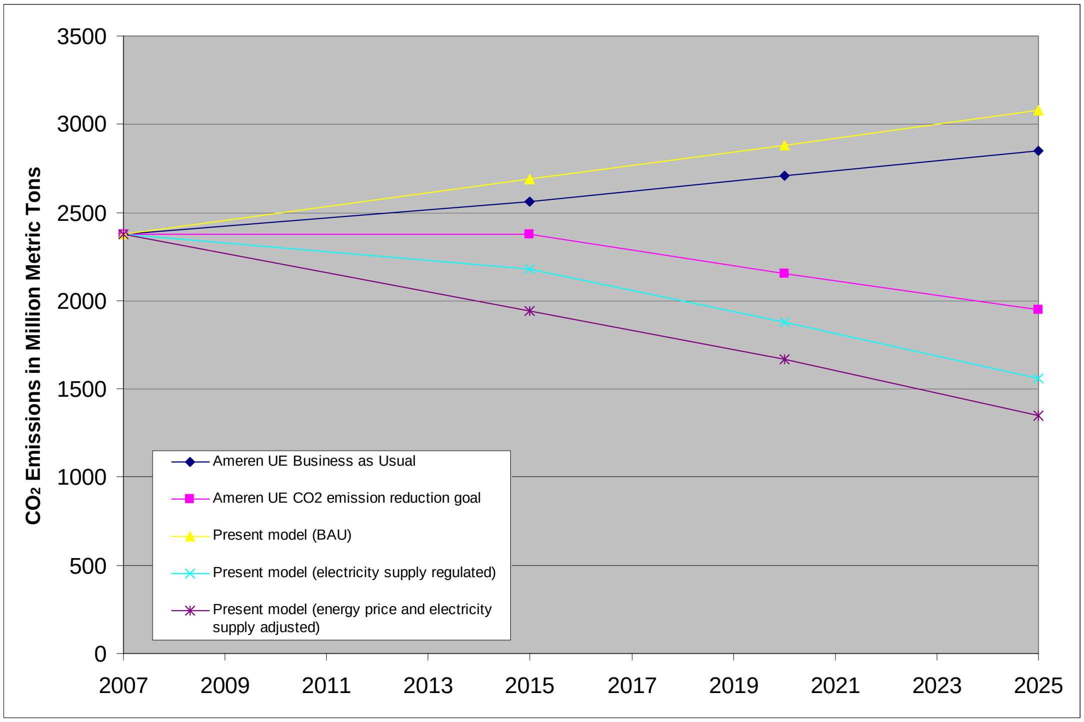


Figure 4.10: Annual CO_2 emissions calculated by the present model and the Ameren UE model [14]. CO_2 emissions are in million metric tons of CO_2.

Both models show the same trend in CO_2 emissions; in the BAU case the emissions increase while the mix of energy generation sources in future years causes the CO_2 emissions to decrease. However, the present model projects much larger reductions in CO_2 emissions. In Figure 4.10, the CO_2 emissions are shown for the present model under four scenarios: (a) business as usual, (b) energy price and electricity supply fully regulated, (c) energy price fully adjusted and electricity supply fully regulated and (d) energy price and electricity supply fully adjusted. The present model predicts ~10% more reduction in CO_2 emissions in 2025 compared to the Ameren UE model when the electricity supply is fully regulated (cases b and c, the cyan line in Figure 4.10).

If energy prices and electricity supply are fully regulated, by 2025 there is a 49.32% reduction in CO_2 emissions compared to the business as usual case (cyan line in Figure 4.10). The total cost of electricity generation increases by 16.72%.

If electricity supply is fully regulated and energy price is fully adjusted, by 2025 there is a 49.32% reduction in CO_2 emissions compared to the business as usual case (cyan line in Figure 4.10). The total cost of electricity generation will increase by 16.72%. The industrial manufacturing electricity demand will decrease by 35.46%. Total electricity demand decreases by 13.77%. Household electricity demand will decrease by 15.50%. The output will decrease by 1.27%. The electricity price will increase by 16.72%. The market wages will decrease by 1.20%. Household assets will decrease by 1.55%. The consumption will decrease by 1.38%.

The model under the scenario of energy price and electricity supply fully adjusted predicts the largest decrease in CO_2 emissions. If energy prices and supply are fully adjusted, there is a 13.77% reduction in electricity demand by 2025. Electricity price increases by 16.72% and household electricity demand decreases by 15.52%. Household assets decrease by 1.55%. Consumption decreases by 1.399%. The market wages decrease by 1.234%. 47,332 people are laid off and each household faces a layoff rate of 0.039%. Due to the increase in electricity cost and the associated decrease in demand for electricity, CO_2 emissions decrease by 56.30% which corresponds to the purple line in Figure 4.10.

The present model and the Ameren UE model forecast increasing load reduction as the mix of energy generation sources shifts from being heavily dependent on coal to clean coal, natural gas and renewables for electricity generation. This is due to the increased electricity generation cost associated with the switch. Since both models are based on the general equilibrium concept, many of the differences between their predictions can be attributed to the BAU cases being treated differently by the two models.

Chapter 5: 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 values of θ 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 (CES) 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 on-going growth of households and firms over time; it will also capture shifts in supply and demand factors over time.

Appendix A: Data Collected

The following data was collected and has been compiled in a separate document titled, "Appendix A: Data for the M.S. Thesis – An Energy Economic Model for Electricity Generation in the United States, by Lee Chusak, Department of Mechanical, Aerospace and Structural Engineering, Washington University in St. Louis, August 2009." A CD-ROM of this data is included with this thesis.

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 1980-2006 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. 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.

8. 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.

9. US CO_2 emissions from energy consumption for each sector from 1980 to 2005. Sectors: residential, commercial, transportation, electric power. Source: EIA, 2008.

10. US electricity demand from 1980 to 2006 for each sector. Sectors: residential, commercial, industrial, transportation as well as total. Source: EIA, 2008.

11. 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.

12. Cost of living statistics (consumer price index) for the Northeast Urban, Midwest Urban, South Urban, West Urban, as well as US total for 1985-2006. Source: Bureau of Economic Analysis, 2008.

13. State level population data for 1970-2007. Source: US Census Bureau, 2008.

14. State level average number of people per household for 2007. Source: Bureau of Labor Statistics, 2008.

15. 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.

16. State level motor-vehicle registration for 2003-2005. Sectors: automobiles, motorcycles, busses and trucks. Source: Bureau of Transportation Statistics, 2008.

