BIOMASS RESOURCES FOR ENERGY IN OHIO: THE OH-MARKAL MODELING FRAMEWORK

DISSERTATION

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By

Bibhakar Shakya, M.S.

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The Ohio State University

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Dissertation Committee:

Professor Fredrick J. Hitzhusen, Adviser

Professor Brent L. Sohngen

Professor Andrew G. Keeler

Approved by

____

Adviser
Graduate Program in Agricultural, Environmental,
and Development Economics

ABSTRACT

The latest reports from the Intergovernmental Panel on Climate Change have indicated that human activities are directly responsible for a significant portion of global warming trends. In response to the growing concerns regarding climate change and efforts to create a sustainable energy future, biomass energy has come to the forefront as a clean and sustainable energy resource. Biomass energy resources are environmentally clean and carbon neutral with net-zero carbon dioxide (CO_2) emissions, since CO_2 is absorbed or sequestered from the atmosphere during the plant growth. Hence, biomass energy mitigates greenhouse gases (GHG) emissions that would otherwise be added to the environment by conventional fossil fuels, such as coal.

The use of biomass resources for energy is even more relevant in Ohio, as the power industry is heavily based on coal, providing about 90 percent of the state's total electricity while only 50 percent of electricity comes from coal at the national level. The burning of coal for electricity generation results in substantial GHG emissions and environmental pollution, which are responsible for global warming and acid rain. Ohio is currently one of the top emitters of GHG in the nation.

This dissertation research examines the potential use of biomass resources by analyzing key economic, environmental, and policy issues related to the energy needs of Ohio over a long term future (2001-2030). Specifically, the study develops a dynamic linear programming model (OH-MARKAL) to evaluate biomass cofiring as an option in select coal power plants (both existing and new) to generate commercial electricity in Ohio. The OH-MARKAL model is based on the MARKAL (MARKet ALlocation) framework.

Using extensive data on the power industry and biomass resources of Ohio, the study has developed the first comprehensive power sector model for Ohio. Hence, the model can serve as an effective tool for Ohio's energy planning, since it evaluates economic and environmental consequences of alternative energy scenarios for the future. The model can also be used to estimate the relative merits of various energy technologies.

By developing OH-MARKAL as an empirical model, this study evaluates the prospects of biomass cofiring in Ohio to generate commercial electricity. As cofiring utilizes the existing infrastructure, it is an attractive option for utilizing biomass energy resources, with the objective of replacing non-renewable fuel (coal) with renewable and cleaner fuel (biomass). It addresses two key issues: first, the importance of diversifying the fuel resource base for the power industry; and second, the need to increase the use of biomass or renewable resources in Ohio. The results of the various model scenarios developed in this study indicate that policy interventions are necessary to make biomass co-firing competitive with coal, and that about 7 percent of electricity can be generated by using biomass feedstock in Ohio.

This study recommends mandating an optimal level of a renewable portfolio standard (RPS) for Ohio to increase renewable electricity generation in the state. To set a higher goal of RPS than 7 percent level, Ohio needs to include other renewable sources such as wind, solar or hydro in its electricity generation portfolio. The results also indicate that the marginal price of electricity must increase by four fold to mitigate CO_2 emissions 15 percent below the 2002 level, suggesting Ohio will also need to consider and invest in clean coal technologies and examine the option of carbon sequestration. Hence, Ohio’s energy strategy should include a mix of domestic renewable energy options, energy efficiency, energy conservation, clean coal technology, and carbon sequestration options. It would seem prudent for Ohio to become proactive in reducing CO_2 emissions so that it will be ready to deal with any future federal mandates, otherwise the consequences could be detrimental to the state’s economy.

Dedication

To my family,

Dina, Deven, and Neal

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VITA

November 16, 1961 ……………………… Born – Kathmandu, Nepal

1983 ……………………………………… B.S. (Honors) in Agricultural Sciences Haryana Agricultural University, India.

1992 ……………………………………… M.A. in Economics, Department of Economics, The Ohio State University, Columbus, Ohio.

1994 ……………………………………… M.S. in Environmental and Resource Economics, The Ohio State University, Columbus, Ohio.

1989 – 1991 ……………………………… Fulbright Scholar, Graduate Student, The Ohio State University, Columbus.

1992 – 1996 ……………………………… Graduate Research Associate, The Ohio State University, Columbus.

2004 – present …………………………….. Graduate Administrative and Research Associate, The Ohio State University, Columbus.

PUBLICATIONS

1. Bibhakar Shakya and Anne Goodge, "The Prospect of Energy Crops in Ohio: Evaluating Principal Economic, Environmental, and Policy Issues." The Ohio State University and Ohio Biomass Energy Program, 2002.

2. Bibhakar Shakya, "Prospects of Energy Crops in Ohio's Competitive Power Market." In the Conference Proceedings of Renewable Energy: Market Outlook and Strategies- Current and Future, organized by Strategic Research Institute, November, 2000.

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FIELDS OF STUDY

Major Field: Agricultural, Environmental, and Development Economics

Area of Emphasis: Environmental and Resource Economics

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Page

CHAPTER 1

INTRODUCTION

The latest reports from the Intergovernmental Panel on Climate Change (IPCC) have indicated that human activities are directly responsible for a significant portion of global warming trends (IPCC, 2007). Similar reviews published in recent years from the Natural Resources Defense Council, Pew Center on Global Climate Change, Resources for the Future, and Union of Concerned Scientists claim that increased use of fossil fuels and industrial pollution have contributed considerably toward changing the climate systems of our planet (Burtraw and Palmer, 2004; EPRI, 2005; Hawkins, 2004; PEW, 2007; NRDC, 2005; USC, 2004). The use of clean and sustainable energy resources will be pivotal to mitigate greenhouse gas (GHG) emissions and reduce their negative impacts on climate change. At present, more than 21 states in the U.S. have made increased efforts to reduce greenhouse gas emissions to mitigate global warming (Rabe, 2006). With Ohio's heavy reliance on fossil fuels, particularly for electricity generation, it is imperative that Ohio initiate and adopt similarly aggressive short and long-term plans to decrease its emissions of greenhouse gases.

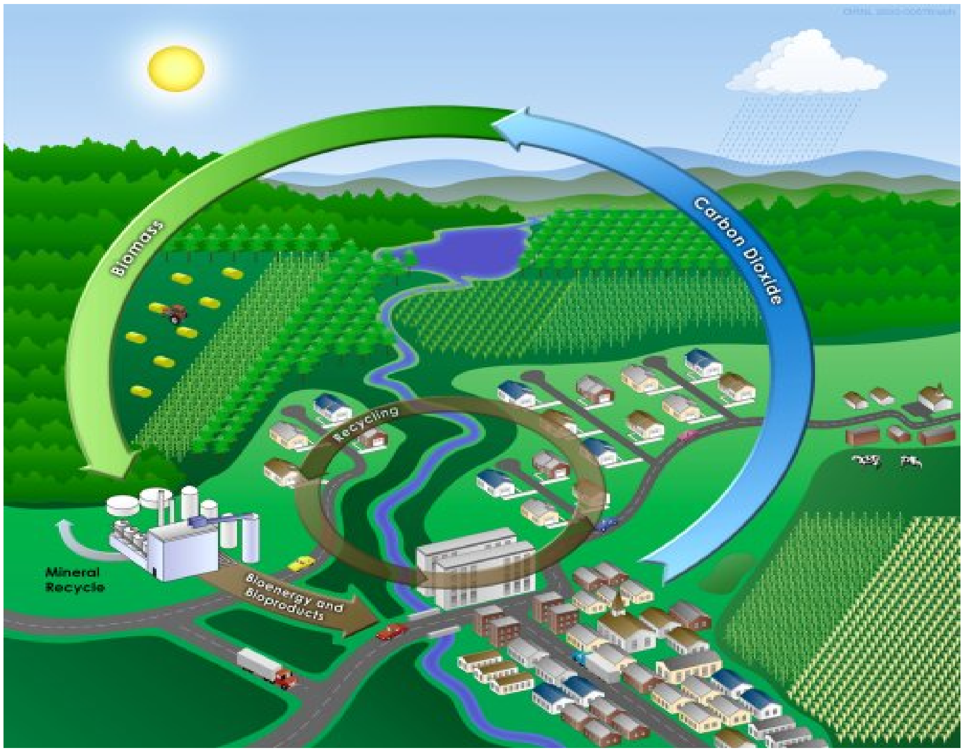
In response to the growing concerns regarding climate change and to create an environmentally sustainable future, biomass resources have come to the forefront as a clean and renewable energy source, since they have the greatest potential to complement traditional sources of energy such as coal and oil to meet growing energy demands. Among renewable energy sources, biomass is currently a principal supplier of renewable electricity in the U.S. While hydroelectric power has been the highest supplier of renewable electricity, recent data indicate that biomass resources and hydro power each contribute about 46 percent toward the total renewable electricity generation in the U.S. (Figure 2). Furthermore, biomass provides both liquid and gaseous forms of energy such as biofuels (ethanol and biodiesel) and methane from landfills and anaerobic digesters. Biomass materials can also be used to produce a variety of bioproducts, such as chemicals and fibers.

Biomass energy resources are environmentally clean and carbon neutral with net-zero carbon dioxide (CO_2) emissions, since CO_2 is absorbed or sequestered from the atmosphere during the plant growth (Figure 1). Hence, the use of biomass energy eliminates CO_2 emissions that would otherwise be added to the environment with conventional sources of energy produced by using fossil fuels, such as coal. In addition, biomass energy provides several other environmental and social benefits that include reducing air pollutants like sulfur dioxide (SO_2) and nitrous oxide (NO_x), diversifying the rural economic base by complementing farm income, as well as enhancing national energy security (e.g., by production of domestic biofuels that substitute imported oil).

Recognizing such benefits, state and federal legislatures have initiated several key policies in recent years to encourage the use of biomass resources for energy purposes. In the U. S., biomass and other renewables are currently receiving significant policy impetus at the federal, state, county, and even city levels. The Farm Security and Rural Investment Act of 2002 is the first federal farm bill to recognize agriculture as a major stakeholder in the energy security debate and the bill included several policy initiatives to promote the use of biomass energy in the U.S. In 2005, the Energy Policy Act (EPAct 2005) was signed into law and provides major incentives to improve biomass technologies and to boost the use of biopower, biofuels, and bioproducts in the country. The EPAct supports renewable energy research and demonstration programs as well as a number of promotional activities for the development and utilization of biomass resources across the country (BRDI, 2005). Further, the EPAct also accommodates tax credits from 0.75 to 1.5 cent per kWh for qualifying renewable power generators using various renewable sources, including biomass resources and cofiring as an incentive for increased biomass usage (OBEP, 2005, NRBP, 2005). (For complete list of renewable electricity tax credits, see *www.nrbp.org* or *www.energy.senate.gov*).

The agriculture and forestry sectors can play an important role in the country's renewable energy future and contribute significantly in enhancing a cleaner environment. Given the proper policy incentives, Ohio can provide substantial biomass resources for generating renewable energy and sequestering carbon from the atmosphere. As a major agricultural state, Ohio has an abundant supply of crop residues and may offer promising prospects to grow energy crops. Similarly, about 30 percent of Ohio's land is under forest and has an annual growth rate 2.5 to 3 times higher than the harvesting rate. There are more than 180 sawmills and over 2,000 secondary wood manufacturing companies in Ohio, generating a significant amount of industrial wood residues (ODNR, 2004). These biomass resources, from both agricultural and forest sectors, can serve as a viable alternative to generate electricity in the power market. Because of the rising state and federal renewable incentives and requirements, growing demands for clean energy, as well as increasing awareness of global climate change, biomass as a renewable energy resource may become an integral part of Ohio's energy future.

A growing environmental concern in Ohio has been its heavy reliance on coal that provides about 90 percent of the state's total electricity (Table 3). The burning and consumption of this fossil fuel result in substantial greenhouse gases (GHG) and other emissions that cause global warming and acid rain. Hence, the use of biomass energy resources becomes even more important in Ohio, since its power industry is creating considerable air pollution and GHG emissions not only within the state, but it also affects the air quality of the New England states and Canada. It has, therefore, become a high priority for Ohio to diversify its power industry's fuel mix and examine other alternatives for renewable energy generation. Among alternative energy sources, the biomass resource has become a major supplier of renewable power in many states in the U.S. Recent data indicate that the use of biomass energy is increasing in the U.S., as both biomass and hydroelectric power contributed about 3 percent each toward total electricity generation in 2003 (Figure 2; Arvizu, 2005).

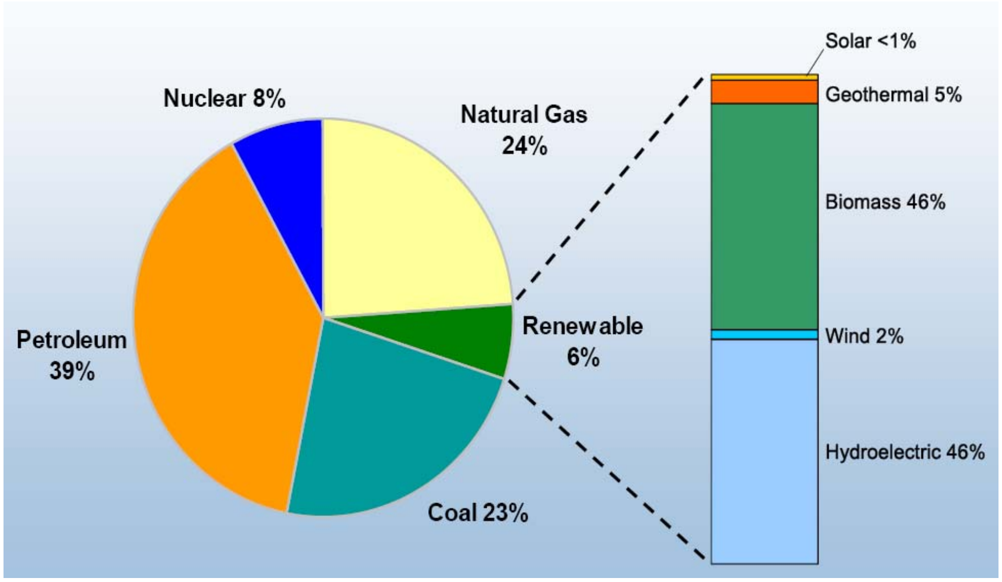


(Source: ORNL, 1999)

Figure 1. Biomass Energy Resource: Carbon Neutral Energy

Given the increasing emphasis on the use of biomass energy in the country and the existing environmental concerns related to energy use in Ohio, this dissertation proposes a comprehensive analysis of the utilization of biomass energy resources to provide renewable power and mitigate GHG emission levels in Ohio. For this purpose, this study adapts the existing MARKAL (MARKet ALlocation) modeling framework to develop

OH-MARKAL for the state of Ohio. MARKAL is a robust mathematical model of energy systems that provides a technology-rich basis for estimating energy dynamics over a multi-period horizon. As a linear programming model, it has been used widely around the world for assessing a broad range of planning and policy issues for energy and the environment. It is a flexible and adaptable methodology for supporting global, regional, national, as well as local decision-making processes. Hence, it can also be used as an analytical tool to achieve environmental and policy goals for Ohio's energy future. By developing OH-MARKAL as an empirical model, this study analyzes major economic, environmental, and policy issues that will have significant impact on the development and utilization of biomass energy resources in Ohio.



(Source: Arvizu, 2005).

Figure 2. Biomass Contribution in Total U.S. Renewable Electricity Supply (2003)

This study examines specifically the prospects of cofiring biomass feedstock in existing coal power plants to generate commercial electricity in Ohio. According to FTO (2004), biomass cofiring can substitute for up to 20 percent of coal in a typical coal power plant. Cofiring utilizes existing infrastructure, thus making it an attractive option of utilizing biomass energy resources with an objective of replacing non-renewable fuel (coal) with renewable and clean fuel (biomass). With this proposed scenario of biomass use for electricity generation, this research addresses two major policy related goals for Ohio. The first objective is to explore potential for increased use of biomass resources in Ohio, since its current use is low compared to other Midwest states (Table 1). As a major agricultural state, Ohio may also be able to provide benefits of using biomass energy for its environment, energy consumers, and the farming communities. The second goal is to address the need to diversify the energy resource mix for the power industry, which is currently heavily based on coal. This extensive use of coal has made Ohio one of the largest emitters of air pollutants and GHG in the nation (Table 5).

The use of biomass for commercial electricity generation not only mitigates GHG emissions, but also provides green (renewable) electricity to consumers in the competitive electric market. Although the green power could potentially fetch a premium price in the market, the current premium pricing is not large enough to expand renewable energy. However, many power companies are still looking for ways to provide such service to their customers where it is required by law to meet air quality standards or renewable portfolio standards (RPS). In Ohio, Bowling Green Municipal Utility currently provides such a green pricing program to its customers. The price of electricity from renewable sources is only \$0.013 more per kWh than the conventional power which is equivalent to about \$8 to \$10 more per month for the average customer (BGMU, 2004). The Public Utilities Commission of Ohio has recently approved Duke Energy's green pricing option for a pilot period through 2008, where it will provide customers the option of paying a premium so that Duke Energy can purchase renewable energy certificates associated with generation from renewable energy sources (PUCO, 2007).

1. Objectives of the Study

By developing the OH-MARKAL model, this dissertation focuses on evaluating the economic, environmental, and policy issues of using biomass energy resources in Ohio with the following specific objectives:

- Evaluate current resource mix in Ohio for power generation and compare level of CO_2 emissions from electricity generation under coal vs. biomass cofiring scenarios.
- Develop alternative biomass cofiring scenarios in selected coal power plants in Ohio.
- Analyze economic and environmental issues of biomass cofiring to generate electricity.
- Examine whether biomass cofiring can become an effective option for more sustainable and cleaner electricity generation in Ohio.
- Suggest effective strategies and sound renewable policies for the successful development and utilization of biomass energy resources in Ohio.
- Recommend potential energy policies for Ohio's economy and environmentally sustainable future.

State	**Hydro-electric Conven.**	**MSW / Landfill Gas**	**Other Biomass**[a]	**Wind**	**Wood / Wood Waste**	**Total**
Michigan	1,310,430	658,861	124,751	2,660	1,018,495	**3,115,197**
Minnesota	721,287	755,142	0	977,760	100,615	**2,554,804**
Wisconsin	1,653,066	387,306	71,629	97,580	61,088	**2,270,669**
Iowa	788,593	97,548	1,149	981,970	0	**1,869,260**
Illinois	138,497	595,850	272,343	18,024	0	**1,024,714**
Ohio[b]	510,835	27,184	0	0	50,561	**588,580**
Indiana	423,953	85,278	0	0	0	**509,231**
Total	**5,546,661**	**2,607,169**	**469,872**	**2,077,994**	**1,230,759**	**11,932,455**

(Source: DOE/EIA, Form EIA-906, 2000)

Note: **a** Agriculture byproducts/crops, sludge waste, tires and other biomass solids, liquids and gases
b Ohio ranks 42nd at the national level. Top ranking states are: WA, CA, OR, NY, AL and TN

Table 1. Renewable Electricity Net Generation by Energy Source and State
(2003 in Thousand KW hours)

The next section of this chapter provides a general overview of the electric utility industry in the U.S. and highlights its current status in Ohio. In the remaining sections, the general trends of biomass energy utilization in the country and its prospects in Ohio are discussed, highlighting that fact that the current use of biomass energy resources for commercial power generation is relatively low, with a few wood and paper industries (Table 6). The final sections examine the current cofiring technology and major issues in cofiring biomass feedstock in coal power plants in Ohio.

2. General Overview of the Electric Utility Industry in the U.S.

The power industry in the U.S. is primarily investor-owned utilities that generate about 75 percent of the electricity in the country (EIA, 2003). Other types of electric utilities include publicly owned, cooperative, and federal electric utilities. In Ohio, rural electric cooperatives and municipalities serve consumers in their respective rural areas and cities; however, more than 90 percent of the total population is served by investor-owned utilities (EIA, State Profile, 2002).

Investor-owned utilities are a vertically integrated industry, providing three services of electricity: generation, transmission, and distribution. These utilities have service monopolies in their respective geographic areas and are obligated to serve all consumers. This was based on the concept of natural monopoly, as the nature of the transmission and distribution system implied that a single company was more efficient in generating low cost power through a bigger generation plant due to the economies of scale. Government regulation of these utilities was instituted not only to protect consumers from monopoly abuses but also to provide reliability and a fair rate of return to the utility. Hence, the industry had been functioning under traditional rate-based regulation in the U.S. until significant restructuring in the power industry started in the late 1990s.

2.1 The Restructuring of the Power Industry in the U.S.

Electric power is the last major industry in the U.S. that is under restructuring to open up for competition, modeled after similarly de-regulated industries like the airlines, banking, and telecommunications. There are many factors that spurred the restructuring of the power industry in the U.S. The following are the three principal factors:

- Improvements in power-generating technology
- Legislative and regulatory mandates
- Regional electricity price variations

Improvements in Power-Generating Technology

The power generation technology has made tremendous progresses in recent years. This revolution in power generation has initiated a brand new way of doing business in the power industry. The "economies of scale" characterizes a production process where the long run average cost can be reduced by increasing the scale (capacity) of the firm. This classic economic principle, once the sole reason for construction of mega power plants in the nation, no longer applies to the power industry. Technological advancements in the power generation sector have made it possible to produce power on a relatively small scale and in a more efficient manner than traditional power plants. Such new power plants can also be built in substantially less time and will require less capital investment than the existing power generation plants. Improved technology has made new power generators cleaner, cheaper, and more efficient. Hence, technological improvements in the generation sector have made an important impact on the restructuring of the U.S. power industry.

Legislative and Regulatory Mandates

The power industry in the U.S. had benefited from the natural monopoly status with certain geographic areas comprising its service territories. However, a significant change in the power industry was initiated with the Public Utility Regulatory Policies Act (PURPA) in 1978. This act allowed non-utility generators to enter the wholesale power market. The following landmark legislative and regulatory mandates were important for the progress of the power industry toward a competitive market (DOE/EIA-X037, 2000).

> **(a) The Public Utility Regulatory Policies Act of 1978 (PURPA):** The PURPA required the electric utilities to interconnect and buy electricity generated by any non-utility (competitor) that met the criteria established by the Federal Energy Regulatory Commission (FERC). Its main purpose was to encourage the efficient use of fossil fuels in electric generation by using co-generators and by the use of renewable resources through independent small power producers. This act

showed that the transmission grid could be opened up successfully for non-utility generators, and paving the way for wholesale competition, which was achieved by the Energy Policy Act of 1992.

(b) The Energy Policy Act of 1992 (EPACT): The EPACT opened access to transmission networks and provided exemption to certain non-utilities (competitors) from the restrictions of the Public Utility Holding Company Act of 1935 (PUHCA). The PUHCA permitted only the integrated single utility company to enter the electric market, thereby giving no room for non-utility generators to enter in electric power sales. The dawn of electric restructuring started with the EPACT as it facilitated the competition at the wholesale level by opening up the access to transmission network to all competitors.

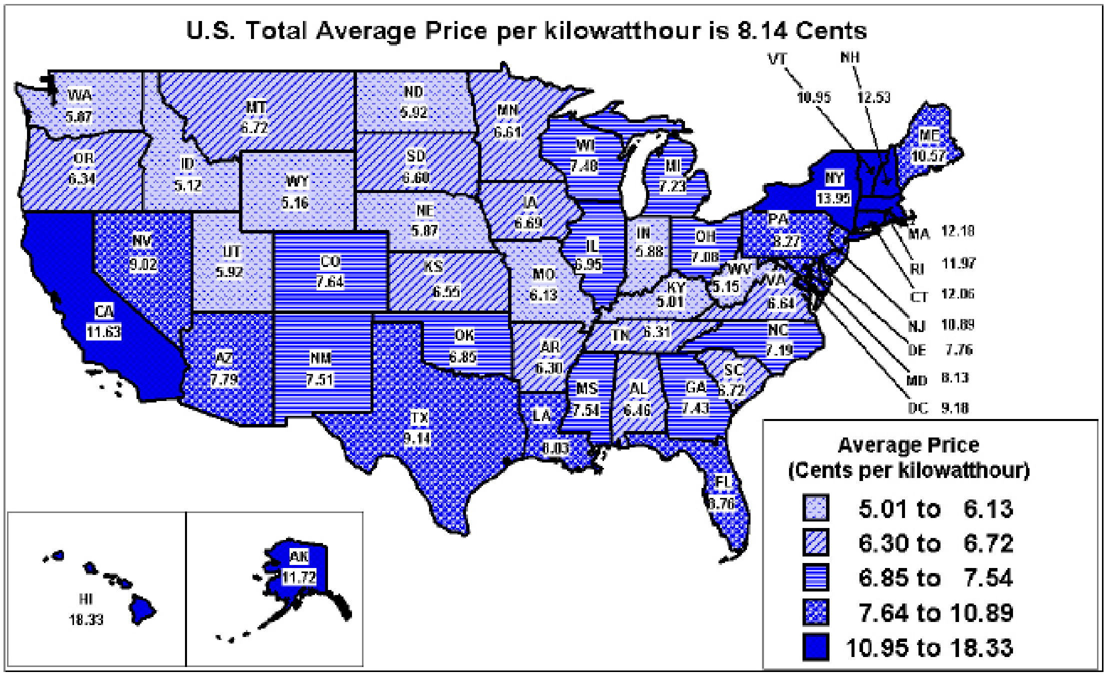
(c) FERC Orders 888 and 889 of 1996: Order 888 opened transmission access to non-utilities to establish wholesale electric competition, while Order 889 required utility companies to share information on their available transmission capacity via electronic systems. The main objectives of these Orders were to encourage wholesale competition and eliminate the power monopoly over the transmission of electricity.

Because of the above-mentioned legislative and regulatory mandates, especially the FERC Order 888 that created the competitive wholesale power markets, restructuring of the power industry was considered in several states in the U.S., including Ohio (DOE/EIA, 2003).

Regional Electricity Price Variations

The regional variations in electricity price prompted the ideas of efficiency gain by opening up the market for competition. The electricity price across the nation widely differs and sometimes the difference is fairly large, even between the neighboring states

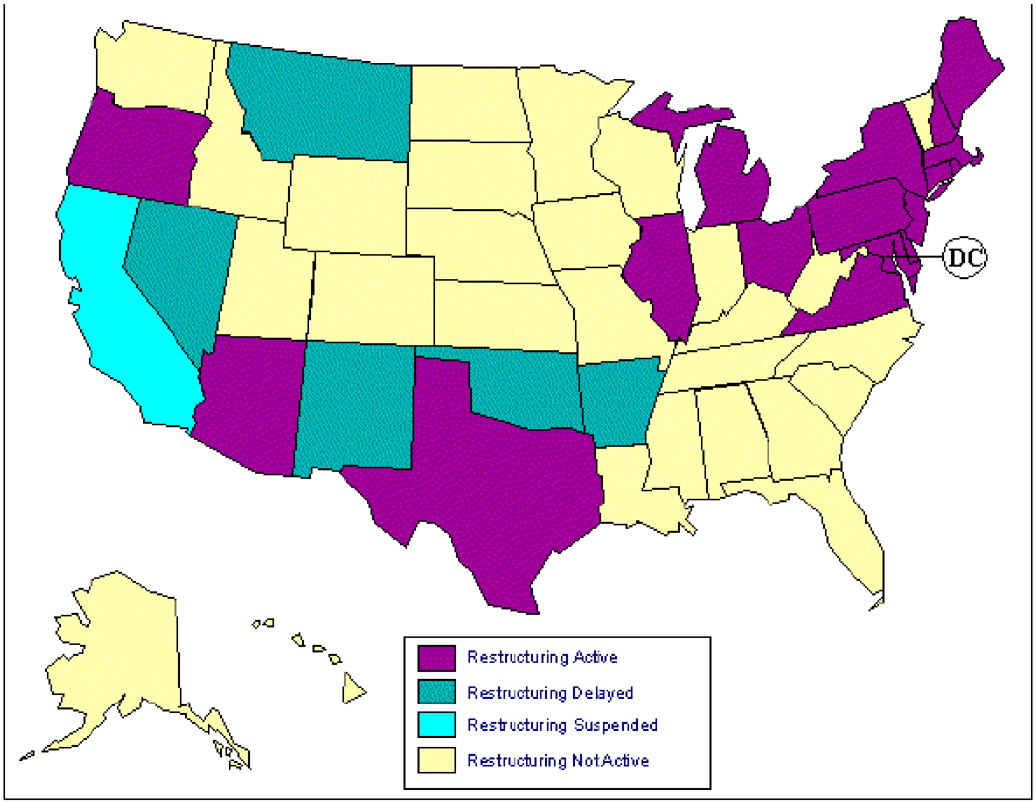
(Figure 3). Such differences in electric rates between states and, in Ohio's case, even within a single state (e.g., the electric rates in northeastern Ohio are much higher than in central and southern Ohio), induced the passage of electric restructuring legislation around the nation due to the possibility of efficiency gain. Restructuring initially started in states where electric rates were higher than the national average, like in most northeastern states and California. Although electric rates in Ohio are slightly below the national average, it is the price variability within the state that has prompted political and legislative attention for a transition to a competitive market. The average price for electricity is about 12 cents/KWh in northeast Ohio as compared to 8 cents/KWh in central and southern Ohio (PUCO, 2002).



Note: Data is displayed as 5 groups of 10 States and the District of Columbia.

Source: Energy Information Administration, Form EIA-861, "Annual Electric Power Industry Report."

Figure 3. U.S. Total Average Price per kWh by State
(2005)



(Source: DOE/EIA, 2003)

Figure 4. Status of State Electric Industry Restructuring Activity (2003)

The restructuring of the electric utility industry began in early 1990s, and California became the pioneer state in electric restructuring by opening its electric market for competition in 1998. However, California faced many challenges during the restructuring phases, including the severe power shortage in the summer of 2000 (DOE/EIA, 2000). During that time, there were periods of frequent blackouts around the San Francisco area, and electric prices in the San Diego region increased to more than double the existing market price. The shortage of electricity and high electric prices were primarily caused by a lack of generating capacity and because of the immature market system that failed to manage demand and supply risk (DOE/EIA, 2000). Currently, the restructuring process in California has been suspended (DOE/EIA, 2003).

Despite the major setbacks in California, many other states including Ohio did continue with their respective electric restructuring plans by moving toward a competitive market, with significant economic and environmental implications. Figure 4 illustrates the current status of electric industry restructuring activities in each state. There are 24 states and the District of Columbia which have either enacted the restructuring legislation, or issued a regulatory order to implement retail access, thus allowing customers to choose their own supplier of electricity generation services. A few states like Arkansas, Montana, Nevada, New Mexico, and Oklahoma have postponed their plans of adopting retail competition. Several states (in color yellow Figure 4) have decided not to consider a restructuring process.

Competition in the electric generation sector remains an attractive alternative to regulation, as the regulated market provides less incentive to improve efficiency (Palmer *et. al.,* 2002). Similar to what happened in industries such as the airlines, banking, and telecommunications, it is hoped that the generation portion of power supply will become more efficient in a competitive market. As the current electric restructuring process is focused only on the generation sector, the remaining transmission and distribution sectors of the power industry, with their strong natural monopolistic characteristics, will still be regulated for the foreseeable future.

2.2 Current Status of Ohio's Power Industry

Ohio, with its $13 billion electric utility industry, is the third largest generator of electricity in the U.S. after Texas and California (DOE/EIA, 2002). The electric utility industry has an enormous impact on the well being of Ohio's economy, providing electricity to over 4.6 million customers, which is about 90 percent of Ohio's electric users. The industry employs more than 20,000 people and financially supports 17,000 retirees. The industry operates about 253 power plants and facilities in Ohio and pays over 967 million in state and local taxes each year (Table 2).

Retail electric competition began in Ohio after the adoption of the electric restructuring legislation in the summer of 1999 (Senate Bill 3, 1999). Under its restructuring plan, the generation portion of the industry was opened up for market competition and consumers were given the ability to select their electric generation company, either to save money or to choose power sources that they consider environmentally cleaner. However, there is not much opportunity for consumers without competitors in the market. Due to lower electricity prices in Ohio, the choice for electric suppliers in the state has been minimal or does not exist at all.

Ohio (2002)	**AE**	**AEP**	**CIN**	**DP&L**	**FE**	**Total**
Customers	28,924	1,390,593	664,538	504,762	2,074,000	**4,662,817**
Employees	24	7,156	3,721	1,478	7,817	**20,196**
Plants & Facilities	1	78	26	25	123	**253**
Retirees	68	7,174	1,295	1,700	7,000	**17,237**
Revenues (billion)	$0.065	$3.513	$4.453	$1.173	$4.334	**$13.538**
Taxes Paid (million)	$3.4	$255.6	$174.1	$101	$433	**$967.1**

(Source: Ohio Electric Utility Profile, 2002. http://www.oeui.org/profile.htm)

Note: AE, Allegheny Energy; AEP, American Electric Power; CIN, Cinergy; Dayton Power and Light Company; and FE, First Energy Corp.