Appendix B: Mathcad Code for US Economic Model for Aggregate Policy Analysis

Section A of this appendix shows the input data (aggregate) to the model and the steady state initialization values used in the model. Section B recalculates the equilibrium using the calibration parameters in section A. Section C calculates the policy change when electricity supply and the energy price are fully regulated. Section D calculates the policy change when the electric supply is regulated and the energy price is adjusted as well as when both the electricity supply and energy price are fully adjusted. In this section, every variable ending with "adjust" corresponds to the case when both the electricity supply and energy price are fully adjusted. Thus, the first set of results in section D is the result when electricity supply is fixed and the second set of results is for the case when the electricity supply is adjusted (for the decreased demand associated with the increase in electricity price).

A. Calibrating the Model **(National Aggregate)**

(all values in million dollars at 2000 constant prices)

(all electricity data in million megawatts)

$x := \frac{6222.152941 \cdot 1000}{123035470.6}$ $z := \frac{941.5058824 \cdot 1000}{123035470.6}$

$NF := 22424294.12$ $NC := 76203145.98$ $NE := 621239.1632$

$N := NF + NC + NE$ $N = 9.924868 \times 10^{7}$

$M1 := 1$

$w := \frac{16.18138219 \cdot 2000}{1000000}$

$p := 0.06935819$

$\mu1 := 0.03050851$

$\mu2 := 0.022675405$

$\mu3 := 0.009513399$

$\mu4 := 0.0599737$

$\mu5 := 0.049816$

$\mu6 := 0.0724957$

$\mu7 := 0.039934096$

$\mu8 := 0.08$

$\mu9 := 0.348$

$\mu10 := .052352941$

$r := 0.05$ $\delta := 0.075$

(electricity demand)

$$EH := 1131315\cdot\frac{N}{123035470.6}$$

$$EF := 1009157\cdot\frac{N}{123035470.6}$$

$$EC := 988220\cdot\frac{N}{123035470.6}$$

(electricity generated)

$ES1 := 1826291.495$

$ES2 := 697759.68$

$ES3 := 287800.0588$

$ES4 := 106884.89$

$ES5 := 553372.5878$

$ES6 := 36861.22371$

$ES7 := 18113.24335$

$ES8 := 14881.80335$

$ES9 := 498.2435882$

$ES10 := 7287.555529$

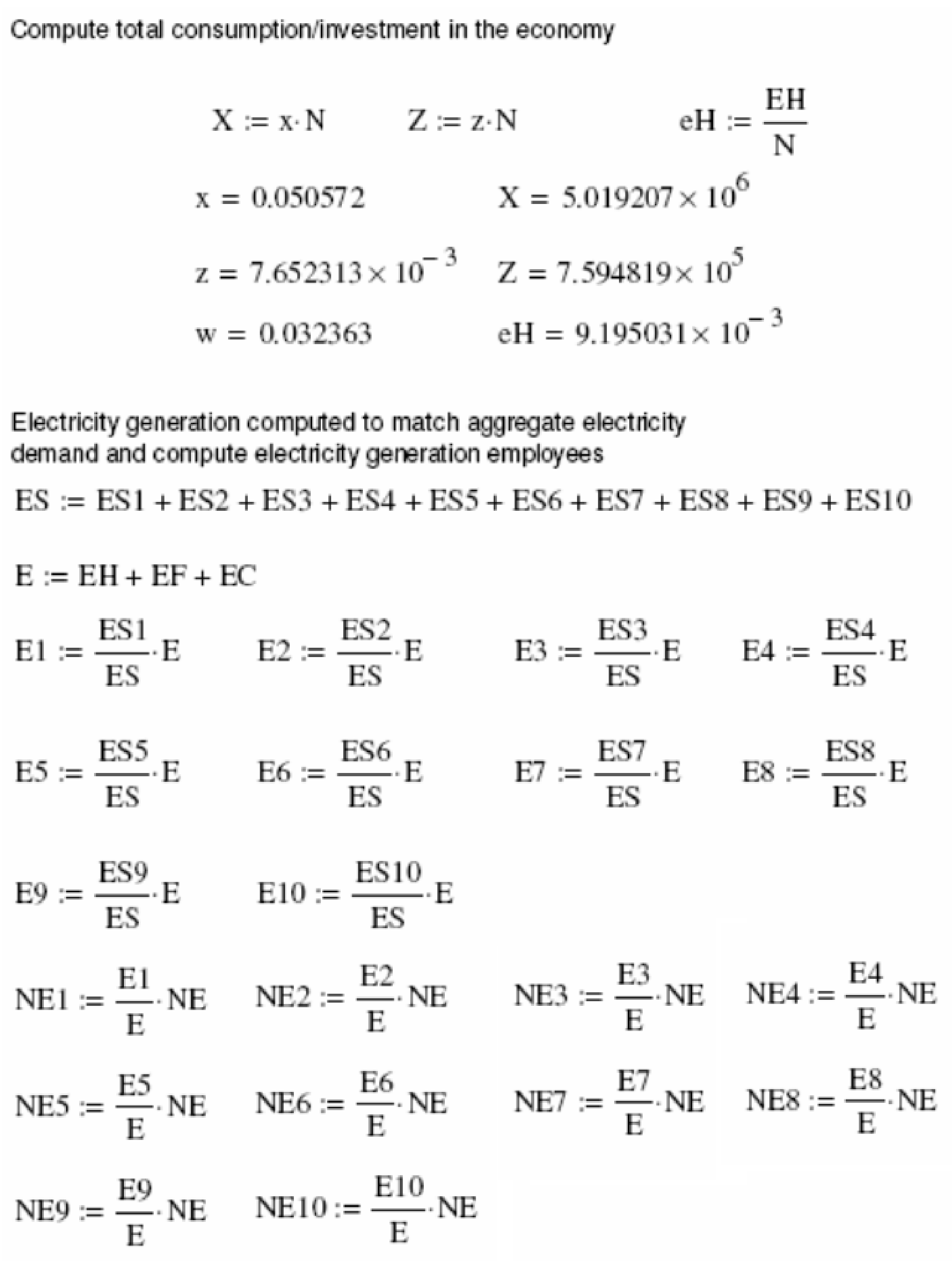
(emission in million metric ton of CO2)