Table 2. Economic Impact of Ohio's Investor-Owned Electric Utilities

The Ohio restructuring legislation includes several environmental provisions that are designed to increase consumer awareness on the advantages of competition and the environmental impacts of electric generation. As competition in the electric industry moves forward in the future, the demand for clean and renewable energy could increase in Ohio — a pattern that has been highlighted in many other states (Shakya and Goodge, 2000). The following three key environmental provisions are included in Ohio's restructuring law:

- **Environmental Disclosure (Ohio Revised Code Section 4928.10)**: This provision ensures that consumers are informed of their energy choices and their potential environmental impacts on a regular basis. The law requires that the electric utility companies provide a customer with standardized information comparing their projected, with the actual and verifiable, resource mix and its environmental characteristics.

- **Energy Efficiency Revolving Loan Fund (Sections 4928.01(A) (25) and 4928.61 to 4928.63):** The loan fund legislation reserves funding for financial assistance to energy efficiency projects. The law describes the various types of projects to be funded under this provision, which include renewable and biomass projects.

- **Net metering standards (Section 4928.67):** The Ohio law defines net metering as "measuring the difference in an applicable billing period between the electricity supplied by an electric service provider and the electricity generated by a customer-generator which is fed back to the electric service provider" (SB 3, 1999). The producers of renewable and biomass energy can benefit from this provision.

In addition to these environmental provisions, the Ohio Electric Restructuring Act of 1999 directed the state's investor-owned electric companies to spend up to $16 million for statewide and local consumer education programs prior to and during the first year of electric competition. The law provides an additional \$17 million to education programs for the reminder of the transition period (Section 4928.42, SB3, 1999). This education program was directed for consumers to become aware and informed regarding the choices for their electric services.

2.3 Electricity Generation, Coal Uses, and GHG Emissions

When fossil fuels, such as coal, are burned to generate electricity, various gases and particulates are released into the atmosphere. The primary emissions during the burning of fossil fuels are sulfur dioxide (SO_2), nitrogen oxide (NO_x), mercury, and carbon dioxide (CO_2). Although some of these pollutants are captured by pollution control devices, the utility industry is a major source of air pollution and GHG emissions, and it is responsible for 68 percent of SO_2, 22 percent of NO_x, 40 percent of mercury, and 39 percent of CO_2 emissions in the U.S. (Palmer *et. al*., 2004). While CO_2 is the most critical GHG associated with climate change, SO_2 and NO_x contribute to the airborne particulates accountable for thousands for premature deaths each year, especially among the elderly and children (Palmer *et. al*., 2004). As a result, health issues related to these emissions are no less serious than their environmental impacts. These pollutants also cause acid rain and smog (visibility impairment). NO_x plays a role in ground ozone formation, which also has many health hazards.

Coal power plants are the largest source of mercury emissions and emit about 50 tons of mercury into the atmosphere per year (EPA, 1998). The EPA also estimates that the level of mercury in the environment has increased considerably as compared to the past century. Mercury is a highly toxic pollutant that is known to cause harmful ecological impacts and neurological damage in children, especially autistic spectrum disorder and mental retardation (Blaxill, 2001 and 2004). The recent medical research shows that there is a possibility that mercury could cause or contribute to autism and other neuro-developmental disorders. The incidence of autism has increased 10 times from 6 in 10,000 in the 1980s to 60 in 10,000 in recent years (Blaxill, 2001 and 2004; CDC, 2007).

There seem to be a general consensus among scientists, public health officials and economists that the benefits gained in public health by reducing these air pollutants are far greater than the costs associated with such reduction measures (Palmer *et. al*., 2004). However, in order for the policy be effective, it should be well formulated and designed to address the mitigation of all these four emissions associated with power generation.

In the U.S., coal-based power plants produce more SO_2, NO_x, mercury, and CO_2 than any other type of power plants. About 50 percent of the total electricity generated in the country comes from coal, which is higher than the world's average coal consumption for electricity (Table 3). These emissions become even more pertinent for Ohio, since more than 90 percent of its electricity is coal-based, making Ohio one of the major polluting states in the country (Table 5). In addition, coal generally contains more sulfur than other fossil fuels, emitting more pollution per unit of electricity generation (DOE/EIA, 2002). The following section briefly describes the elements that make up air pollution and GHG emissions from the utility industry.

Sulfur: Ohio coal contains higher sulfur than western coal, thus being responsible for corresponding high SO_2 emissions (Table 4). When coal is burned in the power plant, the sulfur combines with the oxygen in the air to form SO_2. This SO_2 further mixes with oxygen and other trace substances in the air to form other sulfate compounds. Other fossil fuels such as petroleum oils (both light and heavy) also contain sulfur, but on a much smaller proportion than in coal per BTU content. The amount of sulfur present in natural gas is almost insignificant (DOE/EIA, 2002).

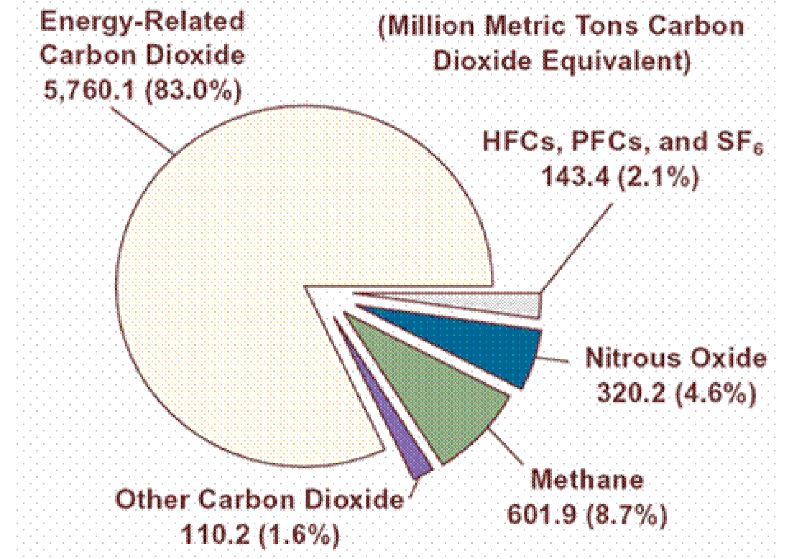
Nitrogen: This colorless and odorless gas makes up about 78 percent of our atmosphere. When fossil fuels are burned in power plants, nitrogen in the atmosphere mixes with oxygen and water during the combustion process to produce several NO_x compounds. Coal also contains nitrogen that is converted to NO_x when it is burned in the power plant. Among various NO_x compounds, the most important one is nitrogen dioxide (NO_2) that makes up photochemical smog giving it a yellowish-brown color (DOE/EIA, 2002). Both SO_2 and NO_x are precursors to acid depositions, as they react and form sulfuric and nitric acid respectively. These acids are absorbed by rain droplets in the atmosphere to cause "acid rain."

Carbon Dioxide: CO_2 is another colorless and odorless gas, which is produced by carbon and carbon compounds contained in coal, petroleum and natural gas during the combustion process in power plants. It is the major GHG, as the energy related CO_2 emissions makes up about 83 percent of the country's total GHG emissions (Figure 5; DOE/EIA, 2004). Coal has the highest carbon content compared to other fossil fuels, resulting in the highest CO_2 emissions per unit of electric output. The current technology to limit the emission of CO_2 from the power plants is cost prohibitive, so it is generally just released into the atmosphere. CO_2 emissions by the power industry have increased by 27.5 percent since 1990, representing 39.4 percent of total U.S. energy-related CO_2 emissions in 2003 (DOE/EIA, 2004).

The increase of CO_2 causes the atmosphere to absorb infrared radiation reflected from the earth that would otherwise have been dissipated into space. This phenomenon could increase average global temperature and is called the "greenhouse" effect, as it is similar to the trapping of the sun energy in a greenhouse. The increase in global temperature could cause significant climatic changes, shift in agricultural zones, the partial melting of the polar ice caps, and flooding of coastal areas. As human activities are responsible for significant global warming trends (IPCC, 2007), efforts are underway to mitigate GHG emissions from all major polluting sources including the utility industry (EPRI, 2005; NRDC, 2005; PEW, 2007; Rabe, 2005, UCS, 2007).

Table 3 shows the use of coal for electricity generation in the world, the U.S. and Ohio. While about 50 percent of electricity comes from coal in the U.S., it provides more than 90 percent of electricity in Ohio, making it one of the largest polluting states in the nation

(Table 3). In addition to being heavily based on coal, the Ohio utility industry uses local coal (40 percent) which contains higher sulfur than the imported coal (Table 4). Currently, Ohio is the number one polluter of both sulfur dioxide (SO_2) and nitrous oxide (NO_x) emissions and number two in CO_2 emissions, even though it is only the third largest producer of electricity in the U.S. (Table 5).



Source: Energy Information Administration, DOE, 2004

Figure 5. U.S. Greenhouse Gas Emissions

Region	Coal	Nuclear	N. Gas	Oil	Hydro	Other Ren.
Ohio	90.4	7.4	1.3	0.3	0.3	0.3
USA	50.0	20.0	17.0	3.0	7.0	3.0
World	39.1	16.6	19.1	7.2	16.2	1.8

(Source: EIA, DOE 2002 and IEA Renewable Info, 2004)

Table 3. Electricity Net Generation by Energy Source

(percent)

Average Quality and Delivered cost	Produced in State (40%)	Imports (60%)
Heat Content (million Btu/short ton)	23.56	23.84
Sulfur Content (% by weight)	3.45	1.98
Ash Content (% by weight)	10.81	11.31
Price/million Btu	1.46	1.36
Price/short ton	34.32	32.47

(Sources: Ohio Coal Statistics, DOE/EIA and FERC, 2000)

Table 4. Coal Used for Electricity Generation in Ohio

Description	Value	U.S. Rank
Net Generation (megawatt hours)	139,904,106	3
Emissions (thousand short tons)		
SO_2	1,172	1
NO_x	385	1
CO_2	135,181	2

(Sources: State Electricity Profiles, EIA, 2002)

Table 5. Ohio's Electricity Generation and Emissions

3. Biomass as a Renewable Energy Resource

Biomass is primarily made up of carbohydrates and lignin, produced from CO_2 and water via photosynthesis in the presence of sun light, thereby capturing solar energy in living plants. The common current and potential biomass energy resources include many types of organic matter, such as agricultural residues, industrial wood residues, logging forest residues, urban wood waste, and dedicated energy crops. Industrial residues such as black liquor from wood pulping, food processing wastes, and farm animal manure can also be used as biomass energy feedstock. The use of such biomass feedstock for energy purposes depends on a variety of factors, such as cost of collection and removal, transportation, effects of residues removal from the field, and energy content characteristics. These resources can be used or grown on a renewable basis to provide the feedstock for energy generation in a sustainable manner and biomass can be used for base-load electricity generation, whereas solar and wind can only be used as intermittent sources. In 2002, biomass resources supplied about six times the energy of geothermal, solar and wind energy sources combined in the nation (Figure 2).

Although the current contribution of biomass resources is only about 3 percent of total U.S. electricity generation, these resources may have the potential to supply a larger share of the nation's electricity generation. As a renewable resource, biomass energy could become a significant source of clean energy in the country, as it reduces air pollution and GHG emissions, enhances energy security, diversifies the energy resource mix, creates jobs, and provides an alternative source of income for farming and rural communities.

Several market studies show that the demand for renewable (green) energy may increase in the competitive power market due to increasing awareness of climate change issues (Chea, 2004; EPRI, 1999, RET, 2000). At the policy level, there is an on-going movement toward providing more incentives to lower emissions levels, requiring utilities to use a portion of renewable resources in their power generation mix (renewable portfolio standard), offering tax credits of 0.75 to 1.5 cents per KWh to use more renewable energy, and establishing tough environmental regulations to reduce air pollution (OBEP, 2005; NRBP, 2005).

Currently, industrial (mostly from wood and paper) residues and processed agro-industry wastes are the main biomass feedstocks used to generate electricity in the U.S. In the short term future, these two sources will be expected to dominate the supply side. In the mid-term, agricultural and forest residues may serve as a major source of biomass feedstock to enable the biomass industry to make more substantial contributions in the production of biofuels, chemicals, and biopower. Several biomass research projects are currently focusing on the residue harvesting, collection, transportation, and other important aspects of the feedstock interface between agriculture and forestry and the biomass power industry (EERE, DOE, 2004). In the long term, a mature biopower industry may develop a market for dedicated energy crops providing supplementary farm incomes to our rural communities.

Taking these issues into account, the Biomass Program under the U.S. Department of Energy (USDOE) has conducted a significant breadth of research on dedicated energy crops. However, recently the U.S. Department of Agriculture (USDA) is taking primary responsibility on research and a program to develop fast-growing trees and grasses as energy crops. Both USDOE and USDA are deeply committed to increase biomass resources for energy use, and the goal is to supply 5 percent of the nation's power, 20 percent of its transportation fuels, and 25 percent of its chemicals by 2030 (USDOE/USDA, 2005).

3.1 Potential Use of Biomass Energy Resources in Ohio

Biomass energy may become a viable alternative in the energy future of Ohio by reducing emission levels, diversifying its much needed energy resource mix, improving rural and farm economies, and generating renewable power. As one of the leading agricultural states, Ohio is a major producer of food crops, most of which generate substantial amounts of crop residues. This is because of Ohio's more than 10 million acres of cropland (Graham and Walsh, 1999) and almost half of the cropland is prime farmland, among the best in the world. Ohio is one of only five states in the U.S. with such large prime farmlands (ODOA, 2002).

Ohio also offers the potential to grow dedicated energy crops if a bio-based industry develops in the future. Energy crops can also be grown on some of the land idled by the Conservation Reserve Program (CRP) which was initiated by the US Department of Agriculture under the Conservation Title in 1985. There are more than 36 million acres of land enrolled under CRP in the country and about 300,000 acres in Ohio (OSUE, 2000). The 2002 Farm Bill recognized the increasing role of the agricultural sector in the energy and environment future of this country since this is the first bill to include energy as a separate title to promote renewable energy in the research, rural development, and conservation titles. The bill also authorizes the allowance of growing dedicated energy crops on the CRP lands (USDA, 2002). Several studies suggest that energy crops can be grown on most of the CRP lands without compromising the CRP's environmental benefits (De La Torre Ugarte *et. al.,* 2000; Downing *et. al.*, 1995; Graham *et. al.*, 1996; Walsh *et. al.,* 1996).

Similar to its agriculture sector, Ohio's forests and forest industries are equally active and contribute significantly to the state's economy. About 30 percent (7.9 million acres) of Ohio is forested with mostly hardwoods (96 percent) and has a growth rate 2.5 times higher than the harvesting rate (ODNR, 2004). Some of the finest hardwoods in the world are grown in Ohio. The value of Ohio's forest products industry is more than $23.8 billion per year. There are a large number of wood industries in the state, approximately 180 saw mills and over 2000 wood manufacturing companies (ODNR, 2004). These companies produce a variety of valuable wood products and also generate a substantial amount of industrial wood residues that can be used for electricity generation (ODNR, 2004, Shakya, 1997, Southgate and Shakya, 1996).

Company	Place	Capacity (MW)	Year
Hoge Lumber Co.	New Knoxvill	3.75	1986
Mead Paper	Chillicothe	10.5	1975
Sauder Woodworking Sawmill	Fulton	7.5	1993
Stone Container Corp.	Coshocton	16.5	1982

(*Source: Shakya, 1997)*

Table 6. Biomass Power Plants in Ohio

Most biomass-based power plants in the nation have been built where the biomass feedstock is cheaply available or incurs disposal costs, such as in wood products and paper industries. Bio-based power plants have also flourished in the areas where the price of electricity is higher than the national average electricity price (Graham *et. al.*, 1996). In Ohio, paper and wood products companies have about 25 small biomass cogeneration plants in various sites of the state, mostly to meet their own energy demand (Southgate and Shakya, 1996), however, few larger plants sell electricity back to their utilities at wholesale rate (Table 6).

The future of biomass energy appears promising due to numerous benefits beyond simply the financial returns. Energy independence, greenhouse gas mitigation, waste reduction, as well as rural economic development are among the benefits. Several other issues, such as unstable fossil fuel prices, advancement in gasification and gas turbine technology, and speedy market development of bio-based co-products (pulp wood or chemicals), could also provide a healthy market for energy crops in the future (Graham *et. al.*, 1996). Potential future carbon policies that reduce greenhouse gas emissions will also make biomass feedstock more competitive with fossil fuels.

All these issues are even more critical in Ohio since its power industry is a heavy user of coal (PUCO, 2002) and biomass energy could play a significant role to reduce greenhouse gas emissions in the state. Keeler (2005) discussed a proposed “Carbon Sequestration Rental Policy” where the rental system works by issuing credits for sequestered carbon for a specific time period (as opposed to indefinite period) which might be appealing to the farming community. This policy will be well suited for energy crops (fast growing trees) as their average rotation period is 10-12 years.

About 25 years ago, an inventory done by Hitzhusen *et. al.* (1982) suggested that wood and crop residues could be a promising renewable energy source in Ohio. It is interesting to note that the same topic of research has been revisited after all these years and recently is gaining a lot more policy attention both at federal and state levels. The study was the first county-based inventory of biomass energy resources in Ohio, which was recently updated by Jeanty *et. al.* in 2005. At the national level, NREL (2005) also conducted the county level biomass resource assessment for Ohio. This dissertation research uses the data available from these various sources, both state and national levels, and primarily focuses on the potential use of biomass resources for cofiring in coal power plants. In this study, the following major categories of biomass feedstocks are considered for cofiring in Ohio:

Forest Residues: Forest residues are logging residues and other removable material left after carrying out silviculture operations and site conversions. Logging residue comprises unused portions of trees, cut or killed by logging and left in the woods.

Mill Residues: Primary mill residues include wood materials (coarse and fine) and bark generated at manufacturing plants (primary wood-using mills) when round wood products are processed into primary wood products, like slabs, edgings, trimmings, sawdust, veneer clippings and cores, and pulp screenings.

Urban Wood Residues: These are wood residues from municipal solid waste (wood chips and pallets), utility tree trimming and/or private tree companies, and construction and demolition sites.

Dedicated Energy Crops: These crops are grown primarily for energy purposes, and the examples of energy crops are switchgrass, willow and hybrid poplar. Although energy crops are currently not grown in Ohio, this study will analyze the potential market for energy crops, if biomass cofiring requires more biomass feedstock. Besides in the traditional cropland, energy crops can also be grown on the CRP lands and other marginal lands that are not suitable for conventional crop production.

3.2 Potential Benefits of Biomass Energy Resources

The current use of energy in the U.S. is heavily based on the fossil fuels, which are non-renewable and have many negative environmental externalities. Biomass, as a renewable energy resource, may offer an alternative to conventional energy sources and provides many environmental, economic, and national energy security benefits.

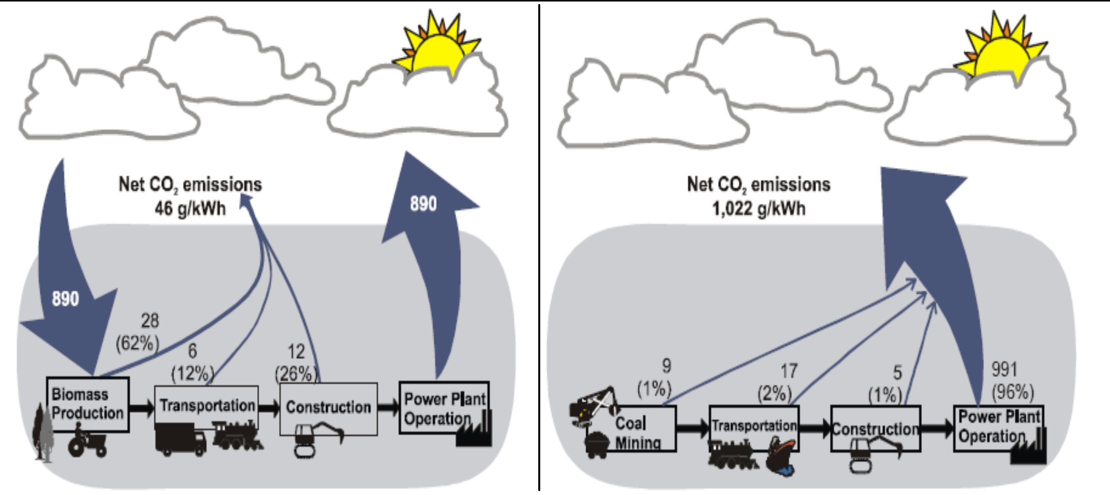
Environmental Benefits: Biomass resources are considered carbon neutral as trees and other plants sequester or capture CO_2 from the atmosphere (Figure 6). Hence, biomass power will generate no net emission of CO_2 and much lower emissions of SO_2 as compared to coal (Mann and Spath, 1999; NREL, 2002). Use of biomass residues and waste for energy generation will solve waste disposal problems for many wood and paper industries. Many animal farms and agro-based industries have also used their biomass waste product to generate power thus solving both disposal and odor problems. Therefore, using biomass to produce energy is an excellent way to dispose of biomass waste materials that otherwise end up in landfills. The following are the major environmental benefits of biomass energy:

- Reduces GHG like CO_2 and methane (landfill-gas-to-energy projects)
- Reduces air pollution, acid rain, and smog
- Keeps waste out of landfills
- Reduces water contamination problems (farm waste to energy project)
- Helps mitigate forest fire and improves forest health, if selective thinning and excess forest residues can be collected and used for energy purposes

Economic Benefits: Biomass energy may potentially provide an alternative source of income to farm communities and rural areas, in addition to playing an important role in global climate change. The use of biomass for energy, if it becomes economically viable will be able to create new markets and employment by developing new processing, distribution, and service industries in rural communities. Energy crops can provide an alternate use of marginal agricultural lands, generating an extra source of income for farmers. The recent farm bill also allows the use of CRP lands to grow energy crops if the environmental benefits of the program (CRP) are not compromised. Using biomass residues or waste (from industries) for energy generation rather than disposing of them in landfills will provide benefits by saving the land-filling costs (average $30/ ton in Ohio).

Due to the small scale of biomass power plants, these plants can probably be built more efficiently as distributed generation in rural and remote communities. The power generated by using biomass is eligible to be marketed as green or renewable power, which can fetch a premium market price, if a green power market develops in the future. The prospect of carbon trading could also make biomass power more attractive and competitive when compared with fossil fuel sources. Furthermore, biomass sources can provide base-load power and is cheaper in comparison to other renewable power sources, such as wind or solar.

National Energy Security Benefits: Biomass resources are domestic, clean, and renewable. The emerging bioenergy and biobased industries offer the prospect of decreased energy imports with renewable and environmentally clean power. There has been tremendous development in biofuels in recent years in both ethanol and bio-diesel. Biomass energy could play a key role in diversifying the energy resource mix and providing national energy security benefits by reducing oil imports. The current research focus on making faster commercialization of cellulosic ethanol (made from switch grass or wood residues) will help enhance the national security benefits. A $4 billion plant has been recently announced in Ohio to be constructed in 2008 that will use 5 millions tons of Ohio coal and more than 2 million tons of wood waste, switch grass and other biomass feedstock per year to produce 50,000 barrels per day of high-quality diesel and jet fuel (Plain Dealer, April 29, 2007). This is a good example of biomass contributing towards Ohio's energy future.



Biomass Power System: 95% Carbon Closure **Coal Power System:** 0% Carbon Closure

(Source: Mann and Spath, 1999)

Figure 6. Net CO_2 Emissions from Biomass and Coal

3.3 Current Use of Biomass Resources for Power Generation

With about 10 Gigawatt (GW) of installed capacity (5 GW from pulp and paper, 2 GW from dedicated biomass, and 3 GW from municipal solid waste/landfill gas), biomass resources have become an integral part of commercial power generation in the U.S. (Arvizu, 2006; EIA, 2002). The recent data indicate that biomass provides as much renewable energy as hydro-power in the nation, about 3 percent each (Figure 2). The bulk of biomass power is currently used as base load power in the existing electrical distribution system. This makes biomass a distinctive renewable energy resource akin to hydro-power in that both are able to provide base load power. Biomass power also provides industrial process heat and steam.

Although the majority of biobased power plants are within the wood products and pulp industries, more than 200 other companies also generate power using biomass resources in the U.S. (Haq, 2002). Until recently, the primary reason for using biomass for power generation in these industries has been the availability of low cost biomass feedstock. However, there is increasing interest among many power marketers to look into environmentally clean electricity such as green power and regulatory requirements, especially Renewable Portfolio Standards (RPS). The RPS requires the utilities to generate a certain percentage of their total electricity output by using renewable resources.

American Electric Power (AEP) based in Columbus, Ohio, is one of the largest utility companies in the U.S. and is seeking bids from energy providers for up to 250 MW of renewable power to meet energy supply requirements (RPS) for its retail customers in Arkansas, Louisiana, Oklahoma, and Texas (PR Newswire, 2004). This has renewed the attention on cofiring biomass with coal, as power companies can provide renewable power and earn emission credits in a relatively short time period.

The common technologies to convert biomass feedstock into electricity are direct-firing and co-firing systems. Most biomass power plants in the U.S. are direct-firing systems which are similar to coal power plants. The biomass feedstock is burned in a boiler to produce high-pressure stream to rotate a turbine and generate electricity. Although this technology is well established, proven, and reliable, its efficiency is lower as compared to coal power plants. Most existing biomass power plants have the efficient level of about mid to higher 20 percent range, whereas coal-fired power plants are far more efficient in the mid 30 to lower 40 percent range (NREL, 2000).

Cofiring could become an economical near-term option to generate biomass power, which involves burning biomass feedstock with coal in the existing coal power plants. It is important to note that biomass feedstock is bulky in nature, low in energy content, and diverse in characteristics. It will be an added burden to power companies to transport, store, and handle the biomass feedstock, including its cost. Unless the benefits of cofiring are higher than these costs of biomass, power companies will not choose this option. However, with increasing concerns of GHG emissions and growing demand for renewable energy, cofiring may become a viable option for power companies.

Cofiring provides an easier option to power companies to generate renewable electricity and reduce CO_2, SO_2 and other air emissions in a relatively short time period. Since it does not require major modifications or construction in the existing coal plants, cofiring is far less expensive than building a new biomass power plant. In addition, biomass is converted to electricity using higher efficiency of a coal power plant as compared to a biomass power plant. Because of these benefits and attributes of cofiring, this study evaluates the prospect of cofiring biomass at 10 and 15 percent levels in Ohio's selected coal power plants and develops various scenarios for economic, environmental, and policy analysis.

4. Cofiring Biomass Feedstock with Coal

One of the attractive and easily implemented biomass energy technologies is cofiring biomass with coal in existing coal power plants, at least in the near future for Ohio. Cofiring is the simultaneous combustion of biomass and coal in the same boiler. Although in the cofiring scenario, biomass can substitute for up to 20 percent of the coal (FTO, 2004), this dissertation study evaluates the prospect of biomass cofiring at 10 and 15 percent levels in selected Ohio coal power plants.

Coal supplies about half the electricity generated in the U.S. (Table 3) and coal-fired electric generating power plants are the foundation of the nation's power system. They will continue to dominate the market for the foreseeable future, as one quarter of the world's coal reserves are found in the U.S. (OFE/DOE, 2004). Emerging coal-based technologies are much cleaner and generate lower CO_2 emissions as compared to traditional coal power plants. However, such technologies generally involve higher costs and mostly apply only to newer coal power plants. Hence, for existing coal power plants, cofiring biomass with coal can be the most effective way to mitigate GHG emissions and generate renewable power to meet consumer's growing demand (Wicks and Keay, 2005).

Biomass cofiring is a proven technology that has been practiced for decades in the wood products industries and more recently in the utility-scale boilers (Table 9). Its prospect in Ohio is worth analyzing, as it could capitalize on the large investment and infrastructure of Ohio's existing coal power plants while mitigating emissions of air pollutants like SO_2 and GHGs like CO_2 (Table 7). Several federal power plants have been cofiring biomass with coal for the past 20 years and are proven to be life-cycle cost-effective in terms of installation costs and net present value (FTO, 2004). Cofiring biomass provides an opportunity to reduce fuel and waste disposal costs while generating renewable power. Most importantly, cofiring allows replacing non-renewable and highly polluting fuel (coal) with renewable and environmentally clean fuel (biomass).

Spurred by a need to diversify the energy mix, mitigate air pollutions and GHG emissions, and meet renewable portfolio standards (RPS), a number of utility companies and power marketers are evaluating biomass cofiring in their power plants. This applies even more specifically for Ohio as its utility industry is heavily based on coal. Table 7 shows the potential CO_2 reduction with 10 percent and 15 percent biomass cofiring in Ohio's coal power plants.

OHIO (2002)	Net Electricity Million MWH	CO_2 Emissions Million tons	CO_2 Reduction Million tons
From all sources (100%)	140.0		
From Coal (90%)	126.5	140.54	
10% Biomass Cofiring	12.6	127.06	13.48
15% Biomass Cofiring	18.9	120.32	20.22

(Source: State Electricity Profiles, EIA, 2002)

Table 7. Cofiring Scenarios and CO_2 Emissions

4.1 Overview of Current Cofiring Technology

The cofiring technology uses biomass feedstock to replace a portion of the coal and fires them together in the existing coal power plants. Biomass cofiring has been successfully demonstrated in nearly all common coal burning boiler types and configurations such as stokers, fluidized beds, pulverized coal boilers, and cyclones. Stoker and pulverized coal boilers are usually medium in generation capacity while cyclones have much larger capacity. It is less expensive to cofire biomass in a stoker boiler. However, cofiring in pulverized coal boilers can also be economically attractive if cheap sources of biomass feedstock are available (FTO, 2004).

Although biomass cofiring seems like a good option for utility industry at least in a near term future as it capitalizes on the investment and infrastructure of existing coal power plants while mitigating air pollutions and GHG emissions. However, there is need for more research and development in cofiring technology for various feedstocks, including issues regarding the characterization and use of ash from cofiring, and corrosion and ash deposition problems (IEA, 2002). Some of the important issues for biomass cofiring are discussed briefly below (FTO, 2004; IEA, 2002):

Fuel Characteristics: Biomass energy resources consist of a wide variety of materials, ranging from grassy and straw derived residues to industrial/forest woody waste to dedicated energy crops. Because of its diverse nature, biomass fuel properties show significantly greater variation as a class. For example, ash content varies from 1 to 20 percent, and nitrogen content varies from 0.1 percent to more than 1 percent (IEA, 2002). As compared to coal, biomass feedstock usually has a high moisture content, potentially high chlorine content, low heating value, and low bulk density. These fuel properties affect the design, operation and performance of cofiring systems.

Fuel Preparation and Handling: Special care should be taken for the fuel preparation and handling of biomass feedstock because biomass contains more moisture, has low density and comes in all different shapes and sizes. Though biomass feedstock can be directly fed into coal belt conveyors in some cases, extra care must be provided to prevent skidding, bridging, and plugging in pulverizers, hoppers, and pipe bends.

Fuel Size: One of the most important factors to a successful cofiring operation is the size of the biomass feedstock which differs based on the boiler types (**Error! Reference source not found.**). Although biomass can be slightly larger than coal since biomass is a more volatile fuel, the size requirement for biomass feedstock depending on the boiler type is important for the smooth operation of the fuel handling system and complete burning of the biomass feedstock (FTO, 2004).

Ash Deposition: Similar to its fuel properties, biomass feedstock also varies greatly in the rate of ash deposition. Crop residues like straw have higher, but woods and wood by-products have much lower ash depositions than coal.

Chlorine-based Corrosion: Biomass feedstock, especially with high chlorine or high alkali fuels, such as herbaceous crops can cause high-temperature corrosion of super-heaters in the coal power plants. However, recent research has shown that this risk is greatly reduced if alkali chlorides from the biomass can interact with sulfur from the coal to form alkali sulfates (IEA, 2002). Hence, the corrosion problem is much lower in cofiring as compared to burning biomass by itself.

Boiler Type	Biomass Size (in inches)
1. Pulverized Coal	< ¼
2. Stoker	< 3
3. Cyclone	< ½
4. Fluidized Bed	< 3

(Source: FTO, 2004)

Table 8. Coal Boiler Type and Required Biomass Size

Fly Ash Utilization: Many power companies sell fly ash for use in making cement and concrete additives. However, the current standard set by the American Society for Testing and Materials allows only "coal ash" to be used in the mixture (NREL, 2000). Fly ashes from herbaceous biomass cofiring may be less appropriate for concrete use, however many research results show that fly ashes from wood-derived biomass have no harmful effects on concrete (BYU, 2001). The U.S. DOE is working together with several utilities in the country to change this standard, so that ash from cofiring biomass can also be sold for cement making purpose (BYU, 2001, NREL, 2000). If this happens, biomass cofiring will be even more attractive to many utilities, as they will be able to take full benefits of cofiring including ash sale.