$D := 2229.756$

$U1 := 1 \qquad U4 := 0.78846154 \qquad U5 := 0.5625$

Compute discounting factor

$$\beta H := \frac{1}{1+r} \qquad\qquad \beta F := \frac{1}{1+r}$$



Compute total consumption/investment in the economy

$$X := x \cdot N \qquad Z := z \cdot N \qquad eH := \frac{EH}{N}$$

$$x = 0.050572 \qquad X = 5.019207 \times 10^{6}$$

$$z = 7.652313 \times 10^{-3} \qquad Z = 7.594819 \times 10^{5}$$

$$w = 0.032363 \qquad eH = 9.195031 \times 10^{-3}$$

Electricity generation computed to match aggregate electricity demand and compute electricity generation employees

$$ES := ES1 + ES2 + ES3 + ES4 + ES5 + ES6 + ES7 + ES8 + ES9 + ES10$$

$$E := EH + EF + EC$$

$$E1 := \frac{ES1}{ES} \cdot E \qquad E2 := \frac{ES2}{ES} \cdot E \qquad E3 := \frac{ES3}{ES} \cdot E \qquad E4 := \frac{ES4}{ES} \cdot E$$

$$E5 := \frac{ES5}{ES} \cdot E \qquad E6 := \frac{ES6}{ES} \cdot E \qquad E7 := \frac{ES7}{ES} \cdot E \qquad E8 := \frac{ES8}{ES} \cdot E$$

$$E9 := \frac{ES9}{ES} \cdot E \qquad E10 := \frac{ES10}{ES} \cdot E$$

$$NE1 := \frac{E1}{E} \cdot NE \qquad NE2 := \frac{E2}{E} \cdot NE \qquad NE3 := \frac{E3}{E} \cdot NE \qquad NE4 := \frac{E4}{E} \cdot NE$$

$$NE5 := \frac{E5}{E} \cdot NE \qquad NE6 := \frac{E6}{E} \cdot NE \qquad NE7 := \frac{E7}{E} \cdot NE \qquad NE8 := \frac{E8}{E} \cdot NE$$

$$NE9 := \frac{E9}{E} \cdot NE \qquad NE10 := \frac{E10}{E} \cdot NE$$

$EH = 9.125947 \times 10^5$

$EF = 8.140539 \times 10^5$

$EC = 7.971647 \times 10^5$

$E1 = 1.298463 \times 10^6$

$E2 = 4.960954 \times 10^5$

$E3 = 2.04621 \times 10^5$

$E4 = 7.599336 \times 10^4$

$E5 = 3.934386 \times 10^5$

$E6 = 2.620771 \times 10^4$

$E7 = 1.287821 \times 10^4$

$E8 = 1.058071 \times 10^4$

$E9 = 354.24283$

$E10 = 5.18133 \times 10^3$

$NE1 = 3.196179 \times 10^5$

$NE2 = 1.221144 \times 10^5$

$NE3 = 5.036767 \times 10^4$

$NE4 = 1.870584 \times 10^4$

$NE5 = 9.684531 \times 10^4$

$NE6 = 6.451055 \times 10^3$

$NE7 = 3.169985 \times 10^3$

$NE8 = 2.604453 \times 10^3$

$NE9 = 87.197228$

$NE10 = 1.27539 \times 10^3$

Compute electricity generation input variables

$$\nu := \frac{\mu1 \cdot E1 - w \cdot NE1}{M1}$$

$$M2 := \frac{\mu2 \cdot E2 - w \cdot NE2}{\nu} \qquad M3 := \frac{\mu3 \cdot E3 - w \cdot NE3}{\nu} \qquad M4 := \frac{\mu4 \cdot E4 - w \cdot NE4}{\nu}$$

$$M5 := \frac{\mu5 \cdot E5 - w \cdot NE5}{\nu} \qquad M6 := \frac{\mu6 \cdot E6 - w \cdot NE6}{\nu} \qquad M7 := \frac{\mu7 \cdot E7 - w \cdot NE7}{\nu}$$

$$M8 := \frac{\mu8 \cdot E8 - w \cdot NE8}{\nu} \qquad M9 := \frac{\mu9 \cdot E9 - w \cdot NE9}{\nu} \qquad M10 := \frac{\mu10 \cdot E10 - w \cdot NE10}{\nu}$$

$\nu = 2.927044 \times 10^{4}$

$M2 = 0.249303$

$M3 = 0.010817$

$M4 = 0.135025$

$M5 = 0.562525$

$M6 = 0.057777$

$M7 = 0.014065$

$M8 = 0.026039$

$M9 = 4.115229 \times 10^{-3}$

$M10 = 7.857166 \times 10^{-3}$

Compute wealth and capital

$$a := \frac{x + p \cdot eH - w}{r} \qquad K := \frac{Z}{\delta}$$

$a = 0.37694$

$K = 1.012643 \times 10^{7}$

Calibrate utility parameter

$$\eta := \frac{x}{x + p \cdot eH} \qquad \eta = 0.987546$$

Calibrate production share using derived model relationships

$$\Gamma(\alpha) := \frac{w \cdot NF}{(1-\alpha) \cdot X + \frac{\alpha \cdot \delta}{r + \delta} \cdot (w \cdot NF)}$$

$$Y(\alpha) := \frac{X}{1 - \frac{\delta}{r + \delta} \cdot \alpha \cdot \Gamma(\alpha)}$$

$\alpha := 0.5$

Given

$$(1 - \Gamma(\alpha)) \cdot Y(\alpha) = p \cdot EF$$

$$\alpha s := \mathrm{Find}(\alpha) \qquad \alpha s = 0.935881$$

$$\phi := 1 - 2 \cdot (1 - \eta) \qquad \phi = 0.975093$$

$\rho := 0.5$

Given

$$\Gamma(\alpha s) = \frac{\phi \cdot \left(K^{\alpha s} \cdot NF^{1-\alpha s}\right)^{\rho}}{\phi \cdot \left(K^{\alpha s} \cdot NF^{1-\alpha s}\right)^{\rho} + (1 - \phi) \cdot (EF)^{\rho}}$$

$$\rho s := \mathrm{Find}(\rho) \qquad \rho s = 0.635049$$

Calibrate electricity generation parameters using derived model relationships

$$\theta := \frac{NE}{E} \qquad \psi := \frac{\nu \cdot M1}{w \cdot NE} \cdot \frac{E}{E1} \qquad B := \frac{E1}{(M1)^{\psi}}$$

$$w \cdot NF + p \cdot EF = 7.821734 \times 10^{5}$$

Compute output and user cost of investment

$$Ys := Y(\alpha s) \qquad q := \frac{\delta}{r + \delta} \cdot \alpha s \cdot \Gamma(\alpha s) \cdot \frac{Ys}{Z}$$