4.2 Status of Existing Cofiring Plants in the U.S.

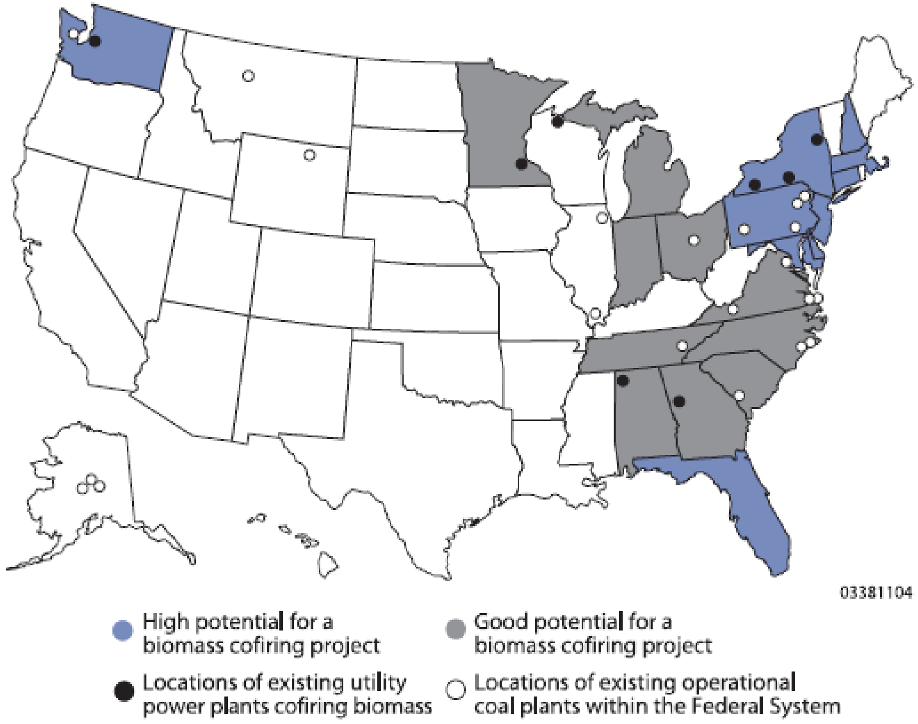
Many biomass cofiring plants are successfully running, both in federally owned and commercial coal power plants. Table 9 provides the list of commercial coal power plants that are currently doing biomass cofiring. Several studies show explicit environmental and economic benefits from cofiring projects in the U.S. (FTO, 2004, Haq, 2002, and Wiltsee, 2000). Since many cofiring plants in the U.S. are currently operating with positive economic and environmental gains, this research study plans to examine whether or not such cofiring projects will be economically and/or environmentally viable in Ohio.

Facility Name	**Company Name**	**City/County**	**State**	**Capacity (MW)**	**Cofiring Percent**
1. 6th Street	Alliant Energy	Cedar Rapids	IA	85	7.7
2. Bay Front	Xcel Energy, Inc.	Ashland	WI	76	40.3
3. Colbert	TVA	Tuscumbia	AL	190	1.5
4. Gadsden 2	Alabama Power Co.	Gadsden	AL	70	<1.0
5. Greenridge	AES	Dresden	NY	161	6.8
6. C.D. McIntosh, Jr	City of Lakeland	Polk	FL	350	<1.0
7. Tacoma Steam Plant	Tacoma Public Utilities	Tacoma	WA	35	44.0
8. Willow Island 2	Allegheny Power	Pleasants	WV	188	1.2
9. Yate 6 and 7	Georgia Power	Newnan	GA	150	<1.0

(Source: Haq, 2002)

Table 9. Existing Power Plants Currently Cofiring with Biomass Feedstock

Utility-scale cofiring projects are illustrated on the map in Figure 7, which also shows the potential candidate states for cofiring projects. The identification of these states is based on the price of coal, estimated price of biomass feedstock and its availability, and average landfill tipping fees (FTO, 2004). The environmental aspects of cofiring, especially reduction in emissions of various air pollutants and GHG, are not taken into account for this classification. If this factor is considered, Ohio may land among the top states in the list since its power industry is heavily based on coal. Nonetheless, Ohio still makes the list of having a “good potential” based on the above-mentioned three factors.



(Source: FTO, 2004)

Figure 7. Potential States for Biomass Cofiring in the U.S.

It appears that states with high average landfill tipping fees (more than $50 per ton) fall under the category of “high potential” for a biomass cofiring project, especially since such projects become more attractive as renewable energy is generated by using biomass residues that would otherwise be land-filled. Although Ohio’s average landfill tipping fee ($29 per ton) is well below all states who are under ‘high potential” category, it is still a “good potential” state for a biomass cofiring project because of the availability of biomass feedstock both from its agriculture and forestry sectors.

4.3 Prospects of Cofiring in the Coal Power Plants in Ohio

Ohio may have a promising prospect of biomass cofiring in its existing coal power plants, by using its abundant biomass resources to generate renewable energy while mitigating significant emission levels of air pollutants and GHG. This study examines the biomass cofiring scenarios even though none of the Ohio’s coal power plants is currently involved in cofiring biomass. At present, there are 21 commercial coal-based power plants in Ohio (Figure 8), with an annual generation capacity of 21,000 MW of electricity (Table 10) (PUCO, 2002). Hence, if biomass cofiring becomes successful in Ohio, it will make use of already existing infrastructure of coal plants to generate renewable power by using biomass resources.

The proposed OH-MARKAL model will develop two scenarios of biomass feedstock cofiring: one at 10 percent, and the other at 15 percent, levels in Ohio’s coal-based power plants. The demand and supply of biomass resources will depend on the level of co-firing biomass in the coal power plants. The sensitivity analysis on the different levels of renewable electricity generation will also be conducted to examine the availability (supply) of biomass feedstocks in the state. The generation of various levels of renewable power and mitigation of various emissions will also depend on the levels of cofiring. In addition, this study will also analyze policy issues such as an emissions cap or a tax on CO_2 emissions that will have impacts on the level of cofiring in these coal power plants.

5. Summary

As human activities are responsible for significant global warming trends, biomass energy is increasingly becoming a viable source of clean and sustainable energy resource. Biomass resources are carbon neutral and will be pivotal to mitigate emissions of greenhouse gases and reduce their negative impact on climate change. The use of biomass resources for energy is even more relevant in Ohio, as the power industry is heavily based on coal, providing about 90 percent of the state's total electricity, while only 50 percent of electricity comes from coal at the national level. Thus, Ohio is currently among the leading producers of the GHG in the nation. The burning of coal for electricity generation results in substantial greenhouse gas emissions and environmental pollution, which are responsible for global warming and acid rain.

This dissertation study will address the two key energy and environmental issues for Ohio. The first issue is the importance of diversifying the fuel resource base for the power industry, rather than primarily relying on coal. The second is the need to increase the use of biomass and other renewable resources in Ohio, since its current use is low as compared to other Midwest states.

(Source: PUCO, 2002)

Figure 8. Location of Coal Based Power Plants in Ohio

Serial No.	**Plant Name**	**County**	**Capacity MW**
1.	J.M. Stuart	Adams	2340
2.	Killen	Adams	600
3.	Ashtabula	Ashtabula	244
4.	Burger	Belmont	406
5.	Beckjord	Clermont	862
6.	Zimmer	Clermont	1300
7.	Conesville	Coshocton	1089
8.	Lake Shore	Cuyahoga	245
9.	Gavin	Gallia	2600
10.	Kyger Creek	Gallia	1269
11.	Miami Fort	Hamilton	1243
12.	Sammis	Jefferson	2220
13.	Cardinal	Jefferson	1830
14.	Eastlake	Lake	1233
15.	Avon Lake	Lorain	596
16.	Bay Shore	Lucas	631
17.	Hutchings	Montgomery	371
18.	Picway	Pickaway	100
19.	Niles	Trumbull	216
20.	Gorsuch	Washington	213
21.	Muskingum R.	Washington	1425
		Total:	**21,033**

(Source: Ohio Power Statistics. PUCO, 2002)

Table 10. Coal Based Electric Generating Power Plants in Ohio

CHAPTER 2

METHODOLOGY

As its main research methodology, this dissertation adapts the MARKAL (MARKet ALlocation) modeling system (Loulou, Goldstein, and Noble 2004) and develops a model for Ohio (OH-MARKAL) to examine biomass feedstock as an option to generate renewable power in the state. MARKAL is a bottom-up, dynamic linear programming model of the energy system that provides a technology-rich basis for analyzing energy and environmental issues over a long term future horizon. The model largely computes energy balances at all levels of an energy system: primary resources, secondary fuels, final energy and energy services. It also computes an inter-temporal partial equilibrium on energy markets: the quantities and prices of the various fuels and other commodities are in equilibrium. This equilibrium ensures that the net economic surplus is maximized over the whole time horizon (Figure 10).

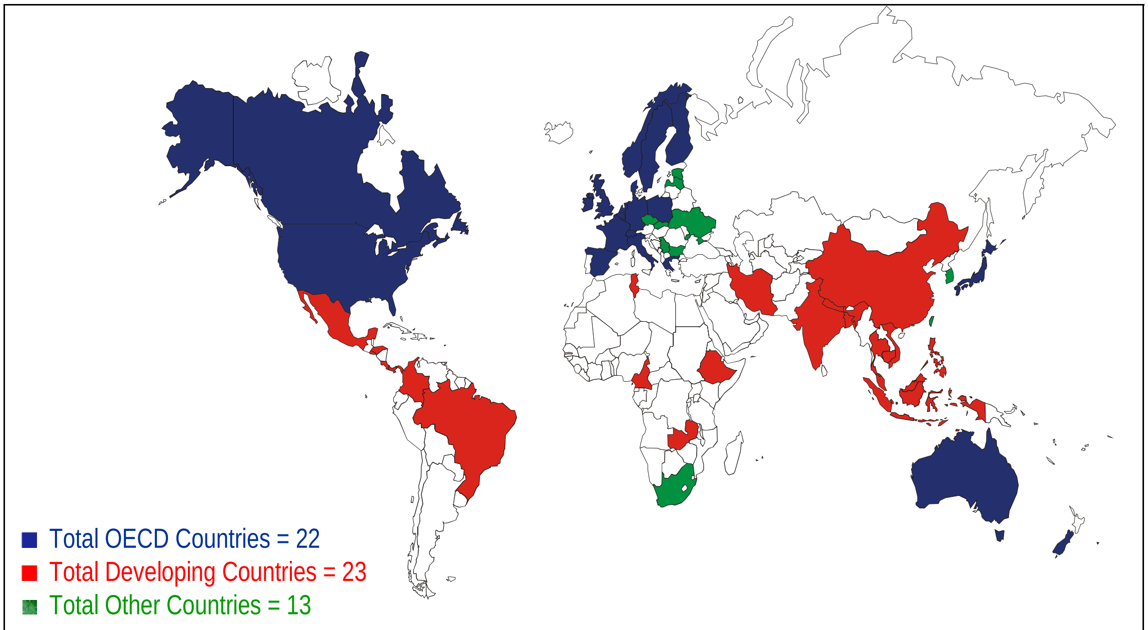
At the federal and state levels, policy makers express their discontent with most energy-economic models as these models often do not provide high-quality and clear information needed to make critical decisions (Munson, 2004). Some of these models have also been criticized as too complex to understand since it is difficult to identify the cause and effect relationship and to distinguish a clear impact of a policy change inside those models. The MARKAL, on the other hand, is recognized for its coherent and transparent framework. Under the MARKAL framework, data assumptions are open and each result could be traced to its technological cause. Because of these preferable qualities, the MARKAL model has been successfully used in many international and national applications as well as in multi-regional scenarios (Figure 9). The MARKAL model has been specifically designed and employed for assessing a wide range of energy, environment, and policy issues which are the primary focus of this research study. Hence, for this research study, the MARKAL model is selected as the principal methodology to evaluate the potential use of biomass energy resources to generate power in Ohio's coal power plants and analyze key economic, environmental, and policy issues for Ohio's energy future.

This chapter provides general overview on MARKAL and a brief discussion on current energy models. The next two sections of this chapter describe the overall structure and formulation of the MARKAL modeling system to provide the necessary foundations for the proposed methodology. These sections are based on "Documentation for the MARKAL Family of Models," by Loulou, Goldstein, and Noble, 2004. The Northeast States for Coordinated Air Use Management has also adapted the MARKAL model at the regional level to study the energy system for nine New England states (NESCAUM, 2005). The efforts are made to develop OH-MARKAL to be as compatible as possible with NE-MARKAL, so that both models can be used together to conduct multi-regional energy and environment policy analyses in the future.

1. The History of MARKAL and its Current Usage

The MARKAL modeling system is based on the methodologies and tools developed by the Energy Technology Systems Analysis Program (ETSAP). The ETSAP is a cooperative research body of the International Energy Agency (IEA) under the Organization for Economic Cooperation and Development (OECD) (www.etsap.org). Although the MARKAL was first developed in the late 1970s, it continues to grow and improve over time. Currently, the model has been successfully implemented in more than 60 countries in various regional, national, and international levels primarily to address a wide range of energy and environmental issues (Figure 9). Many research teams around the world have used this model to analyze their energy and environmental policy issues at the national level. Furthermore, at the international level, it has also been used for the United Nations Framework Convention on Climate Change (ETSAP, 2004).

In North America, the MARKAL family of models has been successfully applied on a multi-regional basis in the National Climate Change Implementation Process (NCCIP) in Canada. Similarly, in Europe and Asia, the MARKAL models have been employed extensively to analyze Clean Development Mechanism (CDM) energy projects. In the U.S., MARKAL has been used extensively by the Department of Energy (DOE) for analysis of the U.S. energy system. In particular, the U.S. Environmental Protection Agency (EPA) has used the model to evaluate potential impacts of new technologies on air emissions and air quality.



(Source: Goldstein et.al., 2004)

Figure 9. MARKAL Users in the World

One of the most recent uses of the model is by the Northeast State for Coordinated Air Use Management (NESCAUM), where the model was successfully adapted as a New England MARKAL (NE-MARKAL) at the regional level that includes nine New England states. NESCAUM's primary objective in developing NE-MARKAL is to conduct various energy and environmental policy simulations with a special focus on the energy services and improving air quality in the region (NESCAUM, 2005). The use (and trade) of energy and its environmental impacts usually go beyond any state boundary. In this context, the proposed OH-MARKAL model in this dissertation can serve as a prototype for other Midwest states. Furthermore, the Ohio model can be extended by including other Midwest states to develop a Midwest MARKAL (MW-MARKAL) for analyzing relevant energy, environmental, and policy issues at the regional level. Hence, this will create a possibility of using NE-MARKAL and MW-MARKAL together in the future for multi-regional energy, environment, and policy evaluations.

2. Current Energy Models

Many energy models are currently in use around the world. However, every model was designed with specific goals of analyzing various economic, environmental, and policy issues. Depending on the research objectives, these models differ significantly in their economic rationale, decision variable, time horizon, and geographic scope. These models also differ widely in the level of detailed information for the commodities and the representation of various technologies. In this section, the general equilibrium and the partial equilibrium models are discussed and compared.

2.1 General Equilibrium Models

Most General Equilibrium (GE) models simultaneously configure the production and consumption of commodities (i.e. fuels, materials, and energy services) and their prices. The price of producing a commodity affects the demand for that commodity, while at the same time the demand affects the commodity's price. A market will reach an equilibrium at price p^* when consumers' willingness to pay is equal to producers' willingness to sell for each commodity at that price. There are numerous models of national or global energy systems using the GE approach. In these models, each sector is represented by a production function designed to simulate the potential substitutions between the main factors of production which are aggregated into a few variables such as energy, capital, and labor. These models are usually referred to as "Top-Down," because they represent an entire economy via a relatively small number of aggregate variables and equations. The production function parameters are calculated for each sector in such a way that inputs and outputs reproduce a single base historical year. These models hence assume that the relationships between sector level inputs and outputs are in equilibrium in the base year.

2.2 Partial Equilibrium Models

In Partial Equilibrium (PE) models, a sector is constituted by a (usually large) number of logically arranged technologies, linked together by their inputs and outputs, and a partial equilibrium is computed via maximization of the total net surplus. Also as "bottom-up" models, PE models are technology explicit and focus primarily on one or two sectors of an economy. For example, MARKAL focuses on the energy sector of an economy where each important energy-using technology is identified by a detailed description of its inputs, outputs, unit costs, and several other technical and economic characteristics. The production function of a sector is implicitly constructed, rather than explicitly specified as in more aggregated models. In MARKAL, demands for energy services are elastic to their own prices. Finally, the model computes supply-demand equilibrium for optimizing the least cost for its entire energy system. The fundamental difference between the GE and PE modeling systems is depicted by:

- GE family of models encompass macroeconomic variables beyond the energy sector, such as capital, labor, wages, consumption, and interest rates

- PE family of models such as MARKAL has a representation of the variety of technologies (existing and/or future), and demand and supply related to a particular sector of an economy, such as the energy sector.

The GE models that include macroeconomic variables may not be as transparent in explaining the sector (energy) specific analysis of the research objectives of this study. In consideration of the overall suitability of this study, the MARKAL model is selected as a methodology for this dissertation since the focus is primarily on the electric sector. This model serves as a particularly effective tool for this research study, since it is a dynamic linear programming model specifically designed to analyze the key economic, environmental, and policy issues of the energy sector.

3. Key Components of MARKAL Structure

The MARKAL energy economy is made up of producers and consumers of energy sources and forms such as coal, natural gas, oil, nuclear, biomass, and electricity (Loulou *et.al.,* 2004). Similar to most computable economic equilibrium models, it assumes perfectly competitive markets for energy carriers—where producers maximize profits and consumers maximize their collective utility. The result is a supply-demand equilibrium that maximizes the net total surplus (i.e. the sum of producers' and consumers' surpluses) (Figure 10). A MARKAL run configures the energy system over a specified time horizon to minimize the net total cost to meet a given energy demand (or equivalently to maximize the net total economic surplus) of the system, while satisfying a number of constraints.

The MARKAL framework used in this study is designed to have 3-year time-periods with three seasons (winter, summer, intermediate), and diurnal divisions (day and night), resulting in six time-slices. These time-slices are only for technologies producing electricity (seasonal and diurnal). A peak requirement is also imposed for these two energy carriers so that enough additional capacity will be installed to meet the peak demand. Such features of MARKAL are quite relevant to OH-MARKAL since the study focuses on the electric industry in Ohio and its detailed specifications in the model become critical to conduct purposeful analysis of the research objectives. The following sections below describe the key elements of MARKAL structure, especially in relation to the OH-MARKAL model.

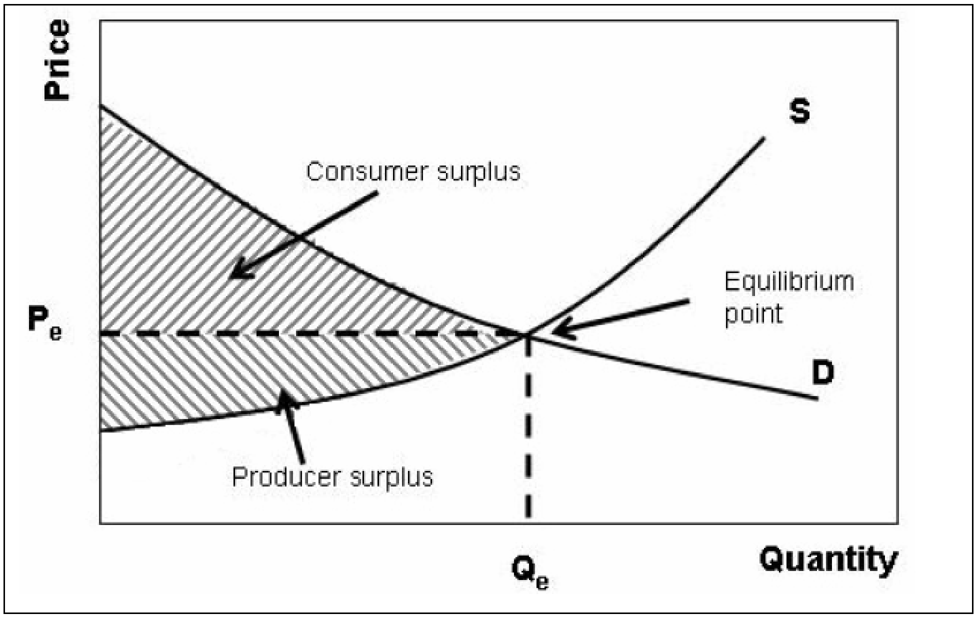


Figure 10. Consumer/Producer Surpluses and Market Equilibrium

3.1 The Reference Energy System

The MARKAL uses the Reference Energy System (RES) as the main foundation for the model that describes the transformation of natural resources ("energy carriers") to serve end-use demands through a series of technologies. Resource technologies characterize resource extraction. Process technologies (including conversion technologies) describe refinery operations, power plants and transportation of energy carriers within the region. Demand technologies constitute those technologies that are used to satisfy energy services directly (i.e. automobiles provide miles traveled and air conditioners provide joules of cooling). In this manner, all aspects of the energy system are described in a technology-based framework with detailed information. A general schematic diagram of the RES is shown in Figure 11.

The structural boundaries of the RES consist of the energy services and the energy sources, both of which are specified not as fixed assumptions, but as supply curves (for energy sources) and demand curves (for energy services). Time-wise, the boundaries are the initial period (when the initially existing system is described), and the end of the horizon (when the remaining capacities are valued).

The top right section of Figure 11 shows the demand for energy services, at a given time period which is specified via a demand curve linking the level of demand to its own price. There are various technologies listed which use the energy carriers such as gas, electricity, and heating oil. These energy carriers are produced by other technologies, represented in the diagram by power or fuel processing plants. To complete the production chain on the primary energy supply side, the diagram shows an extraction source for crude oil, natural gas, and coal. In the RES, when a commodity enters/leaves a process its name is changed (e.g., wet gas becomes dry gas, crude becomes pipeline crude) so that the inter-connectivity between the processes can be properly maintained and identified throughout the network. The various technologies and commodities are classified into sets to keep track of the nature of energy components in the modeling system.

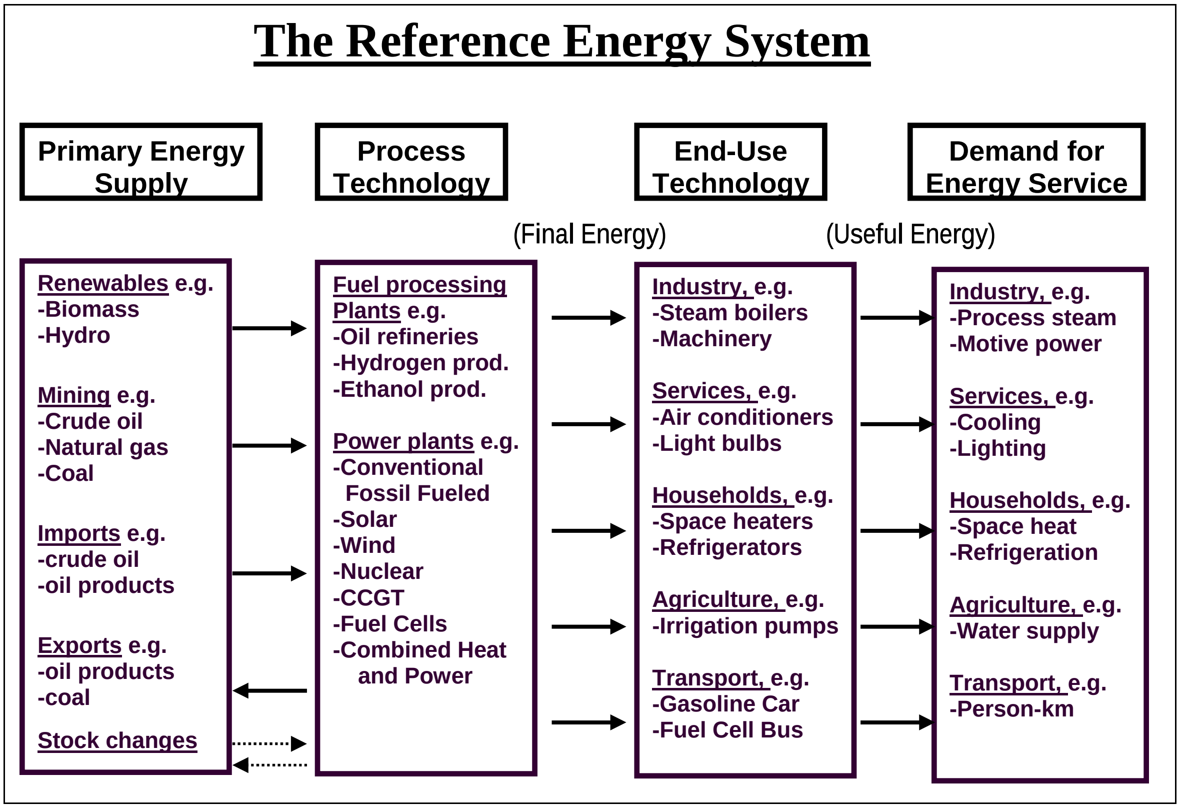


Figure 11. Schematic Diagram of the Reference Energy System

3.2 The Electricity Sector

In the MARKAL model, electric power plants can be characterized by the nature of operation and with the following set designations:

- Load Pattern: Demand
- Load Management: Supply
- Base Load
- Peak Requirements
- Transmission and Distribution: Losses and Costs

Load pattern: Demand

For electricity, the year is divided into six time-divisions (time-slices), using two indices: Winter/Summer/Intermediate, and Day/Night. The demand for electricity in each season and time-of-day is calculated for all demand categories.

Load Management: Supply

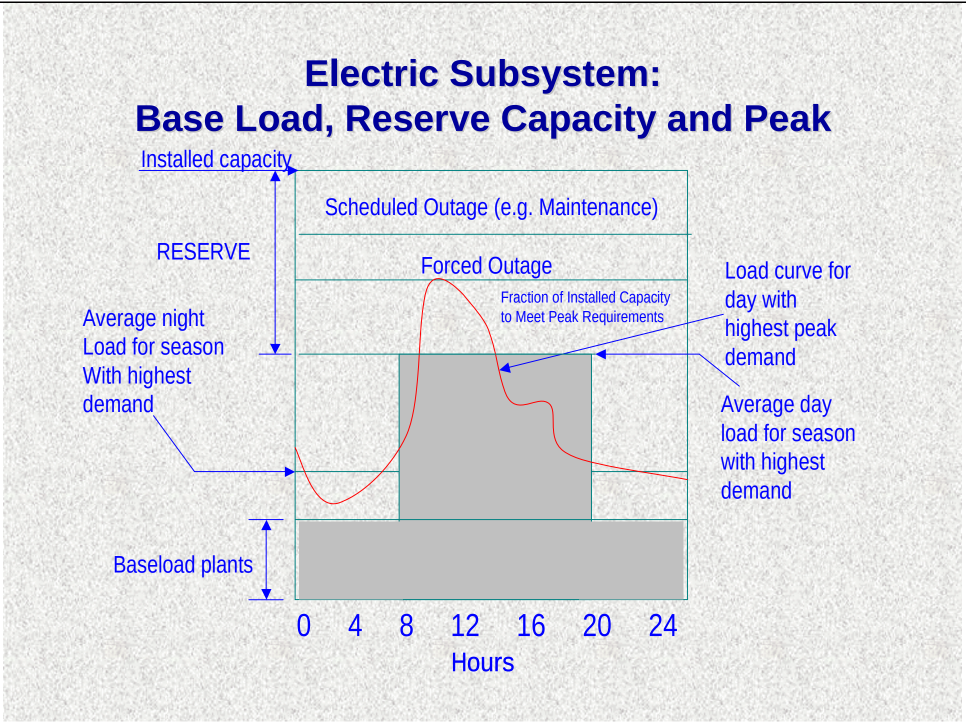
A conversion plant can produce electricity in each time slice up to a level governed by the annual availability factor. Instead of a fixed and constant availability throughout the year, seasonal and time-of-day dependent values may be assumed to reflect resource availability for renewable power plants (hydro, solar, wind). The actual level of production for certain plants is then established as part of the solution of the MARKAL model, subject to these constraints and the demand load pattern.

Base Load

Base load power plants generate electricity at the same rate during day and night of each season. In addition, their aggregate production during the night cannot exceed a modeler-specified share of the total electricity production during the night in each season. Figure 12 shows the part of the load subject to base load generation as the bottom block of the "curve." Examples of base load plants are nuclear and coal-fired plants.

Peak Requirements

A user specified share of the installed capacity of each plant is assumed to contribute to the peaking requirements. The minimum installed capacity is calculated by adding a capacity reserve to the total electricity demands. The reserve margin is chosen by the user for each grid, as a percentage of the demand. The construction of the peak and associated minimum installed capacity requirement is shown in Figure 12. The contribution of demands to the electricity peak can be adjusted by specifying which share of the total demand coincides with the peak. There are number of peaking plants in Ohio that use natural gas as their primary fuel.



Electric Subsystem:
Base Load, Reserve Capacity and Peak

(Source: Loulou et. al., 2004)

Figure 12. Base load, Reserve Capacity and Peak

Figure 12 shows the electric grid network that can be constructed with MARKAL, where link technologies serve as grid exchange connection points. Each grid can be characterized by the various cost and efficiency parameters, and is tracked with separate balance, peak and base load constraints.

Transmission and Distribution: Losses and Costs

The MARKAL model takes into account both centralized and decentralized power plants since the latter plants only face distribution costs while centralized plants are subject to both transportation and distribution costs. Costs and losses of electricity transport and distribution are based on the following factors: investment cost per unit of new transport line capacity; annual fixed O&M cost per unit of installed transmission capacity; investment cost per unit of new distribution capacity; annual fixed O&M cost per unit of installed distribution capacity; and transmission efficiency.

Distribution costs are applied to all centralized and decentralized power plants as both of these plants need to use distribution lines, handling and delivery services . However, losses in the electricity grid occur only at the transmission level, therefore, decentralized plants are not associated with any grid losses. Hence, it is important to specify the type of power plant (centralized and decentralized) in the model.

3.3 Time Horizon

The time horizon is divided into a user-chosen number of time-periods, with each model period having the same user-defined number of years. In an effort to make OH-MARKAL compatible to NE-MARKAL, the exact same time horizon is adapted in this study. The time horizon, thus used in the model has 10 time periods with each period having 3 years (the base year for the model is 2002). The 3-year period is selected in order to make them not long in each period, yet the model time horizon goes out to 30 years. As MARKAL looks for opportunities when capital stock turns over, a shorter than 3-year time period will be not suitable. Any model input/output related to a period applies to each of the 3 years in that period. Similarly, the energy flows and emissions levels represent annual flows in each of the 3 years embodied in a period. All the investment decisions are given in the model and it is assumed to occur in the beginning of each period with the resulting installed capacity available throughout that period.

In the initial period of the model, the quantities of commodities are all fixed at their historical values. At first, the important task for setting up the MARKAL model is to calibrate to the initial period based on these historical values. The main variables to be calibrated are: the capacities and operating levels of all technologies, as well as the extracted, exported and imported quantities for all energy carriers. The associated emission levels from all the related energy sources are also verified. The initial period's calibration also influences the model's decisions over several future periods, since the profile of existing (residual) capacities is provided over the remaining life of the technologies at and after the initial period. During the calibration period, the model primarily makes decisions on the operating and maintenance of the plants to meet the demand of base year.

3.4 Environmental Externalities

In most studies, emission externalities have been modeled in one of two ways: either by introducing an emission tax, or by imposing a emission cap. In the first case, the tax is estimated to represent the external cost created by one unit of emission. In the second approach, it is assumed that such a cost is unknown but that exogenous studies (or regulations, treaties, etc.) have defined a level of acceptable emissions that should not be exceeded. Both of these approaches have merit and have been successfully applied to many MARKAL studies.

In MARKAL, the "damage cost" is introduced which is associated with emissions. The concept of an emission tax can be more accurately represented by the damage cost due to emissions of a pollutant. For this, the following two approaches can be modeled in MARKAL: the environmental damages are computed ex-post, without feedback into the optimization process, and the environmental damages are part of the objective function and therefore taken into account in the optimization process. This element of MARKAL is particularly important for this study (OH-MARKAL) as GHGs emissions from coal burning plants will be incorporated into the model. The study will simulate the model for various policy implications of both emission cap and emission tax.

Emission Cap: This is the upper limit on the emission of a particular GHG or air pollutant which will be enforced by the program. A number of scenarios on emission cap can be developed to analyze the policy implications on the use of various energy resources. The Climate Stewardship Act, Senate Bill 139 is an excellent example of an emissions cap, which would have forced reductions in emissions of greenhouse gases to 2000 levels by 2010 and created an emissions trading program. This bill was sponsored by Senators John McCain (R-Arizona) and Joseph I. Lieberman (D-Connecticut). It was defeated in the Senate with a vote of 60 to 38 on June 22, 2005 (Blum, 2005). Similarly, many more such policies are currently under discussion at the federal level (Table 28).

Emission Tax: Unlike the emission cap, a tax on emissions will allow the use of polluting energy resources, but at a cost. This proposed study will conduct sensitivity analysis by using various levels of an emission tax on CO_2 and will evaluate its impact on energy use and emission levels. Proponents of a tax on carbon strongly argue that it will have a desirable effect on mitigating GHG emissions (Cooper, 2006; Shapiro, 2007). An emission tax on GHG will encourage investments in existing energy efficient technologies, provide economic incentives to develop low-polluting technologies, and promote the use of less carbon intensive fuels and more renewable energy sources such as biomass.

Both the emission cap and tax can be implemented to achieve a policy goal on the use of energy resources and their emission levels and will enhance energy efficiency and conservation. More importantly, they will provide incentives for research and development of clean energy technologies to mitigate GHG emissions (Cooper, 2006; Shapiro, 2007).