Calibrate production scaling factor

$$A := \frac{Ys}{\left[\phi \cdot \left(K^{\alpha s} \cdot NF^{1-\alpha s}\right)^{\rho s} + (1-\phi) \cdot (EF)^{\rho s}\right]^{\frac{1}{\rho s}}}$$

$\alpha s = 0.935881$

$\rho s = 0.635049$

$\theta = 0.246151$

$\psi = 2.82978$

$B = 1.298463 \times 10^{6}$

$Ys = 1.137476 \times 10^{7}$

$q = 8.36827$

$A = 1.102033$

CO2 production parameter

$$\Xi := \frac{D}{E1 \cdot U1 + E4 \cdot U4 + E5 \cdot U5} \qquad \Xi = 1.411515 \times 10^{-3}$$

$$\gamma 1 := \Xi \cdot U1 \qquad \gamma 1 = 1.411515 \times 10^{-3}$$

$$\gamma 4 := \Xi \cdot U4 \qquad \gamma 4 = 1.112925 \times 10^{-3}$$

$$\gamma 5 := \Xi \cdot U5 \qquad \gamma 5 = 7.939773 \times 10^{-4}$$

$$\gamma average := \frac{D}{E1 + E4 + E5} \qquad \gamma average = 1.261249 \times 10^{-3}$$

$$E1 + E4 + E5 = 1.767895 \times 10^{6}$$

Total cost of producing electricity

$$TC := w\cdot(NE1 + NE2 + NE3 + NE4 + NE5 + NE6 + NE7 + NE8 + NE9 + NE10) + v\cdot(M1 + M2 + M3 + M4 + M5 + M6 + M7 + M8 + M9 + M10)$$

Household consumption

$TC = 8.062232\times 10^{4}$

$c := x^{\eta}\cdot eH^{1-\eta}$

$c = 0.04951$

Commercial sector employment parameter

$\zeta := \frac{NC}{EC}$

$\zeta = 95.592729$

B. Rederive the calibrated equilibrium in the benchmark equilibrium

(Enter Yearly Data)

$E1Y := E1$ $E2Y := E2$ $E3Y := E3$ $E4Y := E4$ $E5Y := E5$

$E6Y := E6$ $E7Y := E7$ $E8Y := E8$ $E9Y := E9$ $E10Y := E10$

$NY := N$ $qY := q$

$\mu1Y := \mu1$ $\mu2Y := \mu2$ $\mu3Y := \mu3$ $\mu4Y := \mu4$ $\mu5Y := \mu5$

$\mu6Y := \mu6$ $\mu7Y := \mu7$ $\mu8Y := \mu8$ $\mu9Y := \mu9$ $\mu10Y := \mu10$

$ECY := EC$

(Re-enter exogenous variables)

$E1V := E1Y$ $E2V := E2Y$ $E3V := E3Y$ $E4V := E4Y$

$E5V := E5Y$ $E6V := E6Y$ $E7V := E7Y$ $E8V := E8Y$

$E9V := E9Y$ $E10V := E10Y$ $ECV := ECY$

$NV := NY$ $qV := qY$

$\mu1V := \mu1Y$ $\mu2V := \mu2Y$ $\mu3V := \mu3Y$ $\mu4V := \mu4Y$ $\mu5V := \mu5Y$

$\mu6V := \mu6Y$ $\mu7V := \mu7Y$ $\mu8V := \mu8Y$ $\mu9V := \mu9Y$ $\mu10V := \mu10Y$

(Re-derive endogenous variables using equilibrium relationships obtained in the model)

$$EV := E1V + E2V + E3V + E4V + E5V + E6V + E7V + E8V + E9V + E10V$$

$$NE1V := \theta \cdot E1V \quad NE2V := \theta \cdot E2V \quad NE3V := \theta \cdot E3V$$

$$NE4V := \theta \cdot E4V \quad NE5V := \theta \cdot E5V \quad NE6V := \theta \cdot E6V$$

$$NE7V := \theta \cdot E7V \quad NE8V := \theta \cdot E8V \quad NE9V := \theta \cdot E9V$$

$$NE10V := \theta \cdot E10V$$

$$NEV := \theta \cdot EV$$

$$NCV := \zeta \cdot ECV$$

$$NFV := NV - NEV - NCV$$

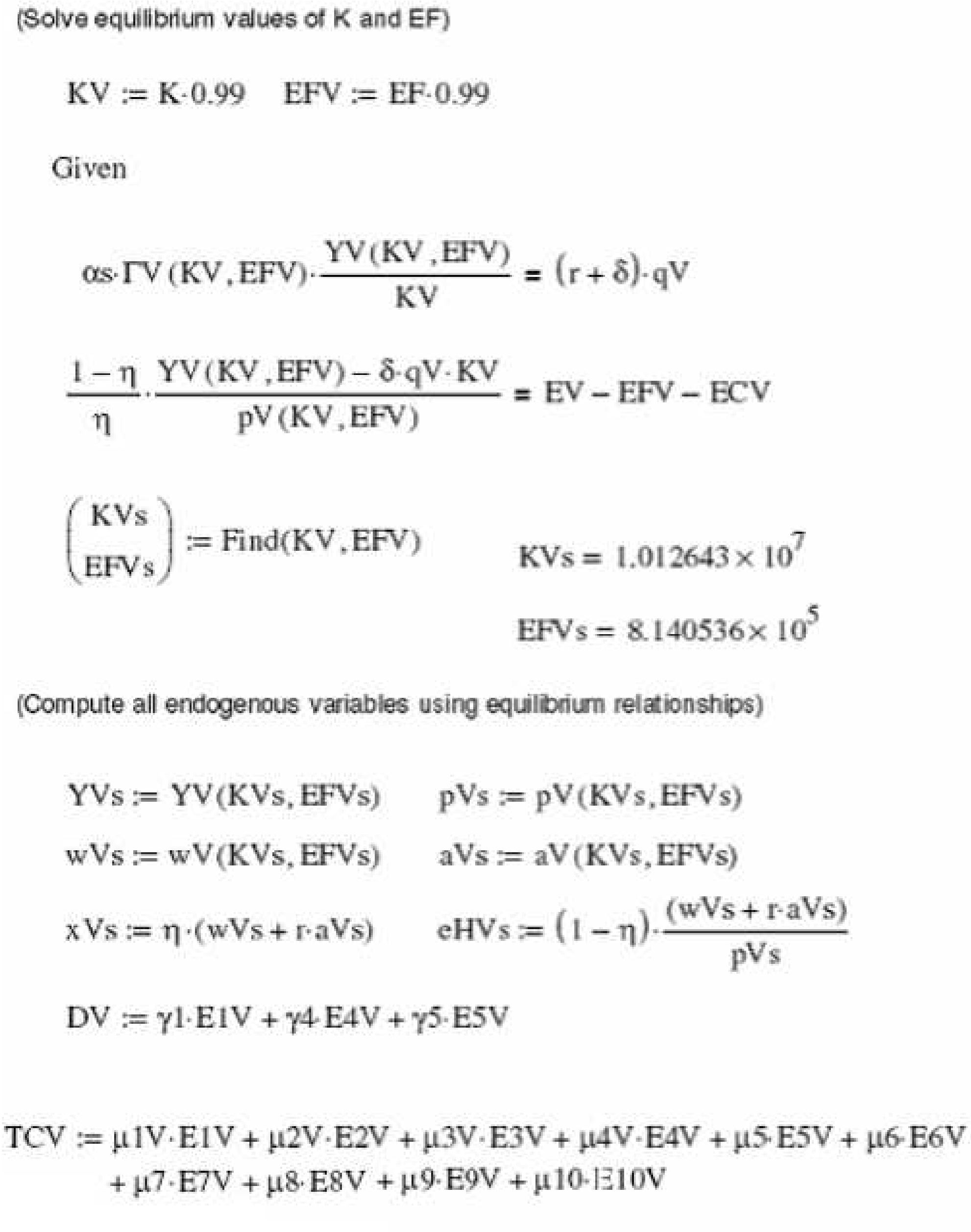
$$YV(KV, EFV) := A \cdot \left[\phi \cdot \left(KV^{\alpha s} \cdot NFV^{1-\alpha s} \right)^{\rho s} + (1-\phi) \cdot (EFV)^{\rho s} \right]^{\frac{1}{\rho s}}$$