4. General Description and Formulation of MARKAL

The MARKAL partial equilibrium is equivalent to the optimization of a linear programming model. A linear programming model is defined as the minimization of an objective function (cost), subject to constraints. The mathematical expressions of the objective function and the constraints are linear in nature and the model is solved by using the standard Linear Programming optimizer. However, the model can also incorporate the non-linear terms in the objective function via step-wise approximation (Figure 13).

An optimization problem formulation consists of the following three types of entities:

- *decision variables:* to be determined by the optimization;
- *objective function*: expressing the criterion to minimize cost (or maximize profit); and
- *constraints*: equations involving the decision variables that must be satisfied by the optimal solution.

The model variables and equations use the following indices:

k:	technology
c:	commodity (energy or material)
t:	time period
s:	time-slice
l:	price level
r,r':	indicates the region (omitted in OH-MARKAL, a single region model)

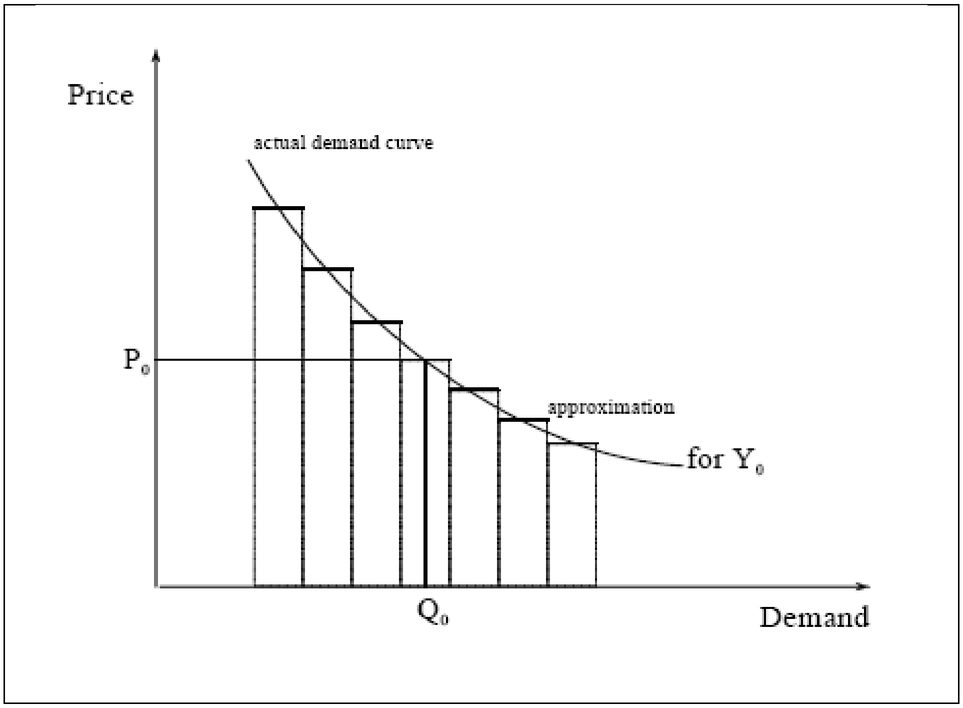


Figure 13. Step-wise Approximation of the Non-linear Terms

4.1 Decision Variables

The decision variables represent the choices made by the model. The various kinds of decision variables in a MARKAL model are elaborated below:

INV(t,k)**:** investment for new capacity addition for technology ***k*** in period ***t***. The investment made in period ***t*** is assumed to occur at the beginning of that period, and is available until the end of its lifetime.

CAP(t,k): installed capacity of technology ***k*** in period ***t.*** The units used here are the same as for investments.

ACT(t,k,s): activity level of technology ***k***, in period ***t***, during time-slice ***s. ACT*** variables are not defined for end-use technologies as it is assumed that activity is always equal to available capacity. However, for the conversion technologies, the annual activity is tracked without the time-slice (the ***s*** index dropped).

MINING(t,c,l): quantity of commodity ***c*** extracted at price level ***l*** in period ***t***; the coefficient in the objective function is the unit cost of extracting the commodity. These are domestic production resources, including physical renewable (such as biomass).

IMPORT(t,c,l), EXPORT(t,c,l): quantity of commodity ***c***, price level ***l,*** exogenously imported or exported in period ***t***. The model does not automatically balance the quantities exported and imported and the quantities may need to be controlled, if necessary. These variables are convenient whenever endogenous trade is not being considered.

TRADE(t,c,s,imp) and TRADE(t,c,s,exp): quantity of commodity ***c*** sold (***exp***) or purchased (***imp***) in period ***t,*** for time-slice ***s*** (for electricity). The trade is balanced by the model in each period. The transportation costs (or transaction costs) to quantities exported and imported can be incorporated in the model.

D(t,d): demand for end-use ***d*** in period ***t.*** In non-reference runs, ***D(t,d)*** may differ from the reference case demand for ***d***, due to the responsiveness of demands to their own prices (own-price elasticity).

ENV(t,p): Emission of pollutant ***p*** in period ***t.***

4.2 Objective Function

The MARKAL objective is to minimize the total cost of the system that will be discounted over the planning horizon. Each time period, the total cost includes the following elements:

- Annualized investments in technologies;
- Fixed and variable annual Operation and Maintenance (O&M) costs of technologies;
- Cost of exogenous energy and material imports and domestic resource production (e.g., mining);

- Revenue from exogenous energy and material exports;
- Fuel and material delivery costs;
- Net economic loss resulting from reduced end-use demands;
- Taxes and subsidies associated with energy sources, technologies, and emissions.

In each period, the investment costs are first annualized, before being added to the other costs (which are all annual costs) to obtain the annual cost in each period. MARKAL then computes a total net present value of all annual costs, discounted to a user selected reference year. This quantity is the one that is minimized by the model to compute the equilibrium. The objective function is the sum over all regions of the discounted present value of the stream of annual costs incurred in each year of the horizon:

$$\boldsymbol{NPV} = \sum_{\boldsymbol{r}=1}^{\boldsymbol{R}} \sum_{\boldsymbol{t}=1}^{\boldsymbol{t}=\boldsymbol{NPER}} (1+\boldsymbol{d})^{\boldsymbol{NYRS}\bullet(1-\boldsymbol{t})} \bullet \boldsymbol{ANNCOST}(\boldsymbol{r},\boldsymbol{t}) \bullet \left(1+(1+\boldsymbol{d})^{-1}+(1+\boldsymbol{d})^{-2}+\cdots+(1+\boldsymbol{d})^{1-\boldsymbol{NYRS}}\right)$$

Where:

NPV is the net present value of the total cost for all regions.
ANNCOST(r,t) is the annual cost in region *r* for period *t.*
d is the general discount rate.
NPER is the number of periods in the planning horizon.
NYRS is the number of years in each period *t.*
R is the number of regions.

The total annual cost *ANNCOST(r,t)* is the sum over all technologies *k*, all demand segments *d*, all pollutants *p*, and all input fuels *f,* of the various costs incurred, namely: annualized investments, annual operating costs (including fixed and variable technology costs, fuel delivery costs, costs of extracting and importing energy carriers), minus revenue from exported energy carriers, plus taxes on emissions, plus cost of demand losses. The *ANNCOST(r,t)* is expressed as follows:

$$
\begin{aligned}
ANNCOST(r,t) = \Sigma_k \{ & Annualized\_Invcost(r,t,k) * INV(r,t,k) \\
& + Fixom(r,t,k) * CAP(r,t,k) \\
& + Varom(r,t,k) * \Sigma_{s,s} ACT(r,t,k,s) \\
& + \Sigma_c [Delivcost(r,t,k,c) * Input(r,t,k,c) * \Sigma_s ACT(r,t,k,s)] \} \\
+ \Sigma_{c,s} \{ & Miningcost(r,t,c,l) * Mining(r,t,c,t) \\
& + Tradecost(r,t,c) * TRADE(r,t,c,s,i/e) \\
& + Importprice(r,t,c,l) * Import(r,t,c,l) \\
& - Exportprice(r,t,c,l) * Export(r,t,c,l) \} \\
+ \Sigma_c \{ & Tax(r,t,p) * ENV(r,t,p) \}
\end{aligned}
$$

Where:

Annualized_Invcost(r,t,k) is the annual equivalent of the lump sum unit investment cost, obtained by replacing this lump sum by a stream of equal annual payments over the life of the equipment, in such a way that the present value of the stream is exactly equal to the lump sum unit investment cost for technology k, in period t.

Fixom(k,t,r), *Varom(r,t,k)*, are unit costs of fixed and operational maintenance of technology k, in region r and period t.

Delivcost(r,t,k,c) is the delivery cost per unit of commodity c to technology k, in region r and period t.

Input(r,t,k,c) is the amount of commodity c required to operate one unit of technology k, in region r and period t.

Miningcost(r,t,c,l) is the cost of mining commodity c at price level l, in region r and period t.

Tradecost(r,t,c) is the unit transport or transaction cost for commodity *c* exported or imported by region *r* in period *t*.

Importprice(r,t,c,l) is the (exogenous) import price of commodity *c,* in region *r* and period *t*; this price is used only for exogenous trade. See below.

Exportprice(r,t,c,l) is the (exogenous) export price of commodity *c,* in region *r* and period *t*; this price is used only for exogenous trade, see below.

Tax(r,t,p) is the tax on emission *p,* in region *r* and period *t.*

The annualized unit investment cost is obtained from the lump sum unit investment cost via the following formula:

$$ANNUALIZED\_INVCOST = INVCOST / \sum_{j=1}^{LIFE} (1+h)^{-j+1}$$

Where,

INVCOST = lump sum unit investment cost of a technology

h = the discount rate used for that technology, also called hurdle rate. If the technology specific discount rate is not defined, the general discount rate d is used.

The hurdle rate h may be technology, sector and/or region specific to reflect the financial characteristics depending on the each investment decision.

4.3 Constraints

While minimizing total discounted cost, the MARKAL model satisfies a large number of constraints to represent the energy system in a region. The following are the major constraints used by the model:

Satisfaction of Energy Service Demands: EQ_DEM(r,t,d)

In the reference case, the model must satisfy these demands in each time period, by using the existing capacity and/or by implementing new capacity for end-use technologies. For each time period *t*, region *r*, demand *d*, the total activity of end-use technologies servicing that demand must be at least equal to the specified demand:

$$\Sigma_k CAP(r,t,k) \geq D(r,t,d)$$

Capacity Transfer (Conservation of Investments) — EQ_CPT(r,t,k)

Investing in a particular technology increases its installed capacity for the duration of the physical life of the technology. At the end of that life, the total capacity for this technology is decreased by the same amount. For each technology *k*, region *r*, period *t*, the available capacity in period *t* is equal to the sum of investments made by the model at past and current periods.

$$CAP(r,t,k) = \Sigma_t INV(r,t',k) + RESID(r,t,k)$$

Where,

RESID(r,t,k) is the capacity of technology *k* due to investments that were made prior to the initial model period and still exist in region *r* at time *t*.

Use of Capacity: EQ_UTL(r,t,k,s)

In each time period, the model may use some or all of the installed capacity in that period according to the Availability Factor (AF) of that technology. However, there is a provision to force specific technologies to use their capacity to their full potential. For each technology *k*, period *t*, region *r*, and time-slice *s*, the activity of the technology may not exceed its available capacity:

$$ACT(r,t,k,s) \leq AF(r,t,k,s) * CAPUNIT * CAP(r,t,k)$$

Electricity & Heat Balance: **EQ_BAL(r,t,c,s)**

The demand and supply of electricity and heat are defined in each time-slice and therefore, are balanced at each time-slice. In each time period, each season and time-of-day, electricity produced plus electricity imported must be at least as much as electricity consumed, plus electricity exported, plus grid losses. A similar balance exists for low temperature heat, although it is only tracked by season. For each commodity $\boldsymbol{c}$**,** time period $\boldsymbol{t}$, region $\boldsymbol{r}$, (and time-slice $\boldsymbol{s}$ in the case of electricity and low-temperature heat), the constraint requires that the use and export of each commodity may not exceed its supply. The supply includes production in the region plus imports.

$$\begin{aligned}
&\Sigma_k\ \mathit{Output}(r,t,k,c)*\mathit{ACT}(r,t,k,s) + \Sigma_l\ \mathit{MINING}(r,t,c,l) + \Sigma_l \\
&\quad \mathit{FR}(s)*\mathit{IMP}(r,t,c,l) + \mathit{XCVT}(c,i) * \mathit{TRADE}(r,t,c,s,i) \quad \geq \text{ or } = \\
&\quad \mathit{XCVT}(c,o)*\mathit{TRADE}(r,t,c,s,e) + \Sigma_l\ \mathit{FR}(s) *\mathit{EXP}(r,t,c,l) + \Sigma_k \\
&\quad \mathit{Input}(r,t,k,c)*\mathit{ACT}(r,t,k,c,s)
\end{aligned}$$

Where,

$\mathit{Input}(r,t,k,c)$ is the amount of commodity c required to operate one unit of technology k, in region r and period t.

$\mathit{Output}(r,t,k,c)$ is the amount of commodity $\boldsymbol{c}$ produced per unit of technology k;

$\mathit{FR}(s)$ is the fraction of the year covered by time-slice $\boldsymbol{s}$ (equal to 1 for non-seasonal commodities).

$\mathit{XCVT}(c,i)$ *and* $\mathit{XCVT}(c,o)$ are transaction or transport costs of importing or exporting one unit of commodity c.

The constraint is $\geq$ for energy forms and = for materials.

Electricity and Heat Peak Reserve Constraint — EQ_EPK/HPK(r,t,c,s)

This constraint requires that in each time period total available capacity of electricity generating technologies exceeds the average load of the peaking time-slice by a certain percentage. This percentage is the Peak Reserve Factor which safeguards against the possible electricity shortfalls due to uncertainties. For each time period $\boldsymbol{t}$ and for region $\boldsymbol{r}$, there must be enough installed capacity to exceed the required capacity in the season with largest electricity (heat) commodity ***c*** demanded by a safety factor *E* called the *peak reserve factor*.

$$\Sigma_k\ CAPUNIT * Peak(r,t,k,c) * FR(s) * CAP(r,t,k) + XCVT(c,i) * TRADE(r,t,c,s,i) + FR(s) * IMPORT(r,t,c)$$
$$\geq$$
$$[1+ERESERVE(r,t,c)] * [\Sigma_k\ Input(r,t,k,c) * FR(s) * ACT(r,t,k,s) + XCVT(c,o) * TRADE(r,t,c,s,e) + FR(s) * EXPORT(r,t,c)]$$

Where:

ERESERVE(r,t,c) is the region-specific reserve coefficient, which allows for unexpected down time of equipment, for demand at peak, and for uncertain hydroelectric, solar, or wind availability.

Peak(r,t,k,c) (< 1) specifies the fraction of technology *k*'s capacity in a region *r* for a period *t* and commodity *c* (electricity or heat only) that is allowed to contribute to the peak load.

Electricity Baseload Constraint: **EQ_BAS(r,t,c)**

Generally, coal based power and nuclear plants are included in the base load set. They require considerable down time for repair, shut down or restart. The base load electricity generating technologies produce the same amount of electricity in both night and day, however, their productions may vary from season to season. Therefore, for base load technologies there are only three activity levels (*ACT)* instead of 6 for other electric generation technologies. Since the maximum fraction of night production usually is supplied by all base load technologies, the base load constraint takes care of this issue. For electricity *c*, in region *r* and period *t,* the base load constraint is:

$$\Sigma_k\ \mathrm{input(r,t,k,c)* Baseload(r,t,c)*ACT(r,t,k,'N')} \geq \Sigma_k\ \mathrm{Output(r,t,k,c)*ACT(r,t,k,'N')}\ \}$$

Where,

Baseload(r,t,c) = the maximum share of the night demand for electricity *c* in region *r* and period *t.*

Emission Cap or Tax: **EQ_ENV(r,t,p)**

The upper limits on emissions of pollutants can be specified in the model. The limits may be set for each time period separately, so as to simulate a particular emission profile or target or in a cumulative fashion. The emissions caps can be set separately to each specific sector or they can also be imposed globally for the entire industry in a region, or for a group of regions.

In each region *r*, for each time period ***t,*** this constraint ensures that the total emission of pollutant ***p*** will not be greater than an upper bound. Pollutants may be emitted when a technology is active, but also when it is inactive (for example a hydro reservoir may emit methane even if no electricity is being produced). Emissions may also occur at the time of construction of the technology. In such cases, the emission coefficient is applied to the activity variable, to the capacity variable, or to the investment variable. This flexibility allows the accurate representation of various kinds of emissions. Technologies may also sequester or otherwise remove emissions as well via the use of a negative emission coefficient.

$$\mathrm{ENV}(r,t,p) = \Sigma_k \{ \mathrm{Eminv}(r,t,p,k)*\mathrm{INV}(r,t,k) + \mathrm{Emcap}(r,t,k,p)*\mathrm{CAP}(r,t,k) + \mathrm{Emact}(r,t,,k,p) * \Sigma_s \mathrm{ACT}(r,t,k,s) \}$$

And, $$\mathrm{ENV}(r,t,p) \le \mathrm{ENV\_Limit}(r,t,p)$$

Where,

> *Eminv, Emcap, Emact* are emission coefficients for pollutant *p* (possibly negative) linked respectively to the construction, the capacity, and the operation of a technology, and
>
> *ENV_LIMIT(r,t,p)* is the upper limit set by the user on the total emission of pollutant *p* in region *r* at period *t*.

Instead of an emission limit, an emission tax *Etax(r,t,p)* can also be used in the model. In this case, the quantity *ENV(r,t,p) * E tax(r,t,p)* is added to the ***ANNCOST*** expression, taxing emissions at a constant rate. In addition, both emissions limit and tax can also be used in the model to simulate the situation where even with tax, there exists an upper limit for a GHG (pollutant) emission.

User-Defined Constraints: **EQ_UDC(r,t,u)**

In addition to the standard MARKAL constraints discussed above, many additional linear constraints to express special conditions can be added in the model. Their general purpose is to constrain the optimization problem in some way to account for factors based either on specific policy or on market behavior that affect investment decisions. For example, there may be a constraint limiting investment in new nuclear capacity (regardless of the type of reactor), or allowing that a certain percentage of new electricity generation capacity must be powered by renewable energy sources to achieve certain level of renewable portfolio standard. In order to facilitate the creation of a new user constraint, MARKAL provides a *template* for indicating:

- the set of variables involved in the constraint, and
- the user-defined coefficients needed in the constraint.

Biomass Feedstock as a primary fuel option on OH-MARKAL

The proposed OH-MARKAL model in this study will have an additional dataset and parameters for biomass resources and an expanded biomass subsystem added to the model. Special emphasis will be given to analyze the potential use of biomass for electricity generation in Ohio. In the beginning of the model period, biomass feedstocks are cofired in selected coal power plants to generate renewable electricity. Later, new cofiring coal plants and new 100 percent using biomass power plants are added in the model to meet the growing demand of electricity in Ohio. The representation of the biomass subsystem in the model will also show its potential capability of displacing traditional fossil fuel usage, such as coal for electricity generation. As a macro-energy systems scenario, the results will highlight the impact on electricity prices, the change in generation fuel mixes, identification of the displaced generating capacity, and the resulting implications for air quality and GHG emissions.

5. Summary

MARKAL (MARKet ALlocation) is a robust mathematical model of energy systems that provides a technology-rich basis for estimating energy dynamics over a multi-period horizon. This chapter describes the formulation of the MARKAL modeling system to provide the necessary foundations for the proposed methodology. The chapter further explains the adaptation of the MARKAL framework to develop the OH-MARKAL model for analyzing major economic, environmental, and policy issues in the context of biomass energy generation in Ohio. The biomass subsystem is added in the model by incorporating additional dataset and parameters for biomass resources, as the primary research objective is to evaluate the prospect of biomass cofiring in Ohio's existing coal power plants to generate commercial electricity, as an alternative energy source.

While this study focuses on the use of biomass resources, specifically by cofiring, OH-MARKAL framework developed in this study can be extended to include other renewable resources such as wind, solar or hydro. Subsequently, this model can further be developed to encompass the entire energy system for Ohio by including transportation, industry, commercial, and residential sectors. The OH-MARKAL can also be extended by including other Midwest states to develop Midwest-MARKAL for analyzing energy and environmental policy issues at the regional level.

The next chapter deals with the model structure and data specifications of OH-MARKAL and develops various economic and environmental scenarios for evaluating their results and impact on the future energy use and environment of Ohio.

CHAPTER 3

MODEL STRUCTURE AND DATA SPECIFICATION

The OH-MARKAL model is a dynamic linear programming model of the energy system that is designed to analyze energy and environmental issues for Ohio over a long term future horizon (2001–2030). The model run configures the energy system (that includes producers and consumers of electricity) to minimize net total cost of the entire system, while satisfying a number of constraints. These constraints can range from a supply limit of any specific fuel (e.g., biomass feedstock) to a CO_2 emission limit. A number of model runs are performed to examine various levels of constraints based on the proposed scenarios, and to conduct sensitivity analyses on several constraints or assumptions (on potential future policy issues) to examine their impact on Ohio's energy future.

The OH-MARKAL functions as a least-cost optimization model of the energy system that is based on the concept of the Reference Energy System (RES). The RES for OH-MARKAL is developed to establish the flow of the primary energy supply (coal, biomass, natural gas, nuclear energy, etc.) via various processes and paths (technologies) to their final destination of sector-wise demand/use of electricity. The electricity demand in OH-MARKAL is derived from three principal sectors: residential, commercial, and industrial. As a bottom-up model, OH-MARKAL is therefore data intensive, requiring a significant amount of information on the energy system, such as price and quantity data on primary fuel resources, various conversion technologies, system constraints and assumptions, and demand data for the final form of energy services.

This chapter describes the model structure and specific underlying data that constitute OH-MARKAL. In addition, the data constraints and assumptions to develop model scenarios on biomass cofiring and other policy related issues will be discussed.

1. The OH-MARKAL Model Structure

The OH-MARKAL Reference Energy System (RES) elucidates the transformation paths of primary energy resources to their final energy form (electricity) at the end-use demand side via series of technologies (Figure 14), where the commodities are represented by flows (lines or links) that pass through processes (boxes). For each process, there can be one or more input commodities and similarly, one or more output commodities. All of these output commodities are finally processed into the energy services (specifically, electricity in the OH-MARKAL context) to be utilized by the demand sectors. This basic principle of linkage through the various flows and processes makes the model transparent, in terms of identifying and using the most efficient potential alternatives available along each path of the RES.

In the OH-MARKAL Reference Energy System (RES), the following constitute the four main technologies in the model:

1. Resource Technology
2. Process Technology
3. Conversion Technology
4. Demand Technology

The Resource Technology is characterized as all available categories of energy resources in Ohio. These include the primary energy resources derived locally from mining (coal, natural gas, crude oil, etc.), renewable energy such as biomass feedstock, and energy imports such as coal, natural gas, oil, as well as nuclear fuel. The Process Technology includes fuel processing plants, refinery operations, and transportation of fuels (via pipelines). The Conversion Technology comprises all power plants where various fuels are converted to electricity such as coal power plants, biomass cofiring power plants, natural gas power plants and nuclear power plants. Lastly, the Demand Technology represents the three primary sectors (Residential, Commercial, and Industrial) as the final consumers of electricity.

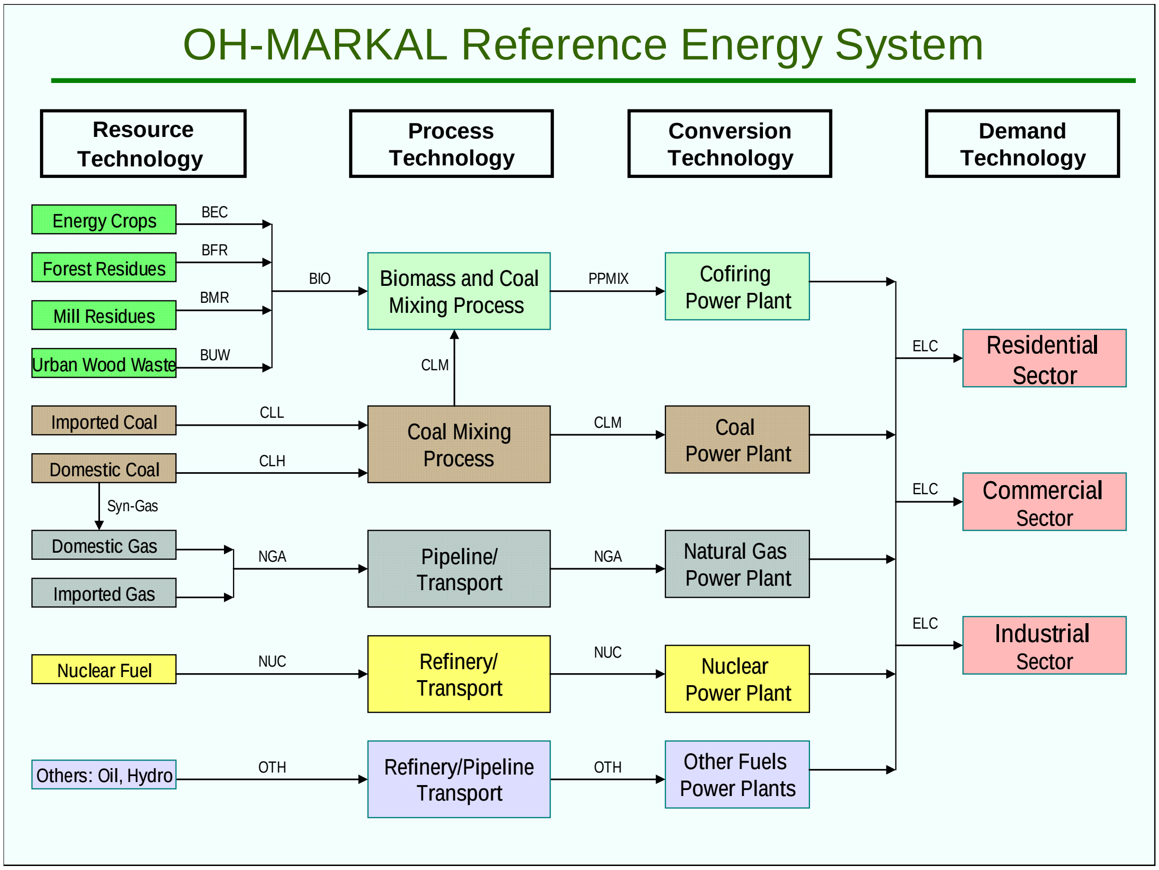


Figure 14. The OH-MARKAL Reference Energy System

The end-use demands of the three sectors correspond to the right-hand-side of the RES that drive the entire energy system. The relationships and inter-connections of Resource, Process, Conversion, and Demand Technologies are illustrated in Figure 14 which is designed for the OH-MARKAL context, and it presents the linkages from primary energy fuels to the final energy demand of electricity in residential, commercial, and industrial demand sectors.

2. Data Specifications

The data gathered for OH-MARKAL come mainly from available national and state sources, such as the Energy Information Administration of the U.S. Department of Energy (as complied for the *Annual Energy Outlook* (AEO), State Data System/Report (SEDS), National Renewable Energy Laboratory (NREL), and Public Utilities Commission of Ohio (PUCO). Because of the overall accuracy and reliability, special effort was made to use data sources at the state and industry level prior to depending on the existing national database. In addition to the description of data and their respective sources, all the underlying assumptions and limitations employed in the model are also discussed. The data and other related model issues are described under the following major categories:

- **2.1 Biomass Feedstock and Cofiring Power Plants**
  - **2.1.1** Feedstock Types and Their Prices: resource supply steps
  - **2.1.2** Potential Cofiring Power Plants
- **2.2 Coal and Other Primary Fuel Sources**
  - **2.2.1** Fuel prices
  - **2.2.2** Emission Levels per technology/fuel
- **2.3 Electric Power Plants in Ohio**
  - **2.3.1** Existing Power Plants: fixed and variable costs, efficiency, availability, technical life duration
  - **2.3.2** Proposed/Approved New Power Plants in Ohio: new investments

2.3.3 Potential Future Options in the Power Sector

2.3.3.1 Emission control devices

2.3.3.2 Clean coal technology

2.4 Electricity Demand and its Future Projections

2.4.1 Seasonal/day-night fractions

2.4.2 Electric reserve margin

2.1 Biomass Feedstock and Cofiring Power Plants

The OH-MARKAL is primarily developed to analyze biomass cofiring as a potential option for Ohio's energy future. The data on type of biomass feedstock, their prices and availability, and the criteria developed for selecting potential cofiring power plants in Ohio are discussed below.

2.1.1 Feedstock Types and Their Prices

Biomass energy resources are abundantly available in Ohio. However, all biomass feedstocks are not suitable for cofiring in coal power plants. The following four types of biomass feedstocks were selected for the OH-MARKAL study based on their heat content, feedstock characteristics, and most importantly, suitability of their use in cofiring purposes in coal power plants.

1. Energy Crops
2. Forest and Logging Residues
3. Mill Residues
4. Urban Wood Waste

Crop residues were not considered in the study, because of the diverse characteristics, distant location from most power plants, and low heat content. In addition, the use of crop residues for energy purpose may have a negative impact on soil fertility and erosion.

Similarly, farm animal waste was not considered in this study, because it is unsuitable for cofiring in power plants due to its high moisture content.

To address the physical, bulky nature of biomass feedstock, and hence, setting limitations on travel distance, the state of Ohio was divided into seven regions, so that the biomass could be transported to the closest potential power plants within each region, given the prospect that cofiring would become a viable option. When the regions were allocated, efforts were made to ensure approximately the same number of counties in each region. The exception was the smaller Region 6 in central Ohio, which constituted the larger of the urban areas in Ohio (Table 13).

The regional supply of biomass feedstocks at different price levels is provided in Table 12, while its supply function is presented in Figure 15. These data are aggregated from the country level data. The OH-MARKAL model at this point does not allow the transportation of biomass feedstock from one region to other. However, this can be modified in the model by incorporating transportation costs for biomass feedstock used in different regions. This study examines whether or not the currently available biomass feedstock in each region may be economically used for cofiring under various policy scenarios. Once we find out the potential level of biomass feedstock used in each region, the transportation of feedstock between regions can be added in the model.

Table 13 shows the regional distribution of the potential cofiring plants and their capacity, based on data provided by Ohio Power Statistics, 2002. Figure 16 illustrates the map of Ohio, showing the seven regions, with the locations of potential cofiring coal power plants in each region. Several studies have shown that a 75 to 100 mile radius is the maximum distance that these feedstocks can be transported to make it economically viable (Southgate and Shakya, 1996; Walsh *et. al.*, 2003). In OH-MARKAL, all the seven regions have less than 75 mile radius, thus making transportation a feasible solution in each region.

2.1.2 Potential Coal Power Plants for Biomass Co-firing

Currently, Ohio has 21 coal power plants with an aggregate capacity of 21,000 MW. Although all these plants may be able to cofire biomass with the coal in their plants, the most likely candidate coal plants for cofiring purposes were selected to evaluate this scenario. Based on the information provided by several industry professionals (Duke Energy, American Electric Power, American Municipal Power, Dayton Power and Light), it was apparent that newer and bigger plants would probably not opt for cofiring biomass, due to the higher cost involved and low emissions reductions benefits. These newer and bigger plants, if they did choose to cofire would require a large amount of biomass feedstock. In addition, these newer plants have already installed emission control devices on their plants, hence giving no additional benefit to the existing NO_x and SO_2 emissions reductions by cofiring biomass.

Based on the phone interviews with Ohio's industry professionals, the three following criteria were developed to select the potential cofiring coal power plants for this study:

- Built before 1970
- < 400 MW capacity at unit level
- No emission control device

Based on these criteria, 15 coal power plants were identified as potential cofiring candidate plants, with an aggregate annual generation capacity of 7,082 MW of electricity. Table 11 provides the list of these plants with their respective generation capacities. This study develops two scenarios of 10% and 15% biomass co-firing in these power plants to analyze various economic and environmental issues.

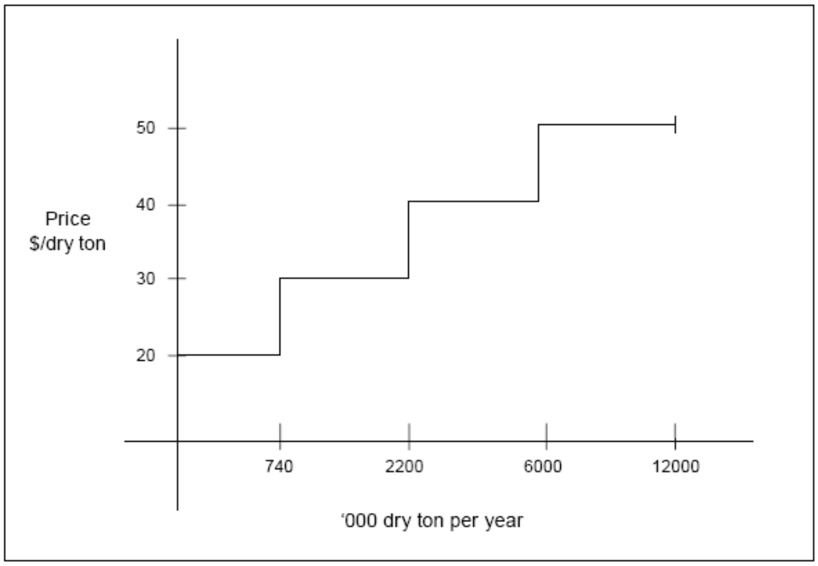


Figure 15. Biomass Feedstock Supply Function

Serial No.	Plant Name	County	Capacity MW
1.	Ashtabula	Ashtabula	244
2.	Burger	Belmont	406
3.	Beckjord	Clermont	704
4.	Conesville	Coshocton	165
5.	Lake Shore	Cuyahoga	245
6.	Kyger Creek	Gallia	1072
7.	Miami Fort	Hamilton	243
8.	Sammis	Jefferson	1020
9.	Eastlake	Lake	636
10.	Avon Lake	Lorain	192
11.	Bay Shore	Lucas	631
12.	Hutchings	Montgomery	371
13.	Picway	Pickaway	100
14.	Muskingum R.	Washington	840
15.	Gorsush	Washington	214
		Total:	7082

(Source: Ohio Power Statistics. PUCO, 2002)

Table 11. Potential Coal Power Plants for Biomass Cofiring

Biomass Feedstock	Region 1	Region 2	Region 3	Region 4	Region 5	Region 6	Region 7	TOTAL
Counties:	14	16	12	14	14	6	12	**88**
*** Forest/Logging Residue**								
$30/dry ton	7,218	75,653	127,632	186,406	23,380	65,833	12,841	**498,963**
$40/dry ton	10,312	108,075	182,331	266,294	33,400	94,047	18,345	**712,805**
$50/dry ton	12,890	135,094	227,914	332,868	41,750	117,559	22,931	**891,006**
***** Urban Wood Waste**								
$ 20/dry ton	75,505	293,718	55,873	34,606	188,531	95,494	44,486	**788,212**
$30/dry ton	121,783	473,738	90,117	55,816	304,083	154,022	71,751	**1,271,310**
**** Energy Crops**								
$40/dry ton	1,092,003	304,394	331,025	110,344	616,392	365,270	985,468	**3,804,896**
$50/dry ton	2,771,760	772,566	840,166	280,054	1,564,455	927,080	2,501,183	**9,657,264**
***** Mill Residues**								
$30/dry ton	19,091	95,781	144,625	312,171	25,076	11,138	20,307	**628,190**
$40/dry ton	24,411	119,726	180,781	390,214	31,345	13,923	25,384	**785,784**
Total:	**2,930,844**	**1,501,124**	**1,338,978**	**1,058,952**	**1,941,633**	**1,212,584**	**2,621,249**	**12,605,364**

Sources: * Jeanty, Wilner, Warren, and Hitzhusen. 2005. "Assessing Ohio's Biomass Resources for Energy." Ohio State University
** Walsh, Marie, *et. al.* 2000. Biomass Feedstock Availability in the United States: 1999 State Level Analysis,
Oak Ridge National Laboratory, Oak Ridge, TN
*** State-wise Biomass Energy Feedstock Database, NREL 2005

Table 12. Regional Biomass Feedstock Supply (Step-wise Curves) in Ohio

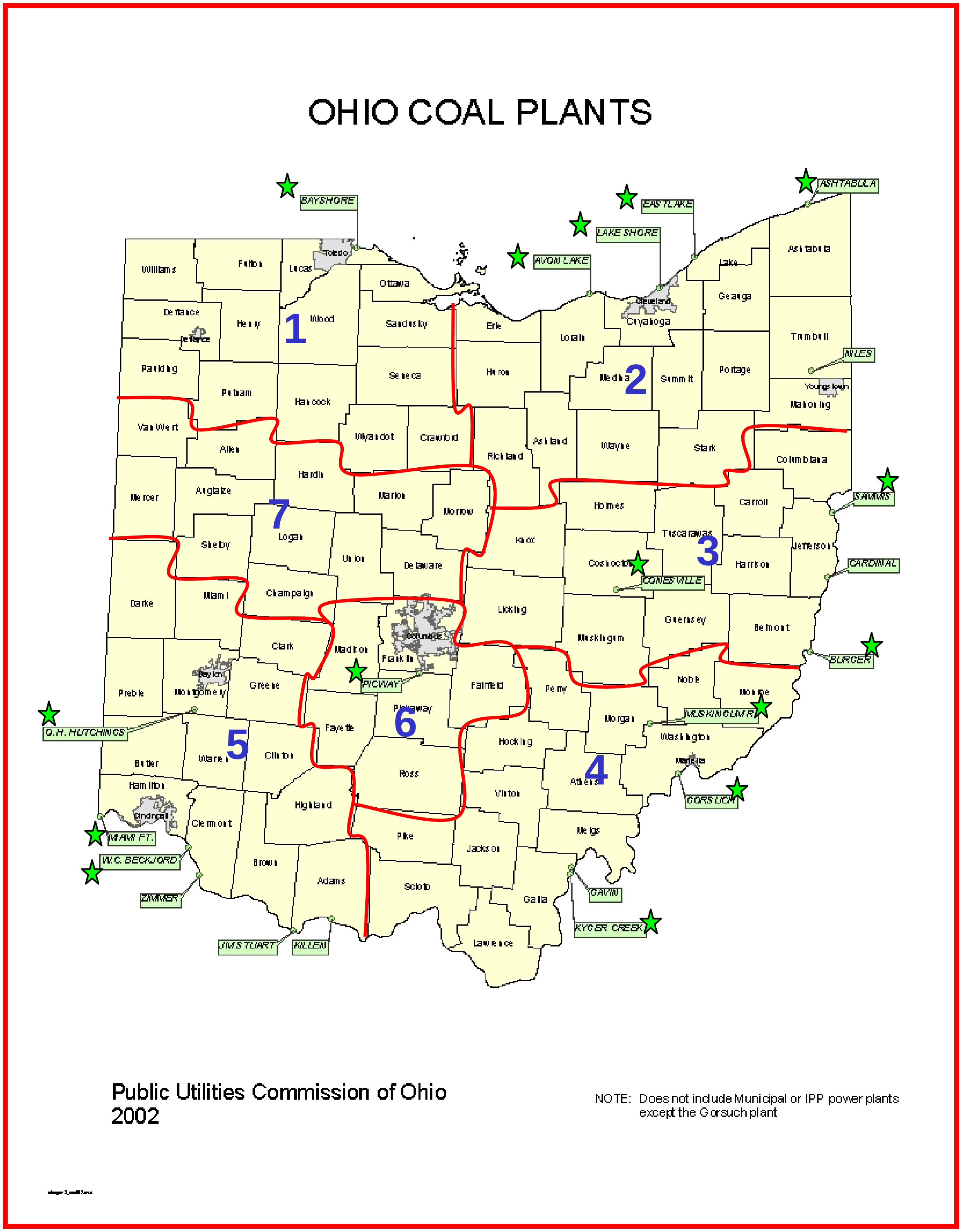


Figure 16. Regional Location of Potential Co-firing Plants in Ohio

	Region 1	**Region 2**	**Region 3**	**Region 4**	**Region 5**	**Region 6**	**Region 7**	**TOTAL**
Counties	14	16	12	14	14	6	12	**88**
Cofiring Plants	1	4	3	3	3	1	0	**15**
Cofiring Units	4	8	9	13	13	1	0	**48**
Capacity (MW)	631	1317	1591	2125.2	1318	100	0	**7082.2**

Source: Ohio Power Statistics, PUCO, 2002

Table 13. Regional Distribution of Potential Cofiring Plants and Counties

2.2 Coal and Other Primary Fuel Sources

Ohio is one of the heaviest users of coal in the nation. In 2002, about 90 percent of electricity in the state came from coal power plants (PUCO, 2004). Ohio uses both domestic and imported coal in its power plants and, on an average, the general ratio of use is about 40 percent domestic and 60 percent imported coal (Ohio Coal Statistics, DOE/EIA, and FERC, 2000). The price of coal generally depends on the type of coal mine and the mining cost. Hence, the surface-mined coal is cheaper than the underground-mined coal (OCDO, 2005). This is likely to be one of the main reasons for the price difference in imported and domestic coals in Ohio (see Table 14). Prices for other primary fuels are also presented in Table 14 and their corresponding emission rates from the power plants are provided in Table 15.

Technical Description	**Fuel Type**	**Price (2002) $/ tBTU**
MINNGA	Domestic natural gas *	4.86
IMPNGA	Imported natural gas *	4.93
IMPCLL	Imported Coal - Low Sulfur *	1.36
MINCLH	Domestic Coal - High Sulfur *	1.46
IMPDSL	Imported Distillate **	6.68
IMPNUC	Imported Nuclear fuel **	0.44

Sources: * EIA's OH Summary Stat, 2002
** Annual Energy Outlook 2006 with Projections to 2030
http://www.eia.doe.gov/oiaf/aeo/excel/figure65_data.xls

Table 14. Fuel Types and Prices for Ohio's Power Plants

Fuel Type	**CO2**	**SO2**	**NOX**	**Hg***
Coal	2101.63	18.92	5.84	0.0589
Oil	3534.59	4.51	21.16	0
Gas	1766.88	0.07	3.66	0
Nuclear	0	0	0	0
Biomass	0	0.13	0.34	0
Wind	0	0	0	0
Solar	0	0	0	0

Source: eGRID 2002, US-EPA. (* Hg in lbs/GWh)

Table 15. Emission Rates (lbs/MWh) in Ohio by Fuel Type

2.3 Electric Power Plants in Ohio

Ohio is the one of the leading producers of electricity and is ranked third in the country (State Electricity Profiles, EIA, 2002). Table 16 below presents the existing power plants in Ohio by fuel type and their capacities. The Figure 17 provides the location of these power plants by county in Ohio.

	Fuel Type	**No. of Plants**	**Capacity ‘000 MW**
1.	Coal	21	21
2.	Natural Gas	12	5
3.	Nuclear	2	2
4.	Gas and Oil	11	3.5
5.	Others	16	1
	Total	**62**	**32.5**

(Source: Ohio Power Statistics. PUCO, 2002)

Table 16. Power Plants in Ohio by Fuel Types and their Capacity

2.3.1 Existing Power Plants: Fixed, Variable, and Other Related Costs

Data for existing power plants are compiled from the national source (eGRID, 2002). The entire data set is too big to present here, however, a subset of the data is presented in Table 17. This data contains the power plant data at the unit level for variables such as: operation date, capacity, fixed cost, variable cost, and the remaining life in years of the plants.

2.3.2 New Power Plants in Ohio

There are two categories of new power plants that are modeled in this analysis. The first category includes the proposed power plants that are under consideration or have been approved by the by the Ohio Power Siting Board, Public Utilities Commission of Ohio (PUCO). These power plants are listed in Table 18 (for coal power plants) and Table 19 (for natural gas power plants). These new coal and natural gas plants will add to the generation capacity of about 9,500 MW in Ohio by 2012 (PUCO, 2006). In addition to these power plants, more new power plants are added in the model for the purpose of conducting sensitivity analyses for various policy scenarios, e.g., to examine whether the capacity of the proposed power plants will be able meet the growing electricity demand by the end of the model horizon in 2029.

Table 20 provides new coal, natural gas and nuclear power plants, while Table 21 presents new biomass and cofiring power plants in Ohio. Additions of new biomass and cofiring plants are necessary in the model, especially to analyze scenarios where carbon constraints or renewable portfolio standards will require more electricity generation capacity that uses biomass feedstock. The candidate cofiring plants proposed in this study may not have enough capacity to meet the higher level of RPS or to increase more biomass feedstock use for lower CO_2 emissions (cap scenario). In addition, a number of these candidate cofiring plants will be retired on 2011 because of their plant age as all of them were built before 1970.

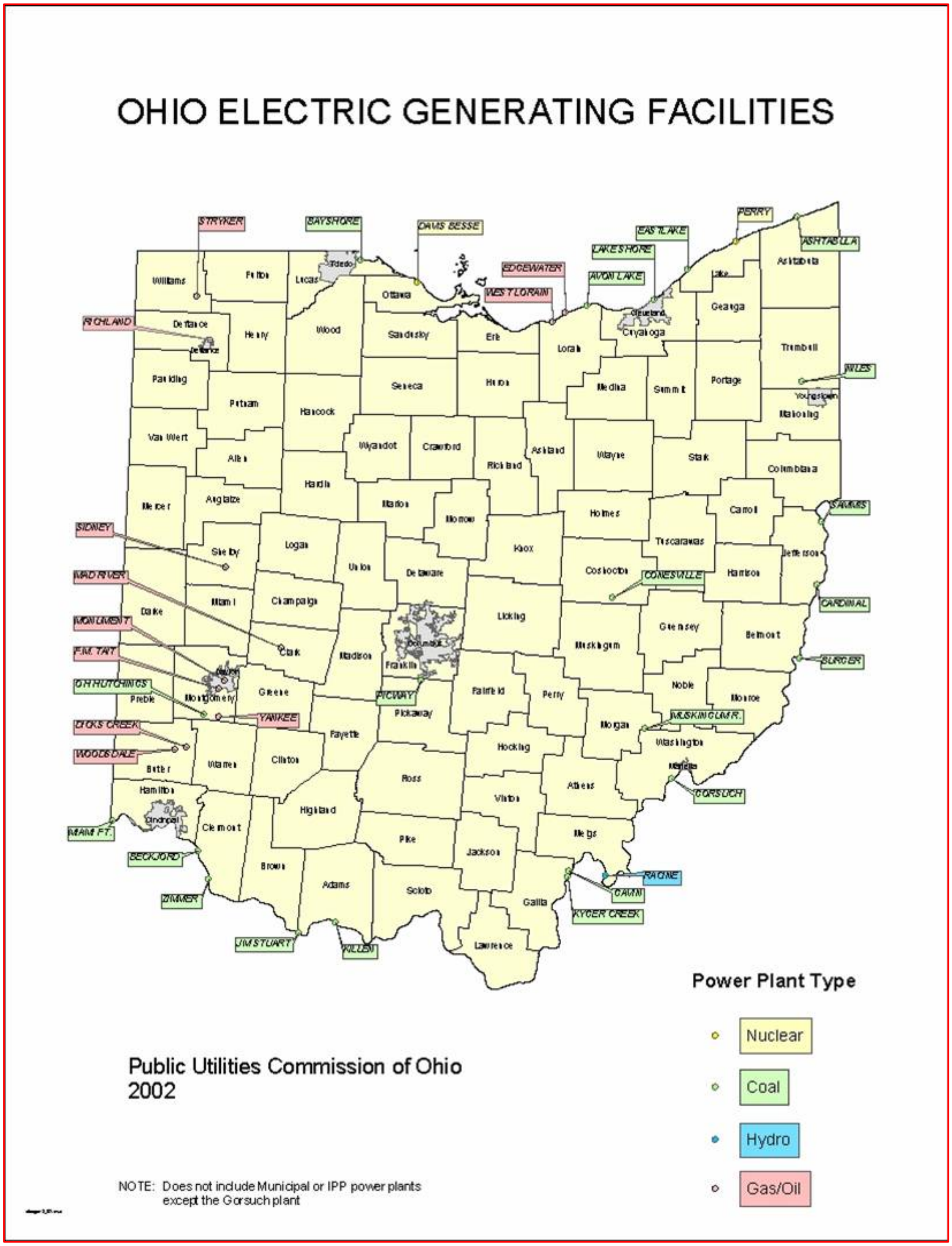


Figure 17. Location of Entire Electric Generating Facilities in Ohio

	* Existing Plants/Technologies				INP(ENT)c	START	LIFE	CAPUNIT	FIXOM	VAROM	RESID
TechName	**TechDesc**	**Units**	**CommIN**	**CommOUT**		**TID**	**TID**	**TID**			2002
E028281	Cardinal:1	tBTU, GW	CLM	ELC	2.847	2002	41	33.270	47.871	1.140	0.600
E028282	Cardinal:2	tBTU, GW	CLM	ELC	2.847	2002	41	33.270	47.871	1.140	0.600
E028283	Cardinal:3	tBTU, GW	CLM	ELC	3.069	2002	41	33.270	47.871	1.140	0.630
E028301	Walter C Beckjord:1 – CoF R5	tBTU, GW	PPMIX5	ELC	3.347	1952	10	33.270	17.859	1.239	0.094
E028302	Walter C Beckjord:2 – CoF R5	tBTU, GW	PPMIX5	ELC	3.290	1953	10	33.270	17.859	1.239	0.094
E028303	Walter C Beckjord:3 – CoF R5	tBTU, GW	PPMIX5	ELC	3.087	1954	10	33.270	17.859	1.239	0.128
E028304	Walter C Beckjord:4 – CoF R5	tBTU, GW	PPMIX5	ELC	3.157	1958	10	33.270	17.859	1.239	0.150
E028305	Walter C Beckjord:5 – CoF R5	tBTU, GW	PPMIX5	ELC	3.094	1962	10	33.270	17.859	1.239	0.238
E028306	Walter C Beckjord:6	tBTU, GW	CLM	ELC	3.041	1969	10	33.270	17.859	1.239	0.421
E02830GT1	Walter C Beckjord:GT1	tBTU, GW	DSL	ELC	6.350	1972	10	33.270	4.997	12.490	0.061
E02830GT2	Walter C Beckjord:GT2	tBTU, GW	DSL	ELC	6.350	1972	10	33.270	4.997	12.490	0.061
E02830GT3	Walter C Beckjord:GT3	tBTU, GW	DSL	ELC	6.350	1972	10	33.270	4.997	12.490	0.061
E028311	Dicks Creek:1	tBTU, GW	NGA	ELC	2.919	1965	10	33.270	0.550	1.590	0.110
E028325	Miami Fort:5 – CoF R5	tBTU, GW	PPMIX5	ELC	5.248	1949	10	33.270	14.761	1.140	0.080
E028326	Miami Fort:6 – CoF R5	tBTU, GW	PPMIX5	ELC	2.951	1960	10	33.270	14.761	1.140	0.163

Source: eGRID, 2002.

Table 17. Data on Existing Power Plants at Unit level

Company	Proposed Location	Capacity (MW)	Tech-nology	Investment (Million $)	Const. Date	Plan for Operation
Nordic Energy	Ashtabula	830	Cogen.	1200	May, 2004	2006
Dominion Energy	Conneaut	600		600	July, 2004	2010
CME International	Hanging Rock	600	IGCC	600	Nov., 2005	TBA
American Muni. Power OH	Letart	1000		1200	Nov., 2005	2012
Global Energy	Lima	600	IGCC	575	Dec., 2005	2008
American Electric Power	Meigs County	629	IGCC	1000	March, 2006	2010
Sunoco	Scioto County	80	Cogen.	80	Sept., 2004	2006
Total:		**4339**		**5255**		

Sources: Tracking New Coal-Fired Power Plants, National Energy Technology Laboratory, 2006.
Public Utilities Commission of Ohio, 2006. www.puco.ohio.gov

Table 18. Proposed New Coal Power Plants in Ohio

Plant Operator	Plant Name	Plant Location	County	Date	MW
Calpine	Fremont	Fremont	Sandusky	6/1/2006	760
Dominion Resources	Dresden	Dresden	Muskingum	6/1/2006	550
Calpine Corp.	Lawrence	Hanging Rock	Lawrence	NA	1100
Hadington/CAES	Norton	Norton	Summit	NA	2700
Total:					**5110**

(Source: Public Utilities Commission of Ohio, 2006.)

Table 19. Proposed New Natural Gas Power Plants in Ohio

Power Plant	**Capacity MW**	**Technology**	**Investment Million $**	**Proposed Date**
Coal Plant 1	2500	IGCC	3,000	2011
Coal Plant 2	2500	IGCC	3,000	2014
Coal Plant 3	2500	IGCC	3,000	2017
Coal Plant 4	1000	IGCC with Sequestration	1,400	2014
Coal Plant 5	1500	IGCC with Sequestration	2,000	2020
Sub-Total:	**10,000**			
Natural Gas Plant 1	1000	Adv. Combine Cycle	1,000	2011
Natural Gas Plant 2	2000	Adv. Combine Cycle	2,000	2014
Natural Gas Plant 3	1500	Adv. Combine Cycle with Sequestration	2,000	2017
Sub-Total:	**4,500**			
Nuclear Power Plant	**800**	Advance Nuclear	1,500	2014
Total:	**15,300**		**18,900**	

(estimated data)

Table 20. Additional New Coal, Natural Gas, and Nuclear Power Plants

Power Plant	**Region**	**Capacity (MW)**	**Technology**	**Investment (Million $)**	**Proposed Date**
Biomass Power Plant 1	1	100	Gasification	100	2011
Biomass Power Plant 2	2	100	Gasification	100	2014
Biomass Power Plant 3	5	100	Gasification	100	2011
Biomass Power Plant 4	7	100	Gasification	100	2011
Biomass Power Plant 5	1	200	Gasification	200	2017
Biomass Power Plant 6	2	200	Gasification	200	2017
Biomass Power Plant 7	5	200	Gasification	200	2020
Biomass Power Plant 8	7	200	Gasification	200	2020
Cofiring Power Plant 1	1	400	Cogen	400	2014
Cofiring Power Plant 2	2	400	Cogen	400	2014
Cofiring Power Plant 3	5	400	Cogen	400	2011
Cofiring Power Plant 4	7	400	Cogen	400	2011
Total:		**2000**		**2000**	

Table 21. Proposed New Biomass and Cofiring Coal Power Plants

2.3.3 Potential Future Options in the Power Sector

Technology in the electric power sector is also dramatically changing as in most other industries. It is expected that there can be major technological advancement during the time horizon period (2002-2030) of this model. These new technology improvements projected by the National Energy Technology Laboratory are presented in Table 22. The new coal power plants proposed in the model at various model periods reflect these improvements of higher plant efficiencies and lower costs.

Technology Improvement	Current	By 2010	By 2020
Plant Efficiency	40%	45-50%	50-60%
Availability	>80%	>85%	>90%
Plant Capital Cost ($/kW)	1000-1300	900-1000	800-900
Cost of Electricity (c/kWh)	3.5	3.0 - 3.2	< 3.0

Sources: Clean Coal Technology Roadmap, National Energy Technology Laboratory
www.netl.doe.gov/coalpower/ccpi/pubs/CCT-Roadmap.pdf

Table 22. New Technology Improvements in Coal Power Plant

All the new coal power plants will also have built-in emission control devices in the future. There are two most commonly used emission control devices: Flue Gas Desulphurization (FGD) for SO_2 and Selective Catalytic Reduction (SCR) for NO_x. The average cost for both of these devices and their efficiency level is given in Table 23. Most power industry professionals expect that it will be cheaper to install these devices than purchase the permits for their emissions in the future and all the existing coal power plants in Ohio will have both of these devices installed by 2010-12 (personal phone interviews, 2006). The older coal plants that are not worthy of investment in these devices will be retired by 2012. Hence, all the new and existing coal power plants in Ohio will be equipped with both these devices that will reduce the emission levels of

SO_2 and NO_x by 98 and 90 percent respectively. Therefore, the emissions of both SO_2 and NO_x will not be an issue for coal power plants in Ohio after 2012. However, the CO2 emission level will likely become the driving force for diversifying the resource mix for electricity generation and increasing the use of renewable energy resources, if a carbon tax or cap policy is implemented in Ohio.

Emission Control Device	Capacity (MW)	Cost/unit (Million $)	Removal (percent)
SOx			
Flue Gas Desulphurization (FGD)	600	200	98
NOx			
Selective Catalytic Reduction (SCR)	800-1000	100	90

Source: American Electric Power, 2000-2005, www.aep.com

Table 23. Average Cost for Emission Control Devices

2.4 Electricity Demand and its Future Projections

The demand for electricity used in this model comes from the Residential, Commercial, and Industrial sectors (Table 24). The demand is based on USDOE, EIA data and the report from the Forecasting Division of the PUCO (Forecast Report, 2004). These reports indicate that there is minimal or no data on import and export of electricity from Ohio. One key factor that makes it difficult to gather such information is that most of these investor owned utilities operating in Ohio also have operations in several other states, and thus isolating Ohio-specific data becomes more complicated.

Several phone interviews and meetings with professionals at the PUCO and several utilities were conducted to delve into electricity export and import in Ohio. The information gathered from these sources indicated that Ohio is very close to being self-sufficient in electricity generation and consumption, although Ohio does both export (to northeastern states) as well as import (from southern and western states) electricity. There were not enough time series data available for exports and imports of electricity in Ohio. However, some cross sectional data indicated that Ohio is a net importer of electricity by a very small margin (EIA, 2002). The amount of electricity imports was so low that it will not have any significant impact on the OH-MARKAL model. Therefore, this model does not include the data on the export and import of electricity. However, these data can readily be incorporated in the model if they become available in the future.

The demand for electricity in each season and time-of-day is calculated for all demand categories and its ratio is applied to the forecast projections. The year is divided into six time-divisions (time-slices), using two indices: Winter/Summer/Intermediate, and Day/Night.

Year	Residential	Commercial	Industrial	Total
2001	161.5	148.5	211.2	521.2
2002	172.7	152.1	201.6	526.4
2003	166.0	154.8	196.3	517.2
2004	168.3	157.9	200.7	526.8
2005	170.5	160.9	204.9	536.3
2006	172.7	163.9	209.1	545.7
2007	174.9	166.8	213.2	554.9
2008	177.1	169.7	217.2	564.0
2009	179.2	172.5	221.1	572.9
2010	181.4	175.3	225.0	581.6
2011	183.5	178.0	213.9	575.3
2012	185.6	180.6	202.1	568.3
2013	187.7	183.2	189.6	560.5
2014	189.8	185.7	199.7	575.1
2015	191.8	188.2	209.3	589.3
2016	193.8	190.6	213.4	597.8
2017	195.8	192.9	217.4	606.2
2018	197.8	195.2	221.3	614.4
2019	199.8	197.4	225.2	622.4
2020	201.8	199.6	228.9	630.3
2021	203.7	201.7	232.6	638.0
2022	205.6	203.8	236.2	645.6
2023	207.5	205.8	239.7	653.0
2024	209.4	207.8	244.2	661.4
2025	211.3	209.8	248.7	669.8
2026	213.2	211.8	255.2	680.2
2027	215.1	213.8	254.7	683.6
2028	217.0	215.8	259.2	692.0
2029	218.9	217.8	263.7	700.4
2030	220.8	219.8	268.2	708.8

(Source: USDOE-EIA, 2004 and Div. of Policy & Market Analysis, PUCO 2004)

History (1997-2002), Forecast (2003-2023)
Trillion BTUs per Year

Table 24. Electricity demand in Ohio and its projections

2.5 Data/Model Assumptions and OH-MARKAL Limitations

The collection of data from the various sources for this model was quite a challenging task, as most of the data required by the model are proprietary industry information. Nonetheless, a significant amount of data (as much as possible) was gathered from industry and state sources. The data, not available at the state level, were collected and complied from the national level data, primarily from the US-DOE's AEO and EIA sources. In addition, the average estimates have been used where utility specific information is not available. For example, there was minimal data on how much a specific utility has spent or planned to spend on installing emission control devices. Therefore, the average cost of these devices (based on plant capacity) was estimated to use in the model (Table 23).

Despite its overall strengths as a dynamic linear programming model, the MARKAL model has its own limitations and disadvantages. The model is particularly data intensive, as it requires large amounts of information for the characterization of technologies and to specify each unit of the primary fuel source in the RES. An enormous effort was therefore made to collect and compile the best quality data available to construct the proposed OH-MARKAL. One of the limitations of this model is that it requires all the assumptions to be made for future changes in demand and prices for the model. Future uncertainties can only be analyzed by developing several potential scenarios, however, sometimes it can become a tedious process on coming up with the reasonable number on potential future scenarios. The dynamic nature of this model implies that the past decisions and future constraints are included in the decision process, but prospective future improvement on efficiencies and technological changes can be incorporated in the model.

Another equally important limitation of this model to consider is that a number of key assumptions must be made, such as the growth in energy demand and technology improvement. The MARKAL model results are sometimes sensitive to even small changes in data assumptions. The use of stepped supply curves at different price levels will partly alleviate this limitation (Figure 15). The changes in energy demand due to efficiency improvements and economic behaviors are often difficult to specify in the model. However, generalized assumptions for future technology and efficiency improvements can be made and incorporated in the model to be tested further by sensitivity analyses. Similarly, uncertainties in the model can also be evaluated by developing various model scenarios. Once the model is well specified and the calibration is done, running the multiple model scenarios can be accomplished with relative ease.

The summary of key OH-MARKAL's assumptions and limitations is given below:

- The demand forecast for electricity is based on EIA and PUCO data which is estimated to increase at an average rate of 2 percent per year. Energy conservation and efficiency plans could reduce the demand for electricity in the future. A new scenario needs to be developed to incorporate such change in demand in the model.
- The average ratio of domestic and imported coals use in Ohio's coal power plants is at 40:60 respectively. There are differences in BTU content, sulfur content and price of these two types of coal (Table 4).
- The price forecasts of coal, natural gas, nuclear fuel for next 30 years are based on the data from AEO, 2006 (DOE/EIA-0383, 2006). Any changes in these prices in the future needs to be adjusted in the model for policy evaluations.
- The supply of biomass feedstock and its price is expected to increase at a modest rate of 1.5 percent per model period (Table 12).
- The supply of biomass is limited to only the region where each plant is located. If the demand for biomass feedstock increases in the future, inter-regional biomass transportation needs to be included in the model. Similarly, the model can also be improved by incorporating the data on biomass supply from neighboring states as most of the coal power plants are located close to the boarder (Figure 8).

However, for this model, there is enough supply of biomass to meet the demand in each region.

- The model has a lower limit for natural gas plants to generate at least 2 percent of total electricity generation to capture the peaking demand.
- The nuclear power plants have, on the other hand, a upper limit of 8 percent to generate electricity in Ohio. The model also incorporates a new nuclear power plant in year 2014 so that it can generate about 8 percent of electricity through out the model years (Table 20).
- Since a number of existing cofiring power plants will be retired in year 2012, several new cofiring and 100 percent biomass plants are proposed in the model starting year 2011 to 2020 (Table 21).
- The model cannot be used to contrast tax vs. cap scenarios, because the results will be the same for both scenarios unless the administrative costs in each scenario can be identified and specified in the model.

2.6 OH-MARKAL Model's Strength

The OH-MARKAL model uses a coherent and transparent framework, where the data assumptions are open and each result may be traced to its technological cause (open data and model architecture). Its analytical framework of developing multiple model scenarios is ideally suited for examining the technology choices to accomplish optimal energy, environmental, and policy goals. This Ohio model also greatly benefits from MARKAL's wide use at regional, national and global levels for assessing a wide range of energy and environmental planning and policy issues.

At the international level, MARKAL is considered one of the most widely used "bottom-up" models among the economic models used in energy, environment, and climate change policy analyses (www.etsap.org). One of the key reasons for the model's implementation in this study was based on the success of the MARKAL model in the northeastern states to evaluate similar energy and environmental issues. Recently, the framework was used by the Northeast States for Coordinated Air Use Management

(NESCAUM), where the model was adapted as a New England MARKAL (NE-MARKAL) that includes nine New England states to evaluate various energy and environmental policies at the regional level.

3. The OH-MARKAL Template

All the data for OH-MARKAL model is organized in various spreadsheets of Excel workbook. The ANSWER[1] software is used to manage these worksheets as well as to conduct the model runs. The ANSWER is a Windows based interface for working with the MARKAL modeling system that provides a user friendly tool to manage data, develop model scenarios, conduct model runs, and analyze results. In general, the information for Commodities, Technologies, and Constraints in ANSWER worksheets is divided into two categories: Declaration and Data sheet. On the declaration sheet, all the commodities, technologies, and constraints are defined and the actual data associated with them are presented on the Data sheet.

The OH-MARKAL ANSWER has the following three declaration worksheets as described in Table 25:

- **Technologies Declaration Sheet**
- **Commodities Declaration Sheet**
- **Constraints Declaration Sheet**

The Data sheet in OH-MAKAL is, however, organized in the following worksheets. The ANSWER does allow more than one sheet for any categories of data, so that it will be easy to manage a large set of data.

- **Demand_data**: Sector-wise electricity demand data and their forecast throughout the model horizon.
- **Tech_Data_EPP**: Contains the technical data on existing power plants: fixed cost, variable cost, plant capacity, plant start date, plant life, etc.

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[1] ANSWER software is developed by Noble-Soft Systems Pty Ltd. For more information on the software, please visit: http://www.noblesoft.com.au/

- **Tech_Data_NewPP**: Contains the technical data on proposed new power plants: fixed cost, variable cost, plant capacity, plant start date, plant life, etc.
- **Tech_Data_Sup**: Contains price data for both domestic and import primary energy fuels like coal, natural gas, nuclear and biomass feedstock. Upper bound supply limit in case of biomass feedstock is imposed, and there is no upper bound limit of coal, natural gas and nuclear as these can be imported if more is needed. However, if any of these fuels are used at unreasonably high amounts, this can be corrected.
- **ENT+ENV_Data**: Electric data such as base load and eReserve and also emissions on CO2, NOx, SO2 and Hg.
- **Tech_Data-FuelPRC**: All the fuel mixing technology and supply of primary fuels such as high sulfur and low sulfur coal, biomass feedstock and coal, etc are defined on this worksheet.
- **Constr_Data**: Mixing levels of primary energy fuels (coal and biomass feedstock) are defined here. The mixing ratio can be fixed, lower, and upper bound.