$$\Gamma V(KV, EFV) := \frac{\phi \cdot \left(KV^{\alpha s} \cdot NFV^{1-\alpha s} \right)^{\rho s}}{\phi \cdot \left(KV^{\alpha s} \cdot NFV^{1-\alpha s} \right)^{\rho s} + (1-\phi) \cdot (EFV)^{\rho s}}$$

$$pV(KV, EFV) := \left(1 - \Gamma V(KV, EFV) \right) \cdot \frac{YV(KV, EFV)}{EFV}$$

$$wV(KV, EFV) := (1 - \alpha s) \cdot \Gamma V(KV, EFV) \cdot \frac{YV(KV, EFV)}{NFV}$$

$$aV(KV, EFV) := \frac{1}{r} \cdot \left[\frac{\left(YV(KV, EFV) - \delta \cdot qV \cdot KV \right)}{\eta \cdot NV} - wV(KV, EFV) \right]$$



(Solve equilibrium values of K and EF)

$$KV := K\cdot 0.99 \qquad EFV := EF\cdot 0.99$$

Given

$$\alpha s\cdot \Gamma V(KV, EFV)\cdot \frac{YV(KV, EFV)}{KV} = (r+\delta)\cdot qV$$

$$\frac{1-\eta}{\eta}\cdot \frac{YV(KV, EFV) - \delta\cdot qV\cdot KV}{pV(KV, EFV)} = EV - EFV - ECV$$

$$\begin{pmatrix} KVs \\ EFVs \end{pmatrix} := \mathrm{Find}(KV, EFV) \qquad KVs = 1.012643\times 10^{7}$$

$$EFVs = 8.140536\times 10^{5}$$

(Compute all endogenous variables using equilibrium relationships)

$$YVs := YV(KVs, EFVs) \qquad pVs := pV(KVs, EFVs)$$

$$wVs := wV(KVs, EFVs) \qquad aVs := aV(KVs, EFVs)$$

$$xVs := \eta\cdot(wVs + r\cdot aVs) \qquad eHVs := (1-\eta)\cdot\frac{(wVs + r\cdot aVs)}{pVs}$$

$$DV := \gamma 1\cdot E1V + \gamma 4\cdot E4V + \gamma 5\cdot E5V$$

$$\begin{aligned} TCV := {} & \mu 1V\cdot E1V + \mu 2V\cdot E2V + \mu 3V\cdot E3V + \mu 4V\cdot E4V + \mu 5\cdot E5V + \mu 6\cdot E6V \\ & + \mu 7\cdot E7V + \mu 8\cdot E8V + \mu 9\cdot E9V + \mu 10\cdot E10V \end{aligned}$$

C. Rederive the calibrated equilibrium for policy 1A (replacing)

(Re-enter exogenous variables)

$E1V := E1Y \cdot 0.9 \quad E2V := E2Y \quad E3V := E3Y$

$E4V := E4 \quad E5V := E5 \quad E6V := E6 + 0.01 \cdot E1Y$

$E7V := E7 + 0.01 \cdot E1Y \quad E8V := E8 \quad E9V := E9 + 0.03 \cdot E1Y$

$E10V := E10 + 0.05 \cdot E1Y \quad ECV := EC$

$NV := N \quad qV := q$

$\mu 1V := \mu 1 \quad \mu 2V := \mu 2 \quad \mu 3V := \mu 3$

$\mu 4V := \mu 4 \quad \mu 5V := \mu 5 \quad \mu 6V := \mu 6$

$\mu 7V := \mu 7 \quad \mu 8V := \mu 8 \quad \mu 9V := \mu 9$

$\mu 10V := \mu 10$

(Re-derive endogenous variables using equilibrium relationships obtained in the model)

$EV := E1V + E2V + E3V + E4V + E5V + E6V + E7V + E8V + E9V + E10V$

$NE1V := \theta \cdot E1V \quad NE2V := \theta \cdot E2V \quad NE3V := \theta \cdot E3V$

$NE4V := \theta \cdot E4V \quad NE5V := \theta \cdot E5V$

$NE6V := \theta \cdot E6V \quad NE7V := \theta \cdot E7V \quad NE8V := \theta \cdot E8V$