The reference data and other relevant information on OH-MARKAL are provided on the following worksheets:

- **Bio_Supply Steps**: Contains data on various types of biomass feedstock, their regional availability at different price levels.
- **Upper Bounds**: Maximum aggregate level of biomass feedstock available in each region.
- **Biomass_Supply**: Conversion of biomass feedstock price level from $/dry ton to M$/tBTU (million $ per trillion BTU).
- **OH-CountryLevel_Biomass**: Feedstock availability data at county level
- **Conversions**: table containing various energy and emission conversion factors.
- **Ele_Dm_Sec**: PUCO data on electricity demand forecast for residential, commercial, and industrial sectors.

Worksheet Category	**ANSWER Indicator**	**Description**
Declaration	Commodities	All the commodities (energy carriers, materials, demands, and emissions) are defined and described with their units and set memberships.
Declaration	Technologies	All the technologies (resources, processes, conversion plants, and demand devices) are defined and described, along with their units and set memberships.
Declaration	Constraints	All user-defined constraints (ADRATIOs) are defined and described with their units and set memberships.
Data	Comm_Data	Contains the data associated with commodities (e.g., demand levels, energy carrier efficiencies, electricity transmission and distribution costs).
Data	Tech_Data	Contains the data associated with technologies (e.g., residual capacity, efficiency, availability, input/output fuels, costs).
Data	Constr_Data	Contains the data associated with user-defined constraints (ADRATIOs) by identifying the individual technologies constraint and coefficients.

Table 25. The Description of ANSWER Worksheets

4. Developing OH-MARKAL Model Scenarios

It is well understood both by policy makers and energy professionals that there is no single means to mitigate GHG emissions since the use and generation of energy are so diverse in nature (Arvizu, 2006; PEW, 2007). The options for reducing CO_2 emissions from energy use include: increasing energy efficiency in both consumption and production of electricity, use of clean coal technology with carbon sequestration, and enhancing the use of capturing and storing CO_2. Similarly, increasing the use of renewable energy is one of the principal options available to us toward the low carbon energy future (Arvizu, 2005; Hawkins, 2004; PEW, 2007).

As discussed in the earlier chapters, more than 50 percent of U.S. electricity is generated by burning coal and it is about 90 percent in Ohio. This substantial use of fossil fuels to generate electricity is considered the single largest source of global warming pollution, including SO_2 and mercury (NRDC, 2005). In addition, burning coal and other fossil fuels also release air pollutants that are responsible for acid rain, smog, and cause health problems such as asthma, emphysema and premature death (NRDC, 2005). However, using renewable energy such as biomass to produce electricity causes not only less damage to the environment and our health, but also provides much needed diversity in the electric generation resource mix and contributes to our rural economy.

In the initial stages of this study, the research objectives included all major GHG and pollutants (emission) from the power industry, namely, CO_2, SO_2, NO_x, and Hg. Biomass energy resources, being carbon neutral, also significantly reduce the emission of SO_2, NO_x, and Hg. However, the recent data on SO_2 and NO_x emissions reveal that the effective environmental laws (Clean Air Act 1990) on air pollutants have been successful in reducing the emission levels. The Electric Power Annual time series data from 1994 to 2005 on CO_2, SO_2, and NO_x emissions from energy consumption for conventional power and combined heat-and-power plants in the U.S. shows that emissions for SO_2 and NO_x have decreased by 29 and 49 percent respectively in 2005 as compared to the 1994 levels, while CO_2 emissions during the same time period have increased by 21.7 percent (DOE/EIA, 2006).

According to the power companies in Ohio, it will be more economical and efficient to install emission control devices than to buy emission permits for SO_2 and NO_x in the future. Hence, the assumption is that all the power companies in Ohio will install emission control devices like SCR and FGD (Table 23) to all operating coal power plants by 2012 (personal interviews with Ohio industry professionals). The older power plants where it is uneconomical to install such devices will be retired before 2012.

Since all the operating and new power plants in Ohio will have emission control devices for SO_2, NO_x, and Hg, this study will focus on the carbon policy for Ohio. The emissions of CO_2 from power companies will be a major issue for Ohio due to its heavy reliance on coal and its resulting emissions. Although there is no mandatory carbon reduction policy in place at present, several policies gearing toward low-carbon energy future are being discussed and formulated in many states, including Ohio, and also at the federal level (Table 27 and Table 28). Based on these various renewable energy policies, some proposed and others already implemented in many states around the country, the following four major policy scenarios are developed for OH-MARKAL to analyze major economic and environmental issues related to biomass energy resources in Ohio over a long term future (2001-2030):

- Levels of Biomass Cofiring in Coal Power Plants
- Renewable Portfolio Standards for Ohio
- Caps on Carbon Dioxide Emissions
- Taxes on Carbon Dioxide Emissions

4.1 Levels of Biomass Cofiring in Coal Power Plants

Several pilot and test projects on cofiring suggest that biomass can substitute up to 20 percent of coal (FTO, 2004; Grabowski, 2004; Haq, 2002). If the market for CO_2 develops in the future like SO_2, the cofiring of biomass with coal will be a preferable choice for power plants to mitigate CO_2 emissions (NRDC, 2005). More power plants will be needed for cofiring biomass to generate renewable electricity so that we will be moving toward a lower carbon future. This study develops two levels of biomass cofiring (10 and 15 percent) at selected coal power plants with an objective to analyze the supply limits of biomass feedstock in seven regions in Ohio. In addition, the impacts of biomass cofiring will be evaluated for the electricity generation mix, the marginal electricity price, the emission levels of CO_2, and the use of coal and biomass feedstock for Ohio.

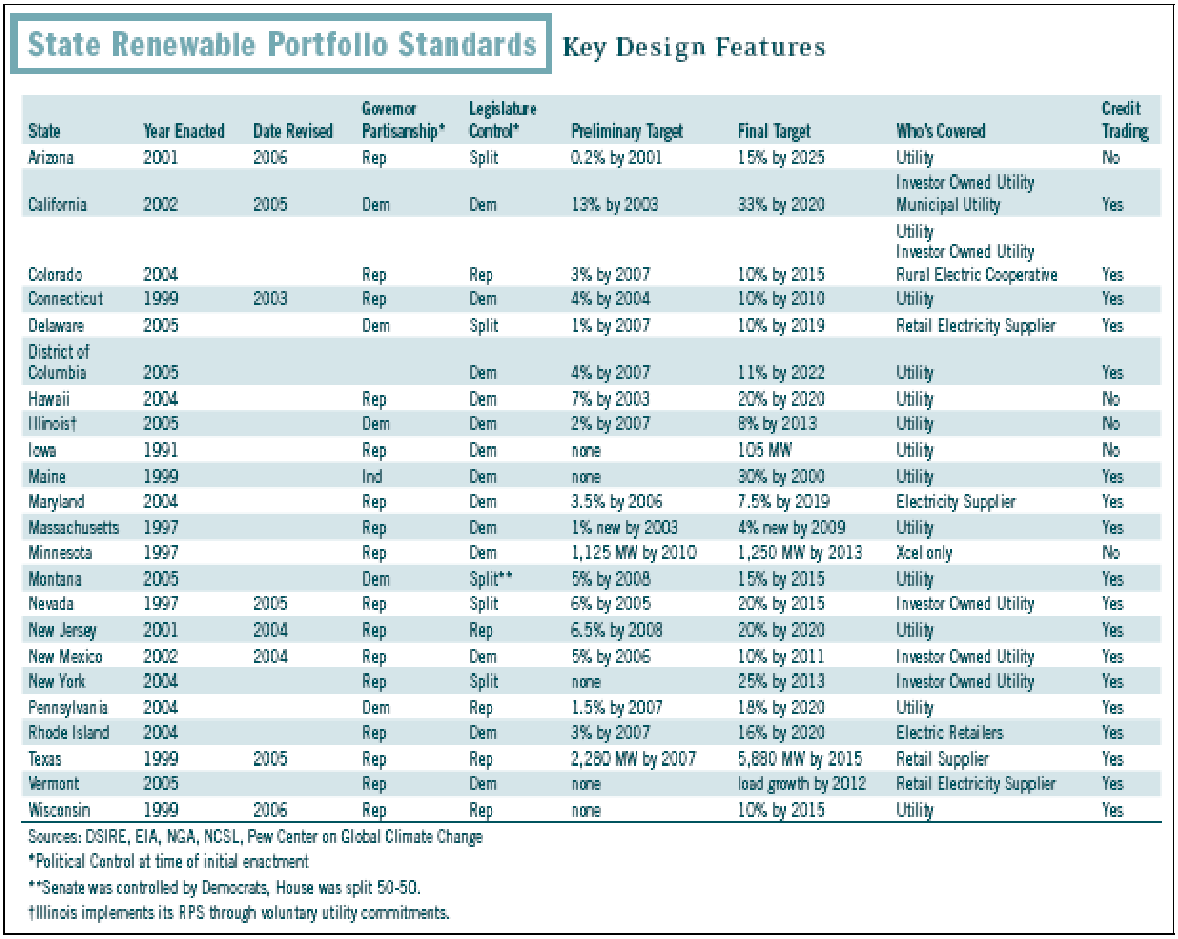
4.2 Renewable Portfolio Standard for Ohio

Although there is a significant potential for the development of renewable energy in the future, the current biomass use in commercial electricity generation has been less than 3 percent at national level, while it is less than 1 percent in Ohio (Table 3). Without significant and sustained policy incentives for renewable energy, it will be too little too late for its increased use to have any positive impact on climate change (PEW, 2004). Among many other viable policy options, a renewable portfolio standard (RPS) has been discussed and endorsed by several states and numerous organizations (NRDC, 2005 and PEW 2004). A RPS will require electricity generators/providers to include a minimum level of renewable energy sources in the electricity mix. More than 20 states have passed renewable portfolio standards that require utilities to generate a percentage of electricity from clean energy resources (Table 26). There have been several policy debates for a national standard that would require 20 percent of the country's electricity to come from renewables by 2020 (NRDC, 2005, NREL, 2004). Supporters argue that a federal renewable portfolio standard will provide the nation with the benefits of using clean energy resources. Since renewable energy resources are becoming cost competitive, portfolio standards help bring consumers clean and renewable energy at affordable rates.

Table 26 and Figure 18 present various levels of state RPS across the nation. California has the most aggressive goal of achieving 33 percent of RPS by 2020, while states like Maine, New York, Nevada, and New Jersey have set RPS at 20 percent or more levels to be accomplished by 2020 (Rabe, 2006). Several other states have 10 percent or more RPS goals to be met by 2010 or later. Based on these RPS levels in various states in the country, this study has developed two RPS scenario for Ohio:

- Achieve 5 percent RPS level by 2030
- Achieve 10 percent RPS level by 2030

There are two reasons for choosing a modest level of RPS for Ohio as compared to other states. One, the current level of renewable electricity generation is less than one percent in the state. Two, this study only takes biomass into account for renewable electricity option. The goal of an RPS in Ohio can be increased to a higher level by including other renewable energy resources like wind, solar, geothermal, and hydro.



State Renewable Portfolio Standards Key Design Features

State	Year Enacted	Date Revised	Governor Partisanship*	Legislature Control*	Preliminary Target	Final Target	Who's Covered	Credit Trading
Arizona	2001	2006	Rep	Split	0.2% by 2001	15% by 2025	Utility	No
California	2002	2005	Dem	Dem	13% by 2003	33% by 2020	Investor Owned Utility Municipal Utility	Yes
Colorado	2004		Rep	Rep	3% by 2007	10% by 2015	Utility Investor Owned Utility Rural Electric Cooperative	Yes
Connecticut	1999	2003	Rep	Dem	4% by 2004	10% by 2010	Utility	Yes
Delaware	2005		Dem	Split	1% by 2007	10% by 2019	Retail Electricity Supplier	Yes
District of Columbia	2005			Dem	4% by 2007	11% by 2022	Utility	Yes
Hawaii	2004		Rep	Dem	7% by 2003	20% by 2020	Utility	No
Illinois†	2005		Dem	Dem	2% by 2007	8% by 2013	Utility	No
Iowa	1991		Rep	Dem	none	105 MW	Utility	No
Maine	1999		Ind	Dem	none	30% by 2000	Utility	Yes
Maryland	2004		Rep	Dem	3.5% by 2006	7.5% by 2019	Electricity Supplier	Yes
Massachusetts	1997		Rep	Dem	1% new by 2003	4% new by 2009	Utility	Yes
Minnesota	1997		Rep	Dem	1,125 MW by 2010	1,250 MW by 2013	Xcel only	No
Montana	2005		Dem	Split**	5% by 2008	15% by 2015	Utility	Yes
Nevada	1997	2005	Rep	Split	6% by 2005	20% by 2015	Investor Owned Utility	Yes
New Jersey	2001	2004	Rep	Rep	6.5% by 2008	20% by 2020	Utility	Yes
New Mexico	2002	2004	Rep	Dem	5% by 2006	10% by 2011	Investor Owned Utility	Yes
New York	2004		Rep	Split	none	25% by 2013	Investor Owned Utility	Yes
Pennsylvania	2004		Dem	Rep	1.5% by 2007	18% by 2020	Utility	Yes
Rhode Island	2004		Rep	Dem	3% by 2007	16% by 2020	Electric Retailers	Yes
Texas	1999	2005	Rep	Rep	2,280 MW by 2007	5,880 MW by 2015	Retail Supplier	Yes
Vermont	2005		Rep	Dem	none	load growth by 2012	Retail Electricity Supplier	Yes
Wisconsin	1999	2006	Rep	Rep	none	10% by 2015	Utility	Yes

Sources: DSIRE, EIA, NGA, NCSL, Pew Center on Global Climate Change

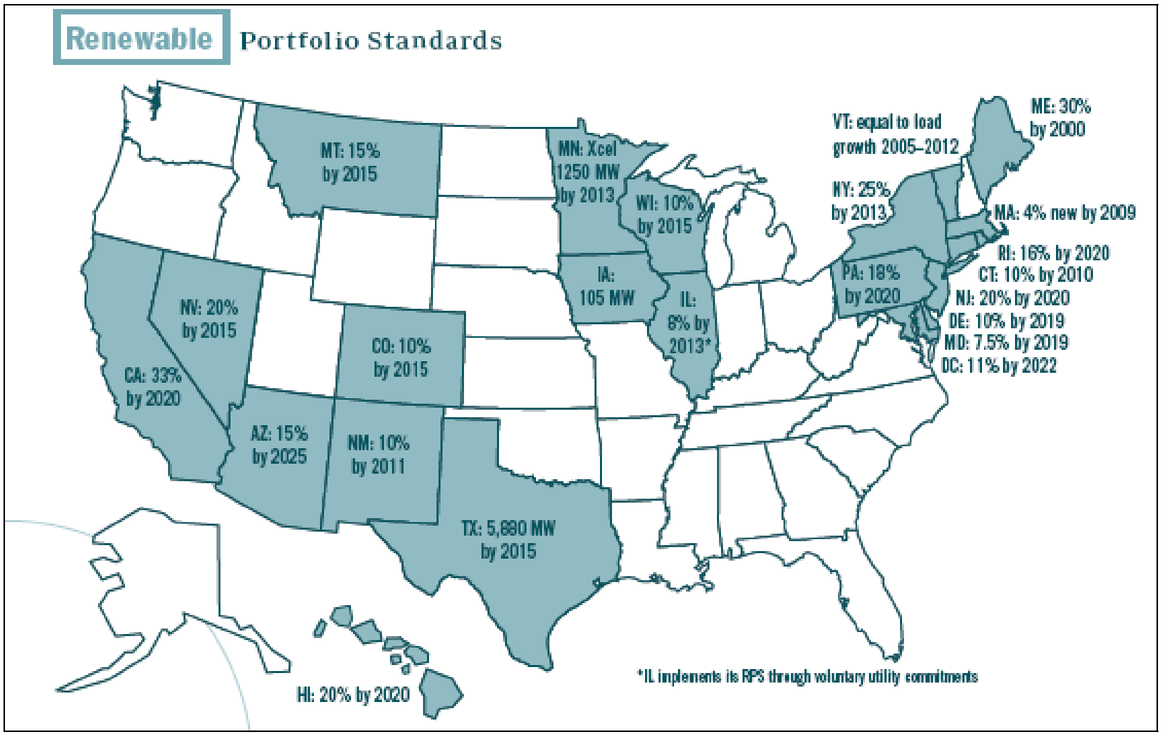
*Political Control at time of initial enactment

**Senate was controlled by Democrats, House was split 50-50.

†Illinois implements its RPS through voluntary utility commitments.

(Source: Rabe, 2006)

Table 26. State Renewable Portfolio Standards



(Source: Rabe, 2006)

Figure 18. State Renewable Portfolio Standards

4.3 Caps on Carbon Dioxide Emissions

Scientific communities around the world believe that human activities that generate GHG emissions are responsible for global climate change (IPCC, 2007; Hawkins, 2004; PEW, 2007; NRDC, 2005; USC, 2004). As a result of these global environmental concerns, the issue of GHG emissions has sparked serious carbon policy discussions both at the national and international levels. Several states in the U.S. have already initiated efforts to reduce CO_2 emissions by 10 percent below 1990 levels by 2020 and achieve up to 80 percent reduction by 2050 (Table 27). Based on the information on Table 27 and Table 28, this study will develop two scenarios of caps on CO_2 emissions for Ohio: achieve 10 and 15 percent below 2002 levels by 2030.

In the U.S., the electric power sector is responsible for 40 percent of total energy-related CO_2 emissions (DOE/EIA, 2006). Carbon dioxide emissions from the U.S. electric power sector increased by 2.8 percent (65.6 million tons), from 2,309.4 million tons in 2004 to 2,375.0 million in 2005 (DOE/EIA-0573, 2005). Carbon dioxide emissions from the electric power sector have grown by 32 percent since 1990, while total carbon dioxide emissions from all energy-related sources have grown by 19 percent (DOE/EIA, 2005). However, power companies are highly unlikely to coordinate their efforts to mitigate CO_2 emissions without a mandatory carbon policy. It is recommended that a regulatory timetable be established for reducing CO_2 emissions so that the power sector can smoothly transition to low-carbon electricity generation (Morgan, Apt, and Lave, 2005).

At the 2006 conference on "Ohio's Response to Federal Environmental Law" at The Ohio State University, most delegates and participants were in agreement that a carbon policy of some sort would be mandated in Ohio and/or nationwide in the near future. Furthermore, the director of Ohio Environmental Protection Agency stated that the question is not whether a CO_2 cap will become a law, but rather, when. The conference discussions concluded that Ohio's policy makers and energy stakeholders should start preparing for a low-carbon energy future, otherwise the costs could quickly be overwhelming to the state's economy.

Entity	**Target**	**Notes and Source**
Arizona: State-wide	2000 levels by 2020 50% below 2000 by 2040	Executive Order 2006-13
California: State-wide	2000 levels by 2010 1990 levels by 2020 80% below 1990 by 2050	Executive Order S-3-05
California: Major industries state-wide	1990 levels by 2020	AB 32
Connecticut: State-wide	1990 levels by 2010 10% below 1990 by 2020	Connecticut Climate Change Action Plan
Maine: State-wide	1990 levels by 2010 10% below 1990 by 2020 75-80% below 2003 long-term	LD 845 (HP 622)
Massachusetts: State-wide	1990 levels by 2010 10% below 1990 by 2020 75-85% below 1990 long-term	Massachusetts Climate Protection Plan of 2004
Massachusetts: Electric Utilities	10% below 1997-1999	CO_2 target only. 310 CMR 7.29
New Hampshire: State-wide	1990 levels by 2010 10% below 1990 by 2020 75-85% below 2001 long-term	The Climate Change Challenge
New Hampshire: Electric Utilities	1990 levels by 2006	CO_2 target only. HB 284
New Jersey: State-wide	3.5% below 1990 by 2005	Administrative Order 1998-09
New Mexico: State-wide	2000 levels by 2012 10% below 2000 by 2020 75% below 2000 by 2050	Executive Order 05-033
New York: State-wide	5% below 1990 by 2010 10% below 1990 by 2020	State Energy Plan of 2002
Oregon: State-wide	Stabilize by 2010 10% below 1990 by 2020 75% below 1990 by 2050	Oregon Strategy for Greenhouse Gas Reductions
Rhode Island: State-wide	1990 levels by 2010 10% below 1990 by 2020	Rhode Island Greenhouse Gas Action Plan
Vermont: State-wide	1990 levels by 2010 10% below 1990 by 2020 75-85% below 2001 long-term	
Regional Greenhouse Gas Initiative: CO_2 emissions from power plants	Cap emissions at current levels in 2009 Reduce emissions 10% by 2019.	Pew Center summary
New England Governors and Eastern Canadian Premiers: Regional economy-wide	1990 levels by 2010 10% below 1990 by 2020 75-85% below 2001 long-term	Climate Change Action Plan of 2001

(Source: http://www.pewclimate.org/)

Table 27. United States - State & Regional Goals for CO2 caps

Entity	***Target***	***Notes & Source***
Climate Stewardship Act of 2003 (McCain-Lieberman) SA. 2028	2000 levels by 2010	As voted on 8/2003 Pew Center Analysis
Climate Stewardship Act of 2003 (McCain-Lieberman) S. 139	2000 levels by 2010 1990 levels by 2016	As introduced 1/2003
Clean Power Act of 2005 (Jeffords) S.150	16% below 2000 levels by 2010	CO_2 from electric generation sector. As introduced 1/2005
Climate and Economy Insurance Act of 2005 (Bingaman)	2.4% yearly reduction in *intensity* during 2010-2019 2.8% yearly reduction in *intensity* during 2020-2024	Pew Center Analysis
Strong Economy and Climate Protection Act of 2006 (Feinstein) **discussion draft**	2006 levels through 2010 0.5% yearly reduction during 2011-2015 1% yearly reduction during 2016-2020 7.25% below current levels in 2020	Discussion draft announcement 3/2006
Clean Air Planning Act of 2006 (Carper) S.2724	2006 levels in 2010-2014 2001 levels in 2015	CO_2 from electric generation sector. As introduced 5/2006
Safe Climate Act of 2006 (Waxman) H.R.5642	2009 levels in 2010 1990 levels in 2020 80% below 1990 levels in 2050	As introduced 7/2006
Global Warming Pollution Reduction Act (Jeffords-Boxer) S.3698	1990 levels in 2020 27% below 1990 by 2030 53% below 1990 by 2040 80% below 1990 levels in 2050	As introduced 7/2006
Global Warming Reduction Act of 2006 (Kerry-Snowe) S.4039	15% below 2010 levels by 2020 65% below 2000 levels by 2050	As introduced 9/2006
United States – Bush Administration	***Target***	***Notes & Source***
Voluntary "greenhouse gas intensity" target for the U.S.	18% below 2002 *intensity* levels by 2012	Announced 2/14/2002 Pew Center Analysis

(Source: http://www.pewclimate.org/)

Table 28. United States - Proposed Federal Legislation

4.4 Taxes on Carbon Dioxide Emissions

One feasible policy option that can be used effectively to mitigate GHG emissions is a tax on CO_2 emissions. It is an example of a pollution tax, also referred as a Pigouvian tax (named after economist Arthur Pigou) that addresses a negative externality of a resource use (Kennedy and Laplante, 2000). It is primarily based on the economic principle that prices of goods and services should reflect or "internalize" all of the societal costs (such as pollutants) that production of the goods or services imposes on society. The prices of gasoline, electricity and fuels in general do not include many of their societal costs, particularly their impact on global warming. A tax on CO_2 emissions offers an incentive for producers of such externalities or societal costs to reduce pollution. In addition, the revenues generated from it can be used to offset the negative impacts of the pollution and invest in cleaner and renewable technologies.

A recent study carried out by the American Consumer Institute suggests that a carbon tax may be a better policy option to reduce CO_2 emissions than a cap and trade option. A tax on CO_2 emissions will impose a cost to businesses and industries requiring them to conserve energy as well as invest in more efficient technologies, both of which actually reduce the CO_2 output, thus achieving the goal of lowering GHG emissions. Carbon cap and trade policy has been criticized for its complexity and high transaction costs. Many leading economists, policy makers, and even industry professionals support a tax over a cap and trade system. In April 2005, Paul Anderson, CEO and Chairman of Duke Energy, proposed to initiate a carbon tax (http://makower.typepad.com). Economist Charles Komonoff and attorney Dan Rosenblum launched a Carbon Tax Center to demonstrate how effectively the tax policy can be implemented to mitigate CO_2 emissions and reduce global warming (www.carbontax.org). Several economic models have predicted the values for GHG reductions, ranging from \$25 to \$150 per ton of CO_2. However, most of them are based on a value between \$25 and \$50 per ton of CO_2 (www.co2e.com). Therefore, this study develops two tax model scenarios: \$25 and \$50 tax per ton of CO_2 emissions.

5. Summary

This chapter describes the model structure of OH-MARKAL, which is based on the Reference Energy System (RES). The RES for OH-MARKAL is developed to establish the flow of the primary energy supply (coal, biomass, natural gas, nuclear energy, etc.) via various processes and paths (technologies) to their final destination of sector-wise demand/use of electricity. The electricity demand in OH-MARKAL is derived from three principal sectors: residential, commercial, and industrial. The RES discussion also included the four main technologies to be employed in the model.

All the data specifications and model assumptions were presented followed by the discussion on OH-MARKAL model's strengths and limitations. The data for OH-MARKAL was compiled from available national and state sources, with the research data categories extensively discussed under four broad themes: biomass feedstock and cofiring power plants; coal and other primary fuel sources; electric power plants; and electricity demands and forecasts. The data for the model were organized in various Excel spreadsheets and developed into a template workbook. The various model scenarios to be addressed by the research objective of this study were also formulated. Finally, rationale for selecting different model scenarios were also presented and compared to similar efforts being taken in several other states in the nation. To meet the research goals of this study, numerous model runs were conducted and their results on primarily electricity price, use of primary energy fuels, and emissions levels will be analyzed and discussed with pertinent policy implications in Chapter 4.

CHAPTER 4

MODEL RESULTS AND POLICY IMPLICATIONS

In Chapter 3, the data and model specifications of OH-MARKAL were presented and discussed. Model specifications of electric power generation plants in Ohio were defined at their unit level in terms of all costs associated with the unit, including the levels of various primary fuels intake and emissions. The final demand for electricity was represented by three primary sectors: residential, commercial, and industrial. The resulting research study completed a fully functioning OH-MARKAL model for the Electric Power Sector of Ohio. This chapter highlights the key model results of various scenarios, beginning with the calibration of OH-MARKAL model to the base year of 2002. The main objective of the model calibration was to establish a viable base case scenario so that the model can be used effectively to analyze proposed policy scenarios and examine their environmental and policy impacts on Ohio's energy future. After successfully calibrating the model, all scenarios proposed in Chapter 3 are analyzed in this chapter and the results are discussed in relation to their potential policy implications for Ohio.

1. Model Calibration for the Base Year 2002

It is important to calibrate the model for the base year, as it validates all data and model specifications that have been applied in the model to replicate the "business-as-usual" results for Ohio. Only then can the model be used effectively to analyze proposed model scenarios to study their environmental and policy implications on the energy future of Ohio. The base case scenario is the representation of Ohio's current status of electricity generation to meet demands from residential, commercial, and industrial sectors, without any new policies in the system as would be introduced in the model later, such as biomass cofiring or a cap on CO_2 emissions. In the base case scenario, although the model has an option to use biomass feedstock for cofiring with coal, it is expected that all cofiring plants will only use coal (without biomass feedstock), since biomass feedstock is financially more costly than coal.

During model calibration, specific efforts are taken to match the results of the base case scenario as close as possible to Ohio's data in 2002. For example, the model will require at least 2 percent of electricity generation from natural gas, since most natural gas plants are peaking plants. Similarly, the contribution from nuclear power plants is limited to 8 percent of total electricity generation based on the current contribution of nuclear power plants in Ohio (PUCO, 2002). These adjustments in the electricity generation mix were necessary because the natural gas plants were not operating in the base year of 2002. Coal power plants were generating electricity even for most of the gas peaking plants, as the model found it cheaper to generate electricity from coal than from natural gas, which is comparatively higher in price. On the other hand, nuclear power plants were operating at full capacity and generating more than 10 percent electricity in 2002, under the model. The upper limit for nuclear power plants becomes equally necessary for CO_2 tax and cap scenarios, because the model would otherwise select an unexpectedly high level of nuclear power generation in Ohio, as nuclear fuel is cheaper in terms of energy content and has zero emission levels.

The model calibration process starts with specifying accurately the energy system based on the existing historic data on energy balances (total electricity generation and consumption), emissions associated with each primary fuel, and fuel prices for the base year 2002. The demand projections for electricity based on the PUCO forecasts, proposed new power plants (new technologies) and emission control devices, as well as forecasts for various fuel prices, which were specified in the base-model system. Once the model is properly specified and all the data are incorporated in the energy system of OH-MARKAL, the model becomes ready for a base case scenario run.

The comparison between the 2002 historic data and the OH-MARKAL results on net electricity generation by fuel type are presented in Table 29. The results of base case calibration of the model are close and similar to the historic data of electricity generation for the year 2002. In addition, the results of the base case scenario are analyzed to validate the existing energy system that depicts a balance of electricity generation and its demand throughout the model periods (Table 30). The base case results on generation mix for the year 2002 does not vary much in model year 2029, except in terms of the renewable electricity generation that increases to 2.17 percent in 2029 from 0.4 percent in 2002 (Table 30). The coal power plants in the model will not be able to meet the growing demand for electricity due to a capacity constraint after model year 2020. Hence, the new proposed biomass power plants start generating electricity after 2020 to meet the growing electricity demand that is not met by the existing coal power plants. Thus, the proportion of renewable power of total electricity generation increases to 2.17 percent by year 2029.

Data Source	Coal	Nuclear	Natural Gas	Oil	Renewable (Biomass)
EIA, DOE 2002	90.4	7.4	1.3	0.3	0.6
Base-Case Scenario (OH-MARKAL result)	89.6	8.0	2.0	0.0	0.4

Table 29. Electricity Net Generation by Fuel Type (percent)

The marginal price of electricity (generation cost at 2002 dollar value) is 2.5 cents/KWh in 2002 and it increases to 4.02 cents/KWh in 2029 (Table 39). Without any new environmental or energy policy in Ohio, the base case model suggests that the primary fuel mix for power generation will change little, as coal will be used to produce 88.17 percent of electricity in 2029 as compared to 89.60 in year 2002. However, the CO_2 emissions will increase from 151.854 in 2002 to 178.823 million tons in 2029, an 18 percent increment as compared to the 2002 level under the base case scenario (Table 40).

As explained in Chapter 3, the model assumes that all the coal power plants in Ohio will have emission control devices installed by year 2012, thus making the emission levels for SO_2, NO_x, and Hg well under the permissible levels. The results for SO_2, NO_x, and Hg emission levels under all scenarios are presented in Table 41, Table 42, and Table 43 to show what impact, if any, biomass cofiring may have on emission levels of these pollutants. The results indicate that biomass cofiring does not reduce NO_x emissions. However, 10 percent biomass cofiring would reduce SO_2 and Hg by 1.5 and 3 percent respectively.

The emission levels for SO_2, NO_x, and Hg even in the base case scenario are well under permissible levels, because all Ohio's coal power plants are planning to install emission control devices for both SO_2 and NO_x by 2012. The impact of biomass cofiring on the reduction of SO_2 will be more significant in a coal power plant that does not have an emission control device. Hence, Ohio's power industry will be able to meet all the emissions standards set for SO_2, NO_x and Hg after 2012. Therefore, the principal focus of this research study is directed towards the reduction of CO_2 emissions in Ohio through the varying model scenarios.

2. Results from OH-MARKAL Model Scenarios

The OH-MARKAL model developed four specific model scenarios to analyze various aspects of biomass cofiring in Ohio. These scenarios are largely based on the existing and proposed policies on energy, environment, and climate change at state, national, and international levels. The rationale of selecting these particular model scenarios has been described in Chapter 3. As indicated earlier, the OH-MARKAL is dynamic and flexible, capable of including other sources of renewable energy such as wind, solar, and hydro power to perform additional energy analyses for Ohio. However, the current model scenarios developed in this study primarily focuses on cofiring biomass feedstock in selected existing coal power plants, including new cofiring and biomass power plants, and their subsequent impact on CO_2 emissions, electricity price, and renewable electricity generation in Ohio.

The results of the model suggest that policy interventions are imperative to make biomass cofiring competitive with coal. Various levels of biomass feedstock use in existing cofiring power plants occur under the RPS, CO_2 Cap, and Tax scenarios in order to meet the constraints imposed by the model. The results also indicate that the proposed biomass cofiring in selected coal power plants and new biomass plants will achieve about 7.44 percent renewable electricity generation in Ohio. The 7 percent level of electricity from renewable biomass reduces the CO2 emissions by 6 percent (Table 40). Furthermore, the study results indicate that biomass feedstock supply at the regional level is sufficient to meet the demand of feedstock from cofiring and proposed new biomass plants in all seven regions (Table 45).

The marginal prices of electricity do not vary much between base case vs. Renewable Portfolio Standard (RPS) of 7 percent level scenarios. Therefore, Ohio can reduce CO_2 emissions by 6 percent without a significant rise in electricity price. However, the marginal price of electricity increases by more than fourfold, once the model is programmed to reduce CO_2 emissions by 15 percent in 2029 as compared to 2002 levels (Table 39). The reason for this high price of electricity is the lack of biomass cofiring plants' capacity to generate more than 7.44 percent of renewable electricity from biomass sources. Hence, the model must replace coal with the more expensive natural gas, which has lower CO_2 emissions than coal, in order to achieve the 15 percent reduction of CO_2 emissions. The model also analyzes a CO_2 tax of a \$100 per ton scenario and the results show a substantial reduction of CO_2 emissions, close to 15 percent of 2002 levels by the end of the model period. With the current data specifications in the model, it is infeasible to generate more than 7.44 percent of renewable electricity and achieve more than a 15 percent reduction of the CO_2 emissions level.

The following is the list of the four principal model runs. Their specific results, with their potential policy implications are described in the sections below:

- ***Levels of Biomass Cofiring in Coal Power Plants***
- ***Renewable Portfolio Standard for Ohio***
- ***Caps on Carbon Dioxide Emissions***
- ***Taxes on Carbon Dioxide Emissions***

2.1 Levels of Biomass Cofiring in Coal Power Plants

The model scenarios of different levels of biomass cofiring were developed specifically to analyze the supply capabilities of biomass feedstock in Ohio, not as a mandated policy option. One of the major drawbacks of biomass feedstock is its bulkiness in nature, which limits the transportation distance from its sources to prospective coal power plants (Haq, 2004). To address this issue, Ohio is divided into seven regions (Figure 16), so that the supply of biomass feedstock to potential cofiring coal plants is within a 75-mile distance in each region. The price of biomass feedstock used in the model includes transportation costs up to 75 miles. The inter-regional supply of biomass was not included in the model. However, the option was kept open, if needed, simply by charging extra transportation costs based on the miles between the regions. Similarly, interstate supply of biomass feedstock from neighboring states has also not been considered in the current model, but can be added later if needed.

All regions have currently one or more operating cofiring coal power plants, except Region 7 (Figure 16). Regions 2, 3, 4, and 5 have three or more cofiring plants while Regions 1 and 6 have only one each. This indicates that Regions 1, 6, and 7 will be potential sites for future cofiring or biomass power plants, given the biomass supply and limited power plants in these regions. Similarly, if we consider the availability of biomass feedstock supply in Ohio, Regions 1, 7, and 5 have higher levels of supply than the rest of the region (Table 12). If both existing cofiring plants and the supply of biomass feedstock are taken into account, Regions 1 and 7 will be the preferred choices for new cofiring or biomass plants in Ohio.

Recent reports have indicated that biomass cofiring up to 20 percent on a thermal basis could be viable on both economic and technical bases for most coal power plants (DOE/EERE, 1997; FTO, 2004; and Grabowski, 2004). Based on these reports, the two scenarios of 10 and 15 percent levels of biomass cofiring with coal were developed in this study to analyze if the regional supply of feedstock would be a limiting factor. The results from this scenario help establish an appropriate level for biomass cofiring for the proposed model scenarios on RPS, CO_2 caps and taxes. A fixed level of biomass cofiring for these scenarios will be selected in order to take into account the aggregate level of renewable electricity generation from selected cofiring coal plants. In addition, under this scenario, the impacts of biomass cofiring are examined for the electricity generation resource mix, the marginal electricity price, the emission levels of CO_2, and the use of coal and biomass feedstock for Ohio.

The results of both 10 and 15 percent levels of biomass cofiring indicated that the supply of biomass feedstock met the demand of biomass feedstock from cofiring coal power plants in each region. Hence, no inter-regional transportation of feedstock was necessary. The renewable electricity in the model comes from existing and new cofiring coal plants, new biomass power plants, and existing hydro plants (Table 11 and Table 21). The existing and new cofiring coal plants contribute 2.43 and 3.33 percent of renewable electricity to total electricity generation at 10 and 15 percent biomass cofiring levels, respectively. However, the total renewable electricity at the 10 percent biomass cofiring level is 4.51 percent of total electricity generation while coal's contribution is 85.84 percent (Table 31). Similarly, at 15 percent cofiring level, total renewable electricity contributes slighter higher at 5.41 percent and coal's contribution becomes 84.94 percent of total electricity generation (Table 32), in comparison to 2.17 percent of renewable electricity and 88.17 percent from coal under base case scenario (Table 30 and).

This translates directly into reduced use of coal (1779.18 and 1762.58 trillion BTU) and increased use of biomass feedstock (78.3 and 98.2 trillion BTU) under 10 and 15 percent cofiring scenarios than that of the base case scenario where 1832.5 tBTU of coal and 26.5 tBTU of biomass feedstock were used (Table 45 and Table 46). Hence, with 10 and 15 percent levels of biomass cofiring, coal usage was reduced by 2.9 and 3.8 percent while the feedstock increased by about 2.95 and 3.71 times respectively, as compared to base case scenario. Due to reduction in coal use under both scenarios, the CO_2 emissions are correspondingly mitigated by 5.53 and 7.22 million tons at 10 and 15 percent biomass cofiring levels respectively, as compared with the base case scenario in 2029 (Table 40). The level of CO_2 emissions are 173 and 171 million tons under 10 and 15 percent of biomass cofiring scenarios in 2029, while it is 179 million tons under base case (Table 40).

In terms of electric price, no significant increases were observed under these scenarios. Marginal electricity prices will be only 4.09 and 4.14 cents/KWh in 2029 under the 10 and 15 percent biomass cofiring scenarios as compared to 4.02 cents/KWh in base case (Table 39). With just a slight increase in the marginal electricity price, reductions of 5.53 and 7.22 million tons of CO_2 emissions (compared with the base case scenario) can be achieved respectively in 2029, under 10 and 15 percent biomass cofiring scenarios (Table 40).

As explained in Chapter 3, several coal firing plants have successfully conducted biomass cofiring test runs that indicated noticeable reductions in CO_2 and SO_2 emissions levels (FTO, 2004). Grabowski (2004) reports that although all the NETL/DOE cofiring projects were technically successful, none of the participating utilities are still cofiring at present. However, with a policy to mitigate CO_2 emissions to a certain level, these utilities may favorably view biomass cofiring as an option. My interviews with Ohio's utility professionals indicate that they will consider cofiring as an option if there is a regulatory requirement in place either for a CO_2 cap or RPS. Therefore, the results of biomass cofiring scenarios of this study indicate that the supply of biomass feedstock in Ohio can support up to 15 percent level biomass cofiring in these selected coal power plants in Ohio.

For the next three scenarios of this study (namely, renewable portfolio standards, caps and taxes on $C0_2$ emissions), the 10 percent level of biomass cofiring is selected as the standard cofiring level, with the assumption that it will be easier to track and take account of the impact of biomass feedstock uses on the electricity generation mix, electric price and emission level. For the utility power plants, a 10 percent level of cofiring would require less biomass feedstock, resulting in easier and cheaper transportation, handling, and storage costs as compared to a 15 percent level of cofiring.

2.2 Renewable Portfolio Standard for Ohio

During the electric power restructuring procedure in Ohio in 1999, a renewable portfolio standard (RPS) was under consideration along with other environmental provisions such as net metering and environmental disclosure of fuel mix. However, the RPS was not included in the final Ohio restructuring legislation. This study develops scenarios to include the various levels of a RPS for Ohio, specifically to evaluate how much renewable electricity can be generated by using biomass feedstock to contribute toward an RPS. Initially, model scenarios for 5 and 10 percent RPS levels were examined. These results showed that a 10 percent RPS level was not feasible in Ohio, mainly due to the plant capacity constraint of cofiring and biomass power plants. By doing sensitivity analyses on the RPS levels, it was determined that the maximum level of an RPS that can be achieved is 7.44 percent by year 2029, given the capacities of cofiring and biomass plants specified in the model. Hence, the 5 and 7 percent levels of RPS scenarios were developed and analyzed in this study.

This level of a RPS for Ohio is fairly low as compared with other states whose goals like that of California are as high as 33 percent by 2020, to lower percentages of 15- 25 by 2015 to 2020 of states such as Arizona, Montana, Nevada, New Jersey, New York, Pennsylvania, and Rhode Island (Table 26). However, it is important to note that this 7.44 percent of RPS level is only coming from using biomass feedstock and small capacity of existing hydro power (Table 44). Ohio could potentially meet higher levels of a RPS similar to those states (mentioned above), if other renewable sources of energy, like wind, solar, and hydro power are used in addition to biomass feedstock. The recent report from the Ohio Department of Development and National Renewable Energy Laboratory suggests that Ohio could generate at least 10-20% of Ohio’s electricity from wind by 2020, powering millions of Ohio homes and realizing significant environmental and economic benefits (Elliott/NREL, 2007).

The following section presents the model results of 5 and 7 percent levels of RPS for Ohio with their potential economic, environmental, policy implications:

- Renewable Electricity (Table 44):
    - 5 Percent RPS: contribution to renewable electricity was 2.48 percent from new biomass power plants (and existing hydro) and 2.52 percent from existing and new cofiring coal plants (Table 33).
    - 7 Percent RPS: contribution to renewable electricity was 4.50 percent from new biomass power plants (and existing hydro) and 2.50 percent from existing and new cofiring coal plants (Table 34).

- Biomass Feedstock use (Table 45): 86.3 and 124.2 trillion BTU (tBTU) of biomass feedstock use under 5 and 7 percent RPS scenarios respectively, as compared to 26.5 tBTU of coal under base case scenario. This indicates an increase in level of use by about 3.26 and 4.69 times as compared to base case.
- Electricity from Coal: 85.35 and 83.35 percent from 5 and 7 percent RPS scenarios respectively (Table 33 and Table 34), as compared to 88.17 percent under the base case scenario.
- Coal Use (Table 46): 1768.9 and 1725.6 tBTU of coal use under 5 and 7 percent RPS scenarios respectively, as compared to 1832.5 tBTU of coal under base case scenario: reduction of 3.47 and 5.83 percent of coal use.
- CO_2 Emission Level (Table 40): 172.3 and 167.9 million tons in 2029 under 5 and 7 percent RPS scenarios respectively, as compared to 178.8 million tons under base case scenario. The data indicates reduction of 3.6 and 6.1 percent respectively, as compared to base case scenario.
- Marginal Price of Electricity (Table 39): this suggests a slight increase in the marginal pricing, with 4.07 and 4.16 cents per KWh in 2029 under 5 and 7 percent RPS scenarios respectively, as compared to 4.02 cents per KWh under base case scenario.

The results from the RPS scenario suggest that Ohio can generate 7 percent of renewable electricity without a significant increase in electricity price. This will also have a positive impact on CO_2 emissions that can be reduced by 6.5 and 8.8 million tons in 2029 under 5 and 7 percent RPS scenarios respectively, as compared to the base case scenario. Furthermore, the supply of biomass feedstock in each region will be enough to sustain a 7 percent RPS, so that inter-regional transportation of biomass feedstock will not be necessary. However, if the capacity of cofiring and biomass power plants increases significantly in the future, the supply of biomass feedstock could potentially be a limiting factor and transporting the feedstock to neighboring regions may need to be added in the model.

If policy initiatives in the state focused on increasing renewable electricity generation, then a RPS appears to be a sustainable policy option to generate the desired level of renewable electricity in Ohio. The current model specifications on cofiring and new biomass power plants indicate that biomass feedstock could provide up to 7.44 percent of renewable electricity in Ohio. However, in order to achieve higher RPS levels, Ohio needs to include other sources of renewable energy such as wind, solar, or hydro into its electricity generation resource mix.

2.3 Caps on Carbon Dioxide Emissions

While the link between human generated greenhouse gas (GHG) emissions and global warming is a hotly debated topic, it has now been accepted in scientific communities around the world that human generated GHG emissions indeed correlate with global warming (IPCC, 2007). As a result of these global environmental concerns, the issue of GHG emissions has sparked serious carbon policy discussions both at the national and international levels. Several states in the U.S. have already initiated efforts to reduce CO_2 emissions by 10 percent below 1990 levels by 2020 and achieve up to 80 percent reduction by 2050 (Table 27). In the U.S., the electric power sector is responsible for 40 percent of total energy-related CO_2 emissions (DOE/EIA, 2006). However, power companies are highly unlikely to coordinate their efforts to mitigate CO_2 emissions without a mandatory carbon policy. It is recommended that a regulatory timetable be established for reducing CO_2 emissions (Morgan, Apt, and Lave, 2005).

One of the possible carbon policies is to require caps on CO_2 emissions not only for electric but also for industrial, commercial, and transportation sectors. For instance, the European Union is a proponent of a carbon caps and trade policy. The following are the advantages of such a policy (Baumert, 1998):

- Assures a certain level of aggregate emissions for which companies/countries trade at market rates.
- Easier to agree on specific emissions reduction levels then tax rates, which may vary widely and may not achieve the level of desired GHG mitigation.
- Allows emissions reductions to take place wherever it is cheaper, regardless of geographic locations, especially since costs associated with climate change have no correlation with the origin of carbon emissions.
- More favorable to private industry since firms can reduce their emissions and gain profit by selling their excess greenhouse gas allowances. If the market for pollution trading works efficiently, it can potentially reduce the emissions level below assigned goals.
- Trading permits could adjust to inflation and external price shocks, while taxes do not.

The OH-MARKAL model is an effective tool to analyze both the economic and environmental impact of a carbon cap policy. Before the results of the carbon cap scenarios are analyzed here, it should be underscored that the only renewable option available at present in the model is biomass feedstock. Substituting coal power by nuclear energy is not considered in the model, since the primary focus on this study was on biomass feedstock. It should also be noted, however, that both carbon caps and tax policies may also favor nuclear power, since it does not have any GHG emissions. With the growing problem of climate change, nuclear power may become an important energy option for the future, especially in the light of advanced nuclear technology developments in recent years. Hence, power from nuclear sources can be a potential research and policy topic for Ohio's energy and environmental future.

The following section presents the model results of two CO_2 cap scenarios, with the goal of achieving a 10 and 15 percent reduction on CO_2 emission levels of 2002 by 2029.

Their potential economic, environmental, and policy implications for Ohio are also discussed:

- Renewable electricity (Table 44): 7.29 and 7.37 percent of renewable electricity are generated under 10 and 15 percent CO_2 cap scenarios respectively, as compared to 2.17 percent of renewable electricity under the base case.
  - Under 10 Percent CO2 Cap: contribution to renewable electricity is 5.3 percent from new biomass power plants (including hydro) and 1.99 percent from cofiring coal plants (Table 35).
  - Under 15 Percent CO_2 Cap: contribution to renewable electricity is 5.34 percent from new biomass power plants (including hydro) and 2.03 percent from cofiring coal plants (Table 36).
- Biomass Feedstock use (Table 45): 126.0 and 127.6 trillion BTU (tBTU) under 10 and 15 percent CO_2 cap scenarios respectively, as compared to 26.5 tBTU of coal under base case scenario. Hence, an increase in levels of biomass use by about 4.75 and 4.82 times as compared to base case.
- Electricity from Coal: 81.66 and 76.72 percent under 10 and 15 percent CO2 cap scenarios respectively (Table 35 and Table 36), as compared to 88.17 percent under base case scenario. Among all scenarios developed in this study, the lowest percentage of electricity from coal is generated under the 15 percent CO_2 cap scenario. However, not all the coal power is replaced by biomass feedstock due to capacity constraints of cofiring coal and biomass power plants. Part of coal power is replaced by natural gas plants since it has lower CO_2 emissions than coal, e.g. natural gas generated about 6 percent more electricity under the 15 percent cap scenario as compared to the base case (Figure 20).
- Coal Use (Table 46): 1500.4 and 1383.22 tBTU of coal use under 10 and 15 percent CO_2 cap scenarios respectively as compared to 1832.5 tBTU of coal use under base case. This significant reduction of coal use by 18.12 and 24.52

percent as compared to base case directly corresponds to reduced level of electricity generation from coal under both cap scenarios.

- CO_2 Emission Level (Table 40): 136.67 and 129.08 million tons in 2029 under 10 and 15 percent CO_2 cap scenarios respectively as compared to 178.8 million tons under base case scenario. The cap scenarios (among all the scenarios developed in this study) provide the highest reduction of CO_2 emissions by 42.15 and 49.74 million tons in 2029 under 10 and 15 percent CO_2 caps respectively, as compared to base case scenario (Figure 28).
- Marginal Price of Electricity (Table 39): 10.03 and 18.33 cents per KWh in 2029 under 10 and 15 percent CO_2 Cap scenarios respectively, as compared to 4.02 cents per KWh under base case scenario. The highest marginal price of electricity is under 15 percent CO_2 Cap scenario, primarily because there is not enough plant capacity to use biomass feedstock to meet the CO_2 cap constraints and hence the electricity is generated by using more expensive natural gas (Figure 29).

As indicated earlier, the caps scenarios will provide the assured level of CO_2 emissions reduction. Hence, if the policy goal is to achieve desired level of CO_2 emissions, this caps option may be a desirable option to consider. The model results conclude that the marginal price of electricity increases significantly under these scenarios, as the cofiring of coal plants and biomass power plants reach their capacities and more expensive natural gas plants start generating electricity to meet CO_2 constraints. This suggests that Ohio needs to address this issue under two options: either increase the plant capacity of cofiring and biomass power plants, or include other sources of renewable energy, such as wind, solar, and hydro power.

While it is critical for Ohio to consider alternative clean energy sources, it is important to underscore that coal will continue to be a principal resource in Ohio's energy future. Any potential carbon policy for Ohio will have major impact on the coal and power industry, since about 90 percent of electricity is generated from coal. Therefore, in addition to developing its renewable energy resources, Ohio needs to invest in clean coal technologies and consider carbon sequestration as an option for the future. Ohio becoming a leader in clean coal technologies is a worthy goal, since coal contributes so significantly toward its economy. Otherwise, if a future policy on CO_2 emission caps or taxes is mandated in Ohio, the costs to the state's economy will increase dramatically.

2.4 Taxes on Carbon Dioxide Emissions

As discussed in Chapter 3, a tax on CO_2 emissions may be an effective policy option that can be used effectively to mitigate GHG emissions. A tax on CO_2 emissions offers an incentive for producers of such externalities or societal costs to reduce pollution. Recent studies, leading economists, policy makers, and even utility industry professionals support that a carbon tax may be a better policy option to reduce CO_2 emissions than a cap-and-trade option.

Former Undersecretary of Commerce for Economic Affairs, Robert Shapiro, and Harvard economist, Richard Cooper also argue that carbon taxes are a more effective way to lower GHG emissions, as they offer the most stable and transparent system for both consumers and industry (Cooper, 2006 and Shapiro, 2007). Unlike the cap-and-trade schemes where geographic relocation of GHG emissions is a potential problem, the universal presence of the carbon tax reduces CO_2 emissions everywhere and improves efficiency. Here are some of the potential advantages of a carbon tax policy (Baumert, 1998; Cooper, 2006; and Shapiro, 2007):

- Raises the price of carbon-based energy, thus providing incentives for the development of new, sustainable and cleaner renewable energy technologies that reduce carbon emissions and increase energy efficiency, until the cost is greater than the tax.
- Does not create the price volatility and administrative problems associated with cap-and-trade.

- Addresses emissions of carbon from every sector, whereas cap-and-trade systems discussed to date have only targeted the electricity industry, which accounts for less than 40% of emissions.
- Carbon tax revenues can be returned to the public through progressive tax-shifting, while the costs of cap-and-trade systems are likely to become a hidden tax as dollars flow to market participants, lawyers and consultants.

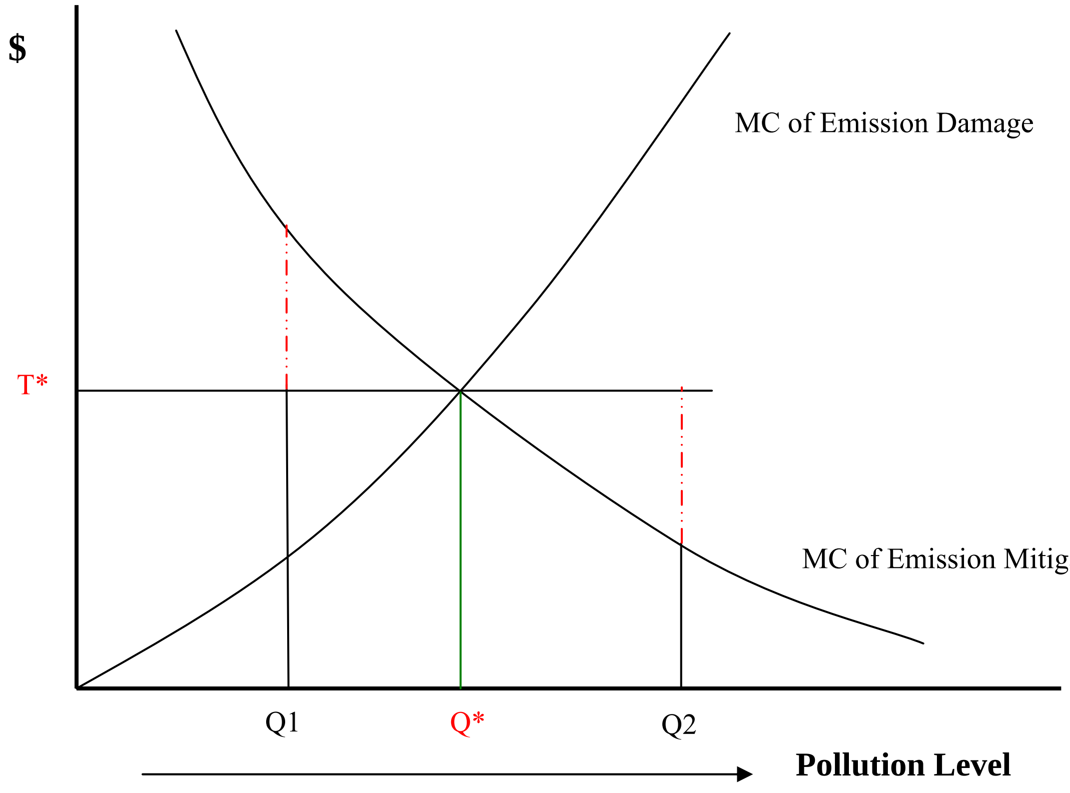


Figure 19. An Optimal CO_2 Emission Tax

As mentioned in the Carbon Caps Section 2.3 of this chapter, a specific tax rate might be difficult to agree upon at the policy level and its quantitative impact on CO_2 emissions may vary, thus not achieving the desired level of GHG mitigation. Though, in theory, an optimal level of carbon tax is easier to calculate by equating the marginal cost of emission mitigation to marginal cost of emission damage (Figure 19), it is complicated to estimate such a number for real world applications. However, such problems can be overcome by revisiting the impact of an initial tax (which should be high enough to provide incentives to tax-avoiding emission reductions) in subsequent years. It will take several years of learning experience to understand the overall impact of the tax in relation to change in GHG emissions (Cooper, 2006). Under the cap-and-trade scenario, it will also probably take about the same number of years to refine the policy, so that the set cap levels have an impact on the climate change.

Several economic models have predicted the values for GHG reductions, ranging from \$25 to \$150 per ton of CO_2. However, most of them are based on a value between \$25 and \$50 per ton of CO_2 (www.co2e.com). Similarly, the two tax model scenarios are also developed with \$25 and \$50 tax per ton of CO_2 in this study. The following are the results and their potential economic, environmental and policy implications for Ohio:

- ➢ Renewable Electricity (Table 44): 5.93 and 7.44 percent of renewable electricity are generated under 25 and 50 dollars per ton CO_2 tax scenarios respectively as compared to 2.17 percent of renewable electricity under the base case. This 7.44 percent is the highest level of renewable electricity generated in comparison to all other model scenarios analyzed by the OH-MARKAL model (Figure 22).
    - 25 dollars per ton CO_2 tax: contribution to renewable electricity is 3.59 from new biomass power plants (including hydro) and 2.34 from cofiring coal plants (Table 37).

  - 50 dollars per ton CO_2 tax: contribution to renewable electricity is 5.17 from new biomass power plants (including hydro) and 2.27 from cofiring coal plants (Table 38).
- Biomass Feedstock use (Table 45): 78.3 and 98.2 trillion BTU (tBTU) under 25 and 50 dollars per ton CO_2 tax scenarios respectively, as compared to 26.5 tBTU of coal under the base case scenario. This shows an increase in level of use by about 2.95 and 3.71 times compared to the base case.
- Electricity from Coal: 84.41 and 82.91 percent under 25 and 50 dollars per ton CO_2 tax scenarios respectively (Table 37 and Table 38), as compared to 88.17 percent under the base case scenario.
- Coal Use (Table 46): 1779.2 and 1762.6 tBTU of coal use under 25 and 50 dollars per ton CO_2 tax scenarios respectively, as compared to 1832.5 tBTU of coal under the base case scenario. Hence, a reduction of 2.9 and 3.8 percent of coal use.
- CO_2 Emission Level (Table 40): 159.3 and 150.66 million tons in 2029 under 25 and 50 dollars per ton CO_2 tax cofiring scenarios respectively, as compared to 178.8 million tons under the base case scenario. Here again, this indicates a reduction of 19.52 and 28.14 million tons, as compared to the base case scenario.
- Marginal Price of Electricity (Table 39): 6.09 and 8.22 cents per KWh in 2029 under 25 and 50 dollars per ton CO_2 tax cofiring scenarios respectively, as compared to 4.02 cents per KWh under the base case scenario.

The results of these tax scenarios indicate that a substantial level of CO_2 mitigation can be achieved without large increases in the price of electricity when compared to CO_2 cap scenarios (Figure 28 and Figure 29). However, the results suggest that highest level of CO_2 reduction is attained under a 15 percent CO_2 cap scenario as compared to rest of the scenarios developed in this study (Figure 26). This OH-MARKAL model cannot be used to compare tax vs. cap scenario, because the results will be the same for both scenarios unless the administrative costs in each scenario can be identified and specified in the model. While running some sensitivity analyses on a carbon tax to compare with a carbon cap, the study indicated that more than \$100 per ton of CO_2 tax is needed to attain similar reductions in the CO_2 level as compared to 15 percent CO_2 caps.

3. Summary

This chapter describes the process of model calibration to validate all data and model specifications, so that the results simulate “business-as-usual” (base case) scenario and match the historic data of year 2002. The base case scenario’s results suggest that coal power plants will not use biomass feedstock for cofiring, because biomass is more expensive than coal and the model will choose coal over biomass to generate electricity. However, new biomass power plants will start generating electricity to meet the growing electricity demand that is not met by coal power plants by the model year 2020. The results further suggest that CO_2 emission levels will increase by 18 percent by 2029 as compared to the 2002 level.

After successful model calibration, various policy scenarios were analyzed to identify key economic and environmental impacts of biomass cofiring in Ohio. The results of all these model scenarios and their relevant policy implications for Ohio were also discussed extensively. The model concluded that rigorous policy interventions are needed to make biomass co-firing competitive with coal. Various levels of biomass feedstock use in cofiring power plants (both existing and new) occur under the RPS, CO_2 caps and taxes scenarios in order to meet the constraint imposed by the model.

The model also suggests that an RPS can be an excellent policy option to generate the desired level of renewable electricity in Ohio. The current model specifications on cofiring and new biomass power plants indicate that biomass feedstock could provide about 7 percent of renewable electricity in Ohio. To achieve higher RPS levels, Ohio needs to include other sources of renewable energy such as wind, solar, or hydro into its electricity generation resource mix. However, if a policy goal is directed towards achieving a certain level of reductions in CO_2 emissions, either a CO_2 cap or tax option should be considered in Ohio.

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others*	tBTU	2.20	2.55	3.25	3.54	3.89	4.23	12.58	15.28	15.75	16.00
	%	0.40	0.45	0.55	0.58	0.64	0.66	1.90	2.22	2.21	2.17
Un-scrubbed Coal	tBTU	247.01	250.50	249.23	247.17	2.77	2.77	0.00	0.00	0.00	0.00
	%	44.99	44.37	41.99	40.83	0.46	0.43	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	76.18	85.77	107.61	120.90	368.46	375.42	387.46	407.87	431.69	455.57
	%	13.88	15.19	18.13	19.97	60.87	58.85	58.41	59.31	60.50	61.80
Cofiring: ** Biomass + Coal	tBTU	168.71	169.24	174.13	173.52	173.47	191.72	196.96	195.73	195.34	194.45
	%	30.73	29.98	29.34	28.66	28.66	30.05	29.69	28.46	27.38	26.38
Coal Sub-Total:	tBTU	491.90	505.51	530.97	541.59	544.70	569.91	584.42	603.60	627.03	650.02
	%	89.60	89.55	89.45	89.46	89.99	89.33	88.10	87.77	87.88	88.17
Natural Gas Plants	tBTU	10.99	11.30	11.88	12.13	12.12	12.77	13.28	13.77	14.29	14.76
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.92	45.16	47.49	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.01	564.52	593.59	605.42	605.28	637.95	663.35	687.67	713.50	737.21
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Note: * Renewable Electricity is coming from existing hydro and biomass power plants.
** Cofiring power plants only use coal under the base case scenario.