$NE9V := \theta \cdot E9V \quad NE10V := \theta \cdot E10V$

$NEV := \theta \cdot EV$

$NCV := \zeta \cdot ECV$

$NFV := NV - NEV - NCV$

$$YV(KV, EFV) := A \cdot \left[\phi \cdot \left(KV^{\alpha s} \cdot NFV^{1-\alpha s} \right)^{\rho s} + (1 - \phi) \cdot (EFV)^{\rho s} \right]^{\frac{1}{\rho s}}$$

$$\Gamma V(KV, EFV) := \frac{\phi\cdot\left(KV^{\alpha s}\cdot NFV^{1-\alpha s}\right)^{\rho s}}{\phi\cdot\left(KV^{\alpha s}\cdot NFV^{1-\alpha s}\right)^{\rho s} + (1-\phi)\cdot(EFV)^{\rho s}}$$

$$pV(KV, EFV) := \left(1 - \Gamma V(KV, EFV)\right)\cdot\frac{YV(KV, EFV)}{EFV}$$

$$wV(KV, EFV) := (1 - \alpha s)\cdot\Gamma V(KV, EFV)\cdot\frac{YV(KV, EFV)}{NFV}$$

$$aV(KV, EFV) := \frac{1}{r}\cdot\left[\frac{\left(YV(KV, EFV) - \delta\cdot qV\cdot KV\right)}{\eta\cdot NV} - wV(KV, EFV)\right]$$

(Solve new equilibrium values of K and EF)

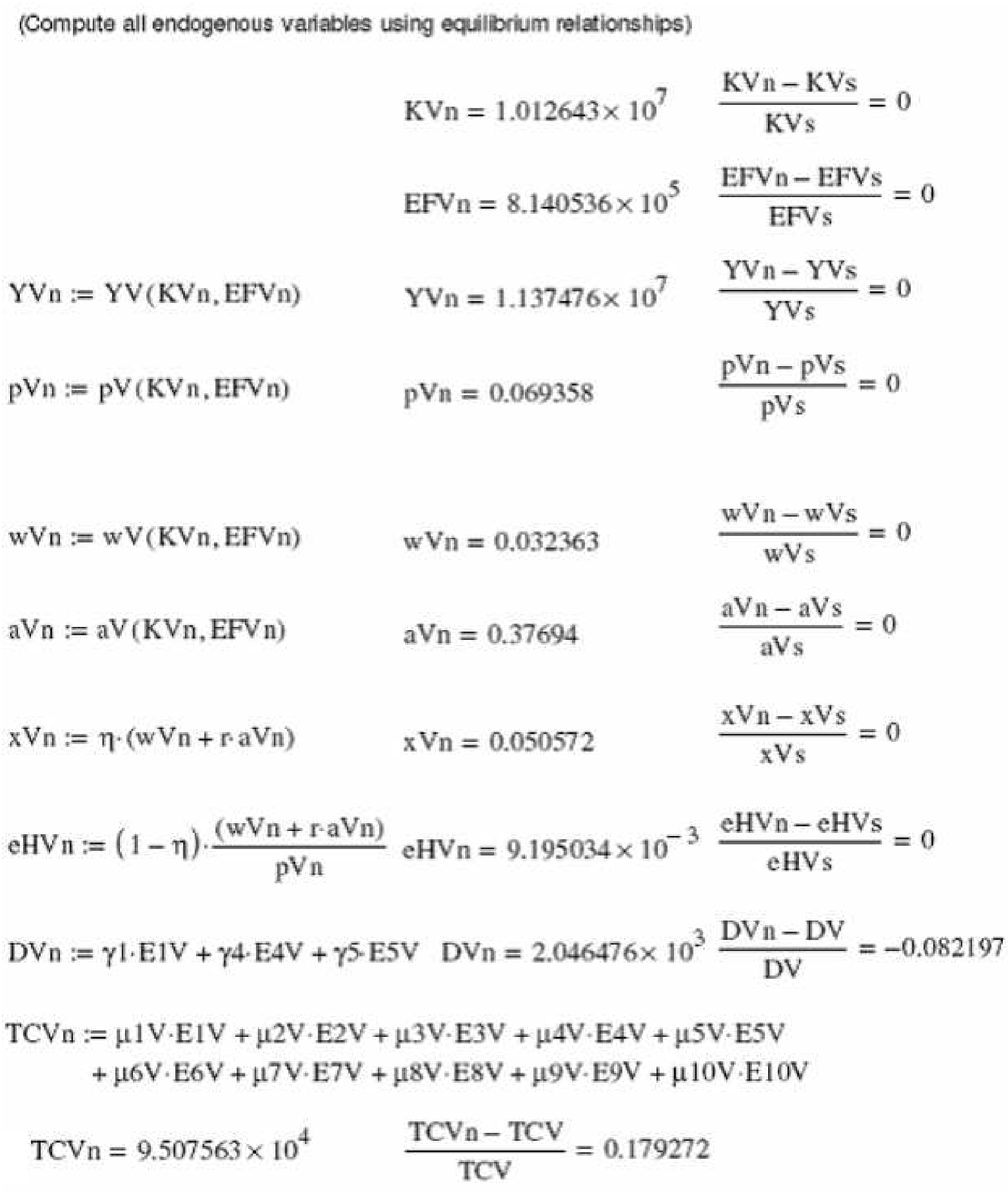
$KV := K\cdot 0.99 \quad EFV := EF\cdot 0.99$

Given

$$\alpha s\cdot\Gamma V(KV, EFV)\cdot\frac{YV(KV, EFV)}{KV} = (r + \delta)\cdot qV$$

$$\frac{1-\eta}{\eta}\cdot\frac{YV(KV, EFV) - \delta\cdot qV\cdot KV}{pV(KV, EFV)} = EV - EFV - ECV$$

$$\begin{pmatrix} KVn \\ EFVn \end{pmatrix} := \mathrm{Find}(KV, EFV)$$



(Compute all endogenous variables using equilibrium relationships)

$KVn = 1.012643\times 10^{7}$ $\quad \frac{KVn - KVs}{KVs} = 0$

$EFVn = 8.140536\times 10^{5}$ $\quad \frac{EFVn - EFVs}{EFVs} = 0$

$YVn := YV(KVn, EFVn)$ $\quad YVn = 1.137476\times 10^{7}$ $\quad \frac{YVn - YVs}{YVs} = 0$

$pVn := pV(KVn, EFVn)$ $\quad pVn = 0.069358$ $\quad \frac{pVn - pVs}{pVs} = 0$

$wVn := wV(KVn, EFVn)$ $\quad wVn = 0.032363$ $\quad \frac{wVn - wVs}{wVs} = 0$

$aVn := aV(KVn, EFVn)$ $\quad aVn = 0.37694$ $\quad \frac{aVn - aVs}{aVs} = 0$

$xVn := \eta\cdot(wVn + r\cdot aVn)$ $\quad xVn = 0.050572$ $\quad \frac{xVn - xVs}{xVs} = 0$

$eHVn := (1-\eta)\cdot\frac{(wVn + r\cdot aVn)}{pVn}$ $\quad eHVn = 9.195034\times 10^{-3}$ $\quad \frac{eHVn - eHVs}{eHVs} = 0$

$DVn := \gamma1\cdot E1V + \gamma4\cdot E4V + \gamma5\cdot E5V$ $\quad DVn = 2.046476\times 10^{3}$ $\quad \frac{DVn - DV}{DV} = -0.082197$

$$\begin{aligned} TCVn := {} & \mu1V\cdot E1V + \mu2V\cdot E2V + \mu3V\cdot E3V + \mu4V\cdot E4V + \mu5V\cdot E5V \\ & + \mu6V\cdot E6V + \mu7V\cdot E7V + \mu8V\cdot E8V + \mu9V\cdot E9V + \mu10V\cdot E10V \end{aligned}$$

$TCVn = 9.507563\times 10^{4}$ $\quad \frac{TCVn - TCV}{TCV} = 0.179272$

D. Rederive the calibrated equilibrium for policy 1
(replacing 10% of source 1 by source 4, changing p fully)
(Re-enter exogenous variables)

$E1V := E1Y \cdot 0.9 \quad E2V := E2Y \quad E3V := E3Y \quad E4V := E4$

$E5V := E5 \quad E6V := E6 + 0.01 \cdot E1Y \quad E7V := E7 + 0.01 \cdot E1Y$

$E8V := E8 \quad E9V := E9 + 0.03 \cdot E1Y \quad E10V := E10 + 0.05 \cdot E1Y$

$ECV := EC$

$NV := N \quad qV := q$

$\mu1V := \mu1 \quad \mu2V := \mu2 \quad \mu3V := \mu3 \quad \mu4V := \mu4$

$\mu5V := \mu5 \quad \mu6V := \mu6 \quad \mu7V := \mu7 \quad \mu8V := \mu8$

$\mu9V := \mu9 \quad \mu10V := \mu10$

(Re-derive endogenous variables using equilibrium relationships obtained in the model)

$$TCVn := \mu1V \cdot E1V + \mu2V \cdot E2V + \mu3V \cdot E3V + \mu4V \cdot E4V + \mu5V \cdot E5V + \mu6V \cdot E6V + \mu7V \cdot E7V + \mu8V \cdot E8V + \mu9V \cdot E9V + \mu10V \cdot E10V$$

$$pVn := pVs \cdot \frac{TCVn}{TCV}$$

$$EVsupply := E1V + E2V + E3V + E4V + E5V + E6V + E7V + E8V + E9V + E10V$$

$NE1V := \theta \cdot E1V \quad NE2V := \theta \cdot E2V \quad NE3V := \theta \cdot E3V \quad NE4V := \theta \cdot E4V$

$NE5V := \theta \cdot E5V \quad NE6V := \theta \cdot E6V \quad NE7V := \theta \cdot E7V \quad NE8V := \theta \cdot E8V$

$NE9V := \theta \cdot E9V \quad NE10V := \theta \cdot E10V$

$NEV := \theta \cdot EVsupply$

$NCV := \zeta \cdot ECV$

$NFV := NV - NEV - NCV$

$$YV(KV,EFV) := A\cdot\left[\phi\cdot\left(KV^{\alpha s}\cdot NFV^{1-\alpha s}\right)^{\rho s}+(1-\phi)\cdot(EFV)^{\rho s}\right]^{\frac{1}{\rho s}}$$

$$\Gamma V(KV,EFV) := \frac{\phi\cdot\left(KV^{\alpha s}\cdot NFV^{1-\alpha s}\right)^{\rho s}}{\phi\cdot\left(KV^{\alpha s}\cdot NFV^{1-\alpha s}\right)^{\rho s}+(1-\phi)\cdot(EFV)^{\rho s}}$$

$$wV(KV,EFV) := (1-\alpha s)\cdot\Gamma V(KV,EFV)\cdot\frac{YV(KV,EFV)}{NFV}$$

$$aV(KV,EFV) := \frac{1}{r}\cdot\left[\frac{(YV(KV,EFV)-\delta\cdot qV\cdot KV)}{\eta\cdot NV}-wV(KV,EFV)\right]$$

$$EVdemand(KV,EFV) := EFV+ECV+\frac{1-\eta}{\eta}\cdot\frac{YV(KV,EFV)-\delta\cdot qV\cdot KV}{pVn}$$

(Solve new equilibrium values of K and EF)

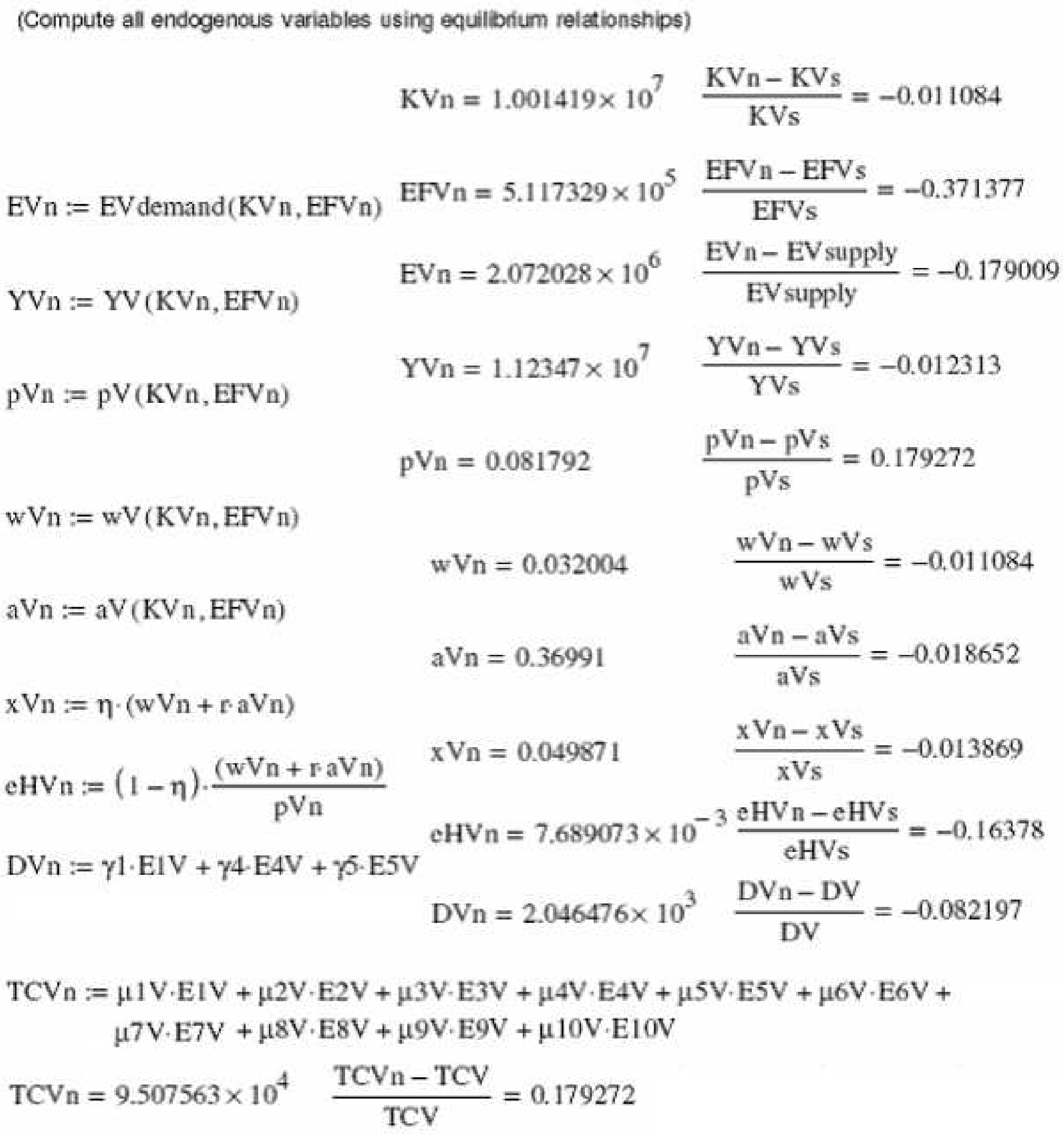
$KV := K\cdot 0.99$ $EFV := EF\cdot 0.99$

Given

$$\alpha s\cdot\Gamma V(KV,EFV)\cdot\frac{YV(KV,EFV)}{KV} = (r+\delta)\cdot qV$$

$$(1-\Gamma V(KV,EFV))\cdot\frac{YV(KV,EFV)}{EFV} = pVn$$

$$\begin{pmatrix} KVn \\ EFVn \end{pmatrix} := Find(KV,EFV)$$



(Compute all endogenous variables using equilibrium relationships)

$$KVn = 1.001419\times 10^{7} \qquad \frac{KVn - KVs}{KVs} = -0.011084$$

$$EVn := EVdemand(KVn, EFVn)$$

$$EFVn = 5.117329\times 10^{5} \qquad \frac{EFVn - EFVs}{EFVs} = -0.371377$$

$$EVn = 2.072028\times 10^{6} \qquad \frac{EVn - EVsupply}{EVsupply} = -0.179009$$

$$YVn := YV(KVn, EFVn)$$

$$YVn = 1.12347\times 10^{7} \qquad \frac{YVn - YVs}{YVs} = -0.012313$$

$$pVn := pV(KVn, EFVn)$$

$$pVn = 0.081792 \qquad \frac{pVn - pVs}{pVs} = 0.179272$$

$$wVn := wV(KVn, EFVn)$$

$$wVn = 0.032004 \qquad \frac{wVn - wVs}{wVs} = -0.011084$$

$$aVn := aV(KVn, EFVn)$$

$$aVn = 0.36991 \qquad \frac{aVn - aVs}{aVs} = -0.018652$$

$$xVn := \eta\cdot(wVn + r\cdot aVn)$$

$$xVn = 0.049871 \qquad \frac{xVn - xVs}{xVs} = -0.013869$$

$$eHVn := (1-\eta)\cdot\frac{(wVn + r\cdot aVn)}{pVn}$$

$$eHVn = 7.689073\times 10^{-3} \qquad \frac{eHVn - eHVs}{eHVs} = -0.16378$$

$$DVn := \gamma1\cdot E1V + \gamma4\cdot E4V + \gamma5\cdot E5V$$

$$DVn = 2.046476\times 10^{3} \qquad \frac{DVn - DV}{DV} = -0.082197$$

$$TCVn := \mu1V\cdot E1V + \mu2V\cdot E2V + \mu3V\cdot E3V + \mu4V\cdot E4V + \mu5V\cdot E5V + \mu6V\cdot E6V + \mu7V\cdot E7V + \mu8V\cdot E8V + \mu9V\cdot E9V + \mu10V\cdot E10V$$

$$TCVn = 9.507563\times 10^{4} \qquad \frac{TCVn - TCV}{TCV} = 0.179272$$

$$\mathrm{DVnadjust} := \mathrm{DVn}\cdot\frac{\mathrm{EVn}}{\mathrm{EVsupply}} \qquad \mathrm{DVnadjust} = 1.680138\times 10^{3}$$

$$\mathrm{TCVnadjust} := \mathrm{TCVn}\cdot\frac{\mathrm{EVn}}{\mathrm{EVsupply}} \qquad \mathrm{TCVnadjust} = 7.805624\times 10^{4}$$

$$\frac{\mathrm{DVnadjust} - \mathrm{DV}}{\mathrm{DV}} = -0.246492$$

$$\frac{\mathrm{TCVnadjust} - \mathrm{TCV}}{\mathrm{TCV}} = -0.031829$$

$$\mathrm{layoff} := \theta\cdot(\mathrm{EVsupply} - \mathrm{EVn}) \qquad \mathrm{layprob} := \frac{\mathrm{layoff}}{\mathrm{NV}}$$

$$\mathrm{layoff} = 1.112074\times 10^{5}$$

$$\mathrm{layprob} = 1.120493\times 10^{-3}$$

$$\mathrm{wVex} := \mathrm{wVn}\cdot(1 - \mathrm{layprob}) \qquad \mathrm{wVex} = 0.031968$$

$$\mathrm{xVex} := \eta\cdot(\mathrm{wVex} + \mathrm{r}\cdot\mathrm{aVn}) \qquad \mathrm{xVex} = 0.049835$$

$$\frac{\mathrm{wVex} - \mathrm{wVs}}{\mathrm{wVs}} = -0.012192$$

$$\frac{\mathrm{xVex} - \mathrm{xVs}}{\mathrm{xVs}} = -0.014569$$

$$\mathrm{eHVex} := (1 - \eta)\cdot\frac{(\mathrm{wVex} + \mathrm{r}\cdot\mathrm{aVn})}{\mathrm{pVn}} \qquad \mathrm{eHVex} = 7.683613\times 10^{-3}$$

$$\frac{\mathrm{eHVex} - \mathrm{eHVs}}{\mathrm{eHVs}} = -0.164374$$

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