Table 30. Electricity Generation by Fuel Type: Base Case Scenario

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others	tBTU	2.20	2.58	3.25	3.54	3.89	4.23	12.09	14.60	14.95	15.30
	%	0.40	0.46	0.55	0.58	0.64	0.66	1.82	2.12	2.10	2.08
Un-scrubbed Coal	tBTU	252.62	253.56	253.56	253.28	2.77	2.77	0.00	0.00	0.00	0.00
	%	46.01	44.91	42.72	41.83	0.46	0.43	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	80.25	89.33	111.76	130.40	389.06	389.51	402.27	420.61	447.13	471.55
	%	14.62	15.82	18.83	21.54	64.27	61.05	60.64	61.16	62.66	63.96
Cofiring: Biomass + Coal	tBTU	159.03	162.61	165.66	157.93	152.90	177.67	182.70	183.71	180.74	179.19
	%	28.97	28.80	27.91	26.09	25.26	27.85	27.54	26.71	25.33	24.31
Coal Sub-Total:	tBTU	491.90	505.50	530.98	541.61	544.73	569.95	584.97	604.32	627.87	650.74
	%	89.60	89.54	89.45	89.46	89.99	89.34	88.17	87.87	87.99	88.27
Natural Gas Plants	tBTU	10.99	11.30	11.88	12.12	12.12	12.77	13.29	13.77	14.29	14.76
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.93	45.16	47.48	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.02	564.54	593.59	605.43	605.31	637.99	663.42	687.71	713.54	737.23
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 31. Electricity Generation by Fuel Type: Biomass Cofiring 10 % Level

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others	tBTU	2.20	2.58	3.25	3.54	3.89	4.23	11.23	13.99	15.12	15.32
	%	0.40	0.46	0.55	0.58	0.64	0.66	1.69	2.03	2.12	2.08
Un-scrubbed Coal	tBTU	261.98	262.92	262.92	262.92	2.77	2.77	0.00	0.00	0.00	0.00
	%	47.72	46.57	44.29	43.42	0.46	0.43	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	96.06	100.23	122.90	139.53	407.01	413.73	418.03	435.48	460.72	486.95
	%	17.50	17.75	20.70	23.05	67.24	64.85	63.01	63.32	64.57	66.05
Cofiring: Biomass + Coal	tBTU	133.86	142.35	145.18	139.18	134.94	153.44	167.80	169.45	166.99	163.80
	%	24.38	25.22	24.46	22.99	22.29	24.05	25.29	24.64	23.40	22.22
Coal Sub-Total:	tBTU	491.90	505.50	531.00	541.63	544.72	569.94	585.83	604.93	627.71	650.75
	%	89.60	89.54	89.45	89.46	89.99	89.34	88.31	87.96	87.97	88.27
Natural Gas Plants	tBTU	10.98	11.30	11.88	12.13	12.12	12.77	13.28	13.77	14.28	14.76
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.92	45.16	47.49	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.00	564.54	593.62	605.46	605.30	637.98	663.41	687.71	713.54	737.26
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 32. Electricity Generation by Fuel Type: Biomass Cofiring 15 % Level

Power Plants By Fuel Type	**Unit**	**2002**	**2005**	**2008**	**2011**	**2014**	**2017**	**2020**	**2023**	**2026**	**2029**
Renewable and Others	tBTU	2.20	2.58	3.25	3.54	3.89	4.23	12.09	14.60	15.07	18.30
	%	0.40	0.46	0.55	0.58	0.64	0.66	1.82	2.12	2.11	2.48
Un-scrubbed Coal	tBTU	252.62	253.56	253.56	253.28	2.77	2.77	0.00	0.00	0.00	0.00
	%	46.01	44.91	42.72	41.83	0.46	0.43	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	80.25	89.33	111.76	130.40	389.06	389.51	402.27	420.61	447.01	462.24
	%	14.62	15.82	18.83	21.54	64.27	61.05	60.64	61.16	62.65	62.70
Cofiring: Biomass + Coal	tBTU	159.03	162.61	165.66	157.93	152.90	177.67	182.70	183.71	180.74	185.53
	%	28.97	28.80	27.91	26.09	25.26	27.85	27.54	26.71	25.33	25.16
Coal Sub-Total:	tBTU	491.90	505.50	530.98	541.61	544.73	569.95	584.97	604.32	627.75	647.77
	%	89.60	89.54	89.45	89.46	89.99	89.34	88.17	87.87	87.98	87.86
Natural Gas Plants	tBTU	10.99	11.30	11.88	12.12	12.12	12.77	13.29	13.77	14.29	14.76
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.93	45.16	47.48	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.02	564.54	593.59	605.43	605.31	637.99	663.42	687.71	713.54	737.26
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 33. Electricity Generation by Fuel Type: Renewable Electricity Standard (5%)

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others	tBTU	2.20	2.58	3.25	3.54	3.89	5.05	11.97	17.69	25.25	33.21
	%	0.40	0.46	0.55	0.58	0.64	0.79	1.80	2.57	3.54	4.50
Un-scrubbed Coal	tBTU	252.62	253.56	253.56	253.71	2.77	2.77	0.00	0.00	0.00	0.00
	%	46.01	44.91	42.72	41.91	0.46	0.43	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	80.25	89.33	111.76	130.08	389.30	382.76	401.07	411.68	429.76	448.85
	%	14.62	15.82	18.83	21.49	64.31	60.00	60.45	59.86	60.23	60.88
Cofiring: Biomass + Coal	tBTU	159.03	162.61	165.66	157.81	152.66	183.56	184.02	189.56	187.80	184.02
	%	28.97	28.80	27.91	26.07	25.22	28.77	27.74	27.56	26.32	24.96
Coal Sub-Total:	tBTU	491.90	505.50	530.98	541.60	544.73	569.09	585.09	601.24	617.56	632.87
	%	89.60	89.54	89.45	89.46	89.99	89.20	88.19	87.43	86.55	85.84
Natural Gas Plants	tBTU	10.99	11.30	11.89	12.13	12.12	12.78	13.29	13.77	14.29	14.77
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.93	45.16	47.48	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.02	564.54	593.60	605.43	605.31	637.96	663.42	687.72	713.53	737.28
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 34. Electricity Generation by Fuel Type: Renewable Electricity Standard (7%)

Power Plants by Fuel Type	**Unit**	**2002**	**2005**	**2008**	**2011**	**2014**	**2017**	**2020**	**2023**	**2026**	**2029**
Renewable and Others	tBTU	2.20	2.58	3.26	3.55	3.89	14.94	13.28	36.19	38.14	39.09
	%	0.40	0.46	0.55	0.59	0.64	2.34	2.00	5.26	5.35	5.30
Un-scrubbed Coal	tBTU	252.62	253.56	253.99	253.20	2.77	1.86	0.00	0.00	0.00	0.00
	%	46.01	44.91	42.79	41.82	0.46	0.29	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	80.25	89.33	111.02	127.71	394.44	389.97	419.23	406.16	446.57	470.06
	%	14.62	15.82	18.70	21.10	65.17	61.13	63.20	59.06	62.58	63.76
Cofiring: Biomass + Coal	tBTU	159.03	162.61	165.94	160.67	147.49	167.41	164.53	176.62	158.15	146.64
	%	28.97	28.80	27.96	26.54	24.37	26.24	24.80	25.68	22.16	19.89
Coal Sub-Total:	tBTU	491.90	505.50	530.95	541.58	544.70	559.24	583.76	582.78	604.72	616.70
	%	89.60	89.54	89.45	89.46	89.99	87.66	88.00	84.74	84.75	83.65
Natural Gas Plants	tBTU	10.98	11.30	11.88	12.11	12.11	12.76	13.28	13.76	14.27	25.05
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	3.40
Nuclear Power Plants	tBTU	43.93	45.16	47.48	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.96	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.01	564.54	593.57	605.40	605.27	637.98	663.39	687.75	713.56	737.27
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 35. Electricity Generation by Fuel Type: CO$_2$ Cap 10% below 2002 Level

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others	tBTU	2.20	2.58	3.26	3.88	3.89	22.05	20.45	37.33	38.56	39.34
	%	0.40	0.46	0.55	0.64	0.64	3.46	3.08	5.43	5.40	5.34
Un-scrubbed Coal	tBTU	252.62	253.56	253.99	250.52	2.77	1.86	0.00	0.00	0.00	0.00
	%	46.01	44.91	42.79	41.38	0.46	0.29	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	80.25	89.33	110.77	126.32	389.82	375.84	412.31	417.23	447.05	430.81
	%	14.62	15.82	18.66	20.86	64.41	58.91	62.15	60.67	62.65	58.43
Cofiring: Biomass + Coal	tBTU	159.03	162.61	166.19	164.46	152.10	174.43	164.31	164.39	149.74	149.81
	%	28.97	28.80	28.00	27.16	25.13	27.34	24.77	23.90	20.99	20.32
Coal Sub-Total:	tBTU	491.90	505.50	530.95	541.30	544.69	552.13	576.62	581.62	596.79	580.62
	%	89.60	89.54	89.45	89.40	89.99	86.54	86.91	84.57	83.64	78.75
Natural Gas Plants	tBTU	10.98	11.30	11.88	12.11	12.11	12.77	13.29	13.76	21.77	60.90
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	3.05	8.26
Nuclear Power Plants	tBTU	43.93	45.16	47.48	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.01	564.54	593.57	605.45	605.26	637.99	663.43	687.73	713.55	737.29
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 36. Electricity Generation by Fuel Type: CO_2 Cap 15% below 2002 Level

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others	tBTU	3.34	3.69	4.04	12.73	15.12	16.49	19.48	19.09	25.75	26.49
	%	0.61	0.65	0.68	2.10	2.50	2.58	2.94	2.78	3.61	3.59
Un-scrubbed Coal	tBTU	241.37	245.65	247.76	237.45	0.00	0.92	0.00	0.00	0.00	0.00
	%	43.96	43.51	41.74	39.22	0.00	0.14	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	86.91	91.61	113.33	125.89	373.17	388.49	410.33	420.37	444.04	467.64
	%	15.83	16.23	19.09	20.79	61.65	60.89	61.85	61.12	62.23	63.43
Cofiring: Biomass + Coal	tBTU	162.49	167.14	169.08	169.08	160.29	168.28	167.25	179.50	173.04	171.97
	%	29.60	29.61	28.49	27.93	26.48	26.38	25.21	26.10	24.25	23.32
Coal Sub-Total:	tBTU	490.77	504.40	530.17	532.42	533.46	557.69	577.58	599.87	617.08	639.61
	%	89.39	89.35	89.32	87.94	88.14	87.41	87.06	87.22	86.48	86.75
Natural Gas Plants	tBTU	10.98	11.30	11.88	12.12	12.11	12.77	13.29	13.77	14.28	14.76
	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.92	45.16	47.48	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.01	564.55	593.57	605.43	605.26	637.99	663.42	687.75	713.54	737.29
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 37. Electricity Generation by Fuel Type: CO_2 Tax $25 per ton

Power Plants by Fuel Type	Unit	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Renewable and Others	tBTU	3.43	3.78	4.13	12.97	16.15	24.68	36.24	36.98	37.56	38.09
	%	0.62	0.67	0.70	2.14	2.67	3.87	5.46	5.38	5.26	5.17
Un-scrubbed Coal	tBTU	240.72	244.24	242.02	216.26	0.00	0.92	0.00	0.00	0.00	0.00
	%	43.84	43.26	40.77	35.72	0.00	0.14	0.00	0.00	0.00	0.00
Scrubbed Coal	tBTU	86.91	91.25	119.94	128.90	352.38	374.65	394.65	413.89	436.83	460.66
	%	15.83	16.16	20.21	21.29	58.22	58.73	59.49	60.18	61.22	62.48
Cofiring: Biomass + Coal	tBTU	163.07	168.81	168.10	187.04	180.04	173.90	166.18	168.07	168.46	167.35
	%	29.70	29.90	28.32	30.89	29.75	27.26	25.05	24.44	23.61	22.70
Coal Sub-Total:	tBTU	490.70	504.30	530.06	532.20	532.42	549.47	560.83	581.96	605.29	628.01
	%	89.37	89.33	89.30	87.90	87.97	86.13	84.54	84.62	84.83	85.18
Natural Gas Plants	tBTU	10.99	11.30	11.91	12.11	12.10	12.76	13.27	13.75	14.27	14.75
	%	2.00	2.00	2.01	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Nuclear Power Plants	tBTU	43.92	45.16	47.49	48.16	44.57	51.04	53.07	55.02	56.43	56.43
	%	8.00	8.00	8.00	7.95	7.36	8.00	8.00	8.00	7.91	7.65
Total Generation:	tBTU	549.04	564.54	593.59	605.44	605.24	637.95	663.41	687.71	713.55	737.28
	%	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

Table 38. Electricity Generation by Fuel Type: CO_2 Tax \$50 per ton

Model Scenarios	**2002**	**2005**	**2008**	**2011**	**2014**	**2017**	**2020**	**2023**	**2026**	**2029**
Base case	2.50	2.63	3.28	2.92	2.93	2.93	3.37	3.65	3.99	4.02
Biomass Cofiring 10%	2.56	2.71	3.34	2.91	3.01	3.04	3.55	3.68	4.08	4.09
Biomass Cofiring 15%	2.60	2.80	3.30	2.99	3.11	3.16	3.63	3.75	4.13	4.14
RPS 5% @ 10% COF	2.56	2.71	3.34	2.91	3.01	3.04	3.53	3.72	4.10	4.07
RPS 7% @ 10% COF	2.56	2.71	3.36	2.93	3.01	3.01	3.51	3.71	4.11	4.16
RPS 10% @ 10% COF *	2.56	2.71	3.58	3.01	3.01	3.03	3.26	5.41	1795.58	1795.86
CO_2 Cap 10% below 2002 level	2.51	2.63	4.25	4.58	2.92	4.79	4.55	7.03	9.47	10.03
CO_2 Cap 15% below 2002 level	2.51	2.63	3.96	4.73	2.92	5.84	5.00	8.70	9.85	18.33
CO_2 Cap 20% below 2002 level *	2.51	2.63	2.57	4.68	3.45	5.87	5.49	9.06	10.04	115.83
CO2 Tax $25 per ton	5.01	5.30	6.51	5.46	5.31	5.32	5.13	5.28	6.08	6.09
CO2 Tax $50 per ton	7.49	7.95	8.13	8.01	8.11	7.86	7.51	7.73	8.20	8.22
CO2 Tax $100 per ton	12.55	13.36	12.95	12.71	12.49	11.78	11.61	11.77	12.68	13.75

Note: * Model Scenarios are infeasible with the technology and resource specifications in the model.

Table 39. Electricity Price (cents/KWh)

Model Scenarios	**2002**	**2005**	**2008**	**2011**	**2014**	**2017**	**2020**	**2023**	**2026**	**2029**
Base case	151.854	156.062	162.996	165.054	163.681	170.678	174.637	174.393	174.312	178.823
Biomass Cofiring 10%	146.337	150.694	157.375	159.444	158.253	164.716	168.756	169.244	168.788	173.290
Biomass Cofiring 15%	144.673	148.746	155.574	157.647	156.782	163.078	166.814	167.490	166.969	171.599
RPS 5% @ 10% COF	146.337	150.694	157.375	159.444	158.253	164.716	168.756	169.244	168.771	172.276
RPS 7% @ 10% COF	146.337	150.694	157.456	159.602	158.352	164.495	168.880	168.380	165.651	167.925
CO_2 Cap 10% below 2002 level	146.337	150.694	157.306	159.235	148.380	151.713	147.952	144.191	140.430	136.669
CO_2 Cap 15% below 2002 level	146.337	150.694	157.278	158.150	147.944	148.459	143.613	138.767	133.922	129.076
CO2 Tax $25 per ton	144.631	149.210	156.227	153.587	144.147	150.873	144.205	150.179	154.959	159.295
CO2 Tax $50 per ton	144.471	149.049	155.233	151.494	140.589	144.636	135.438	141.606	146.202	150.662
CO2 Tax $100 per ton	143.567	148.878	152.305	134.887	117.747	118.535	109.940	116.125	122.990	129.691

Table 40. CO_2 Emission Level (in million tons)

Model Scenarios	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Base case	1913.25	1934.71	1960.11	1949.07	68.88	71.04	54.24	55.62	57.24	58.64
Biomass Cofiring 10%	1813.11	1838.46	1859.02	1825.35	67.21	69.20	52.42	53.90	55.54	56.93
Biomass Cofiring 15%	1719.27	1761.52	1782.78	1758.06	66.74	68.69	51.81	53.29	54.96	56.40
RPS 5% @ 10% COF	1813.11	1838.46	1859.02	1825.35	67.21	69.20	52.42	53.90	55.53	56.60
RPS 7% @ 10% COF	1813.11	1838.46	1859.02	1827.81	67.21	69.11	52.44	53.57	54.52	55.21
CO_2 Cap 10% below 2002 level	1813.11	1838.46	1863.47	1836.95	66.49	61.82	51.01	50.35	49.20	48.01
CO_2 Cap 15% below 2002 level	1813.11	1838.46	1864.81	1828.57	66.37	60.82	50.09	48.65	47.12	44.26
CO2 Tax $25 per ton	1761.86	1808.49	1840.82	1764.15	47.17	54.93	50.28	52.13	53.64	54.99
CO2 Tax $50 per ton	1760.77	1809.08	1802.26	1725.43	46.05	52.97	47.55	49.47	50.90	52.29

Table 41. SO_2 Emission Level (in ‘000 tons)

Model Scenarios	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Base Case	111.28	112.96	117.69	118.72	55.24	57.75	57.13	59.04	61.32	63.54
Biomass Cofiring 10%	109.18	112.33	116.79	115.96	55.24	57.75	57.18	59.09	61.39	63.60
Biomass Cofiring 15%	116.64	120.91	127.08	125.55	55.24	57.75	57.25	59.15	61.37	63.60
RPS 5% @ 10% COF	109.18	112.33	116.79	115.96	55.24	57.75	57.18	59.09	61.38	63.35
RPS 7% @ 10% COF	109.18	112.33	116.79	116.20	55.24	57.68	57.19	58.83	60.51	62.07
CO_2 Cap 10% below 2002 level	109.18	112.33	117.12	116.27	55.24	56.13	57.07	57.25	59.41	66.21
CO_2 Cap 15% below 2002 level	109.18	112.33	117.12	112.13	55.24	55.52	56.46	57.15	62.75	82.34
CO2 Tax $25 per ton	97.88	105.51	110.74	101.14	52.15	55.28	56.55	58.71	60.46	62.64
CO2 Tax $50 per ton	94.56	103.28	106.27	94.60	52.06	54.57	55.11	57.18	59.45	61.65

Table 42. NO_x Emission Level (in ‘000 tons)

Model Scenarios	2002	2005	2008	2011	2014	2017	2020	2023	2026	2029
Base Case	5875.98	5950.85	6046.59	6023.18	781.41	812.47	779.71	799.46	822.81	842.95
Biomass Cofiring 10%	5576.96	5663.22	5744.93	5658.51	757.34	785.99	753.60	774.79	798.39	818.42
Biomass Cofiring 15%	5309.56	5441.84	5526.00	5464.55	750.68	778.58	744.81	765.97	790.08	810.79
RPS 5% @ 10% COF	5576.96	5663.22	5744.93	5658.51	757.34	785.99	753.60	774.79	798.23	813.68
RPS 7% @ 10% COF	5576.96	5663.22	5744.93	5665.64	757.43	784.63	753.80	770.06	783.78	793.65
CO_2 Cap 10% below 2002 level	5576.96	5663.22	5757.63	5690.62	747.08	745.76	733.28	723.71	707.18	690.20
CO_2 Cap 15% below 2002 level	5576.96	5663.22	5761.43	5663.51	745.32	731.31	720.04	699.27	677.39	636.28
CO2 Tax $25 per ton	5428.02	5574.35	5690.79	5467.48	678.01	723.70	722.72	749.30	771.06	790.46
CO2 Tax $50 per ton	5424.39	5575.41	5579.75	5352.02	661.95	695.62	683.50	711.19	731.69	751.61

Table 43. HG Emission Level (in ‘000 tons)

Model Scenarios	**Bio-Ren PP** ELC_Output	**Cofiring PP** ELC_Output	**Cofiring PP Ren_ELC**	**ALL PP** ELC_Output	**Total % Ren_ELC**
Base Case	16.00	194.45	0.00	737.21	2.17
Biomass Cofiring 10%	15.30	179.19	17.92	737.23	4.51
Biomass Cofiring 15%	15.32	163.80	24.57	737.26	5.41
RPS 5% @ 10% COF	18.30	185.53	18.55	737.26	5.00
RPS 7% @ 10% COF	33.21	184.02	18.40	737.28	7.00
CO_2 Cap 10% below 2002 level	39.09	146.64	14.66	737.27	7.29
CO_2 Cap 15% below 2002 level	39.34	149.81	14.98	737.29	7.37
CO2 Tax $25 per ton	26.49	171.97	17.20	737.29	5.93
CO2 Tax $50 per ton	38.09	167.35	16.74	737.28	7.44
CO2 Tax $100 per ton	39.34	142.90	14.29	737.26	7.27

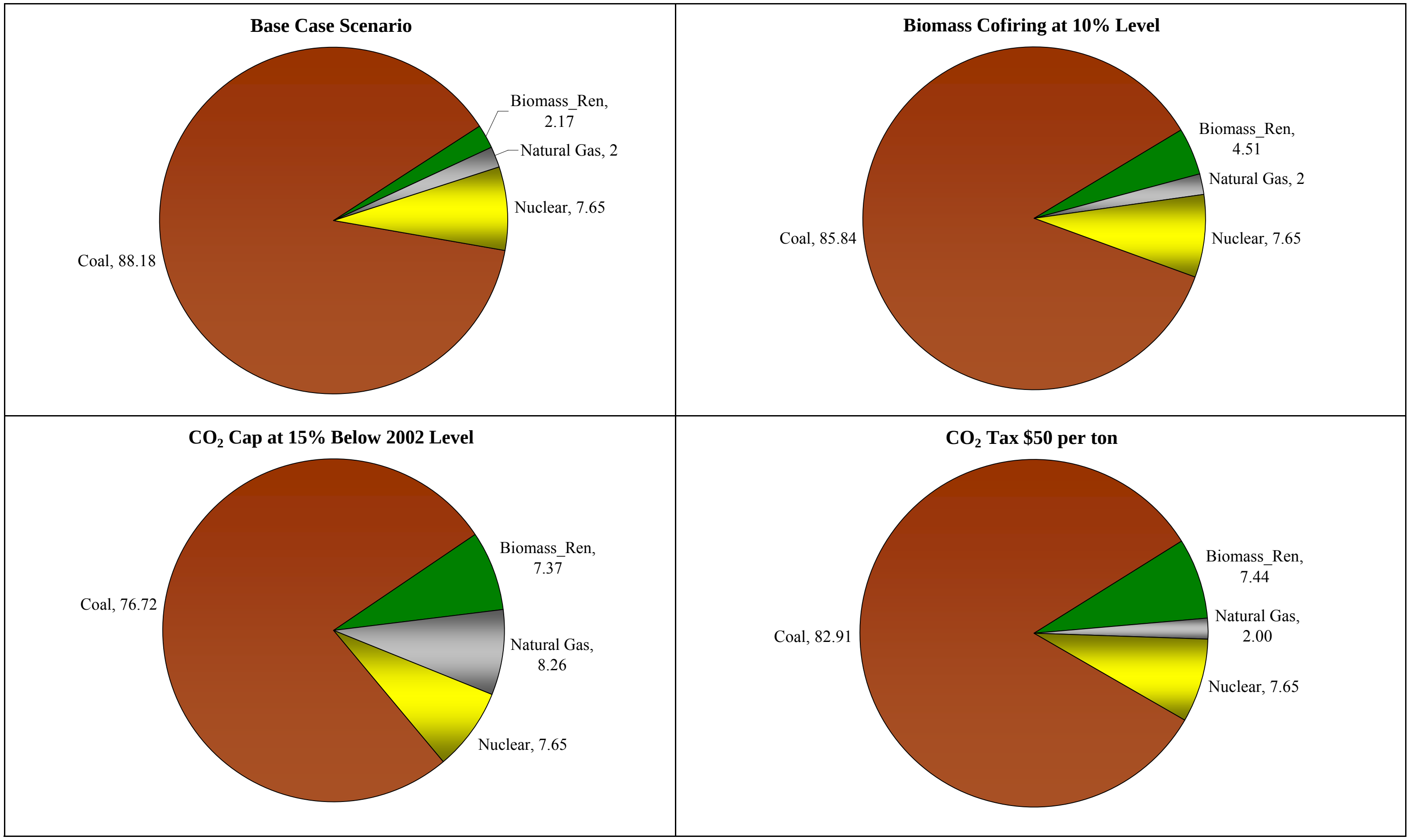
Table 44. Renewable Electricity Generation by 2029 (percentage)

Model Scenrios	**2002**	**2005**	**2008**	**2011**	**2014**	**2017**	**2020**	**2023**	**2026**	**2029**
Base Case	0.00	0.00	0.20	0.00	0.00	0.00	20.70	26.30	26.60	26.50
Biomass Cofiring 10%	48.50	49.90	50.90	48.70	46.30	53.50	74.00	79.80	78.70	78.30
Biomass Cofiring 15%	60.90	65.00	67.00	64.10	61.60	69.00	92.20	99.20	99.80	98.20
RPS 5% @ 10% COF	48.50	49.90	50.90	48.70	46.30	53.50	74.00	79.80	79.00	86.30
RPS 7% @ 10% COF	48.50	49.90	50.90	48.70	46.20	55.60	74.10	87.80	105.80	124.20
CO_2 Cap 10% below 2002 level	48.50	50.00	51.10	49.50	43.50	74.70	68.80	129.90	128.00	126.00
CO_2 Cap 15% below 2002 level	48.50	50.00	51.20	50.10	44.70	94.40	86.80	128.80	126.30	127.60
CO2 Tax $25 per ton	49.80	51.40	52.30	72.30	74.40	78.80	85.40	87.10	101.20	101.90
CO2 Tax $50 per ton	50.40	52.60	52.00	77.60	81.90	101.00	127.20	129.10	129.60	129.90
CO2 Tax $100 per ton	52.80	54.50	52.50	70.20	68.10	91.30	116.10	119.60	122.00	125.60

Table 45. Biomass Feedstock Use (in tBTU)

Model Scenarios	**2002**	**2005**	**2008**	**2011**	**2014**	**2017**	**2020**	**2023**	**2026**	**2029**
Base Case	1475.23	1515.97	1583.36	1603.14	1589.65	1657.18	1695.03	1737.97	1788.70	1832.50
Biomass Cofiring 10%	1421.07	1463.28	1529.15	1549.03	1537.33	1599.60	1638.26	1684.33	1735.63	1779.18
Biomass Cofiring 15%	1404.73	1444.15	1511.43	1531.35	1522.85	1583.50	1619.15	1665.15	1717.55	1762.58
RPS 5% @ 10% COF	1421.07	1463.28	1529.15	1549.03	1537.33	1599.60	1638.26	1684.33	1735.28	1768.87
RPS 7% @ 10% COF	1421.07	1463.28	1529.15	1549.78	1537.52	1596.65	1638.68	1674.05	1703.88	1725.33
CO_2 Cap 10% below 2002 level	1421.07	1463.28	1529.97	1548.47	1515.01	1546.57	1594.09	1573.28	1537.35	1500.43
CO_2 Cap 15% below 2002 level	1421.07	1463.28	1530.15	1538.32	1511.20	1515.15	1565.31	1520.16	1472.59	1383.22
CO2 Tax $25 per ton	1404.32	1448.71	1519.83	1493.53	1473.93	1538.85	1571.13	1628.90	1676.23	1718.40
CO2 Tax $50 per ton	1402.75	1447.13	1510.04	1473.00	1439.02	1477.82	1485.88	1546.06	1590.63	1633.92
CO2 Tax $100 per ton	1384.36	1445.43	1471.38	1290.78	1184.81	1192.53	1207.93	1268.78	1336.41	1402.19

Table 46. Coal Use (in tBTU)



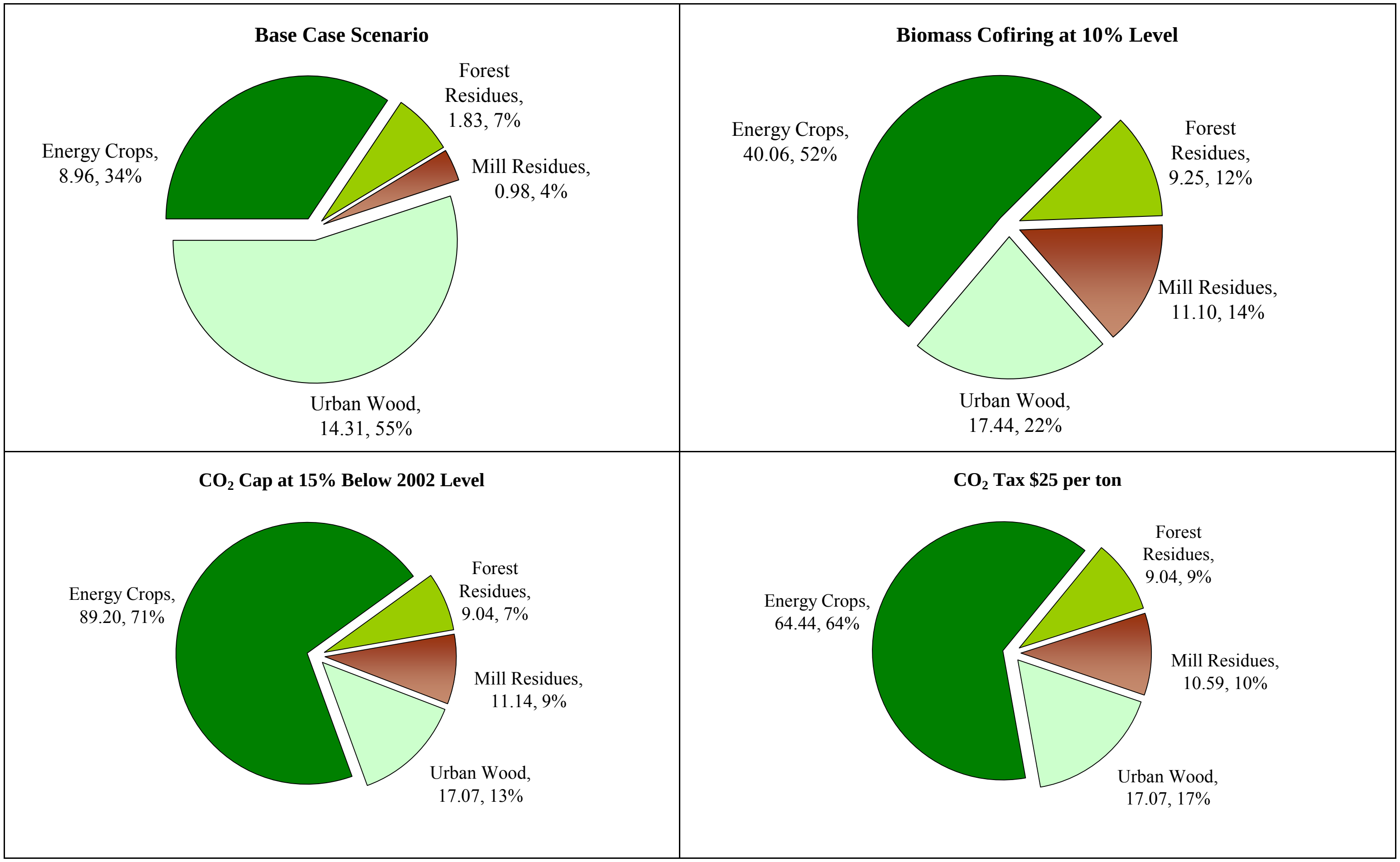
Base Case Scenario

Biomass Cofiring at 10% Level

CO_2 Cap at 15% Below 2002 Level

CO_2 Tax $50 per ton

Figure 20. Electricity Generation by Fuel Type in Model Year 2029



Base Case Scenario

Biomass Cofiring at 10% Level

CO_2 Cap at 15% Below 2002 Level

CO_2 Tax $25 per ton

Figure 21. Biomass Feedstock Use by Type in Model Year 2029

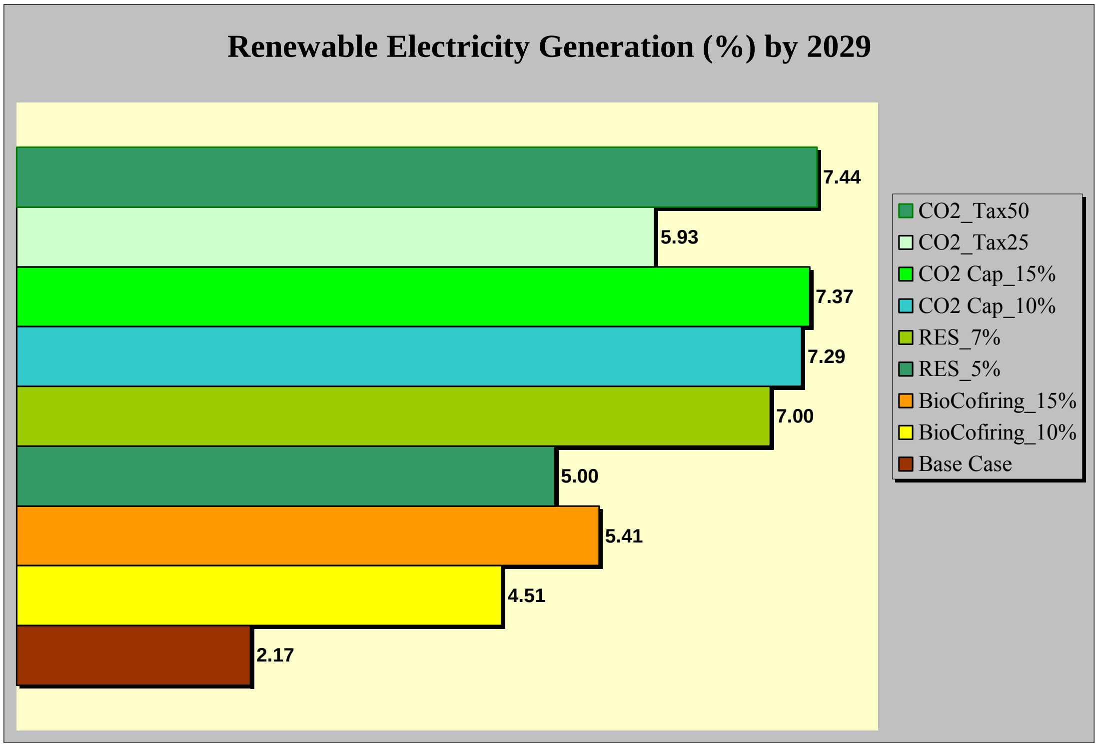


Figure 22. Renewable Electricity Generation by 2029 (percent)

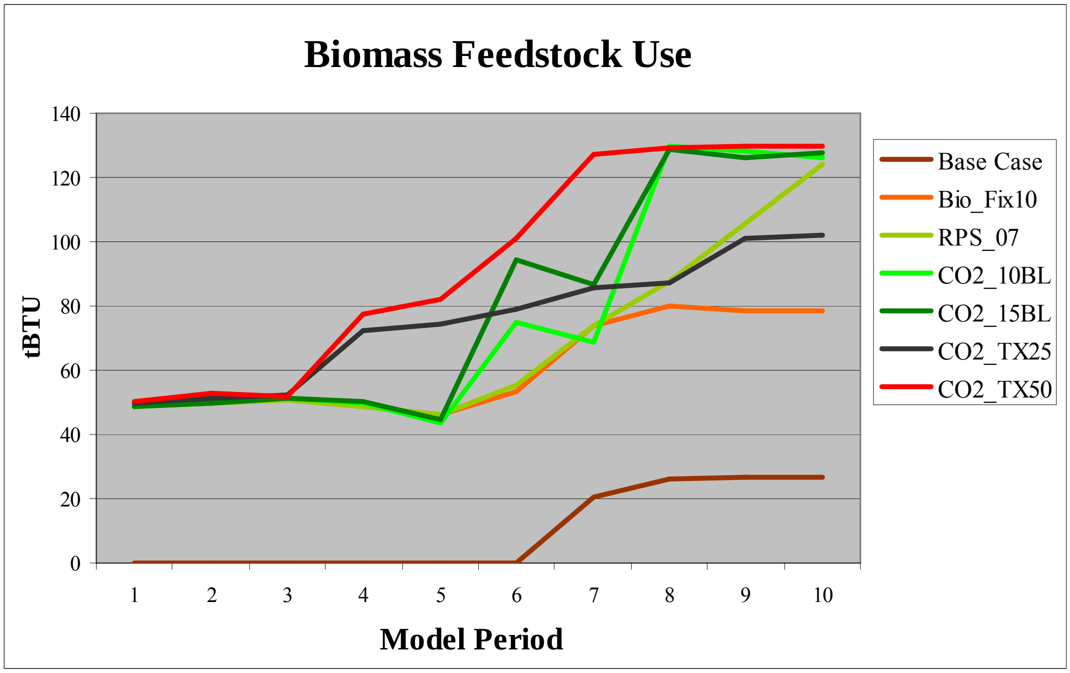


Figure 23. Level of Biomass Feedstock Use under Various Model Scenarios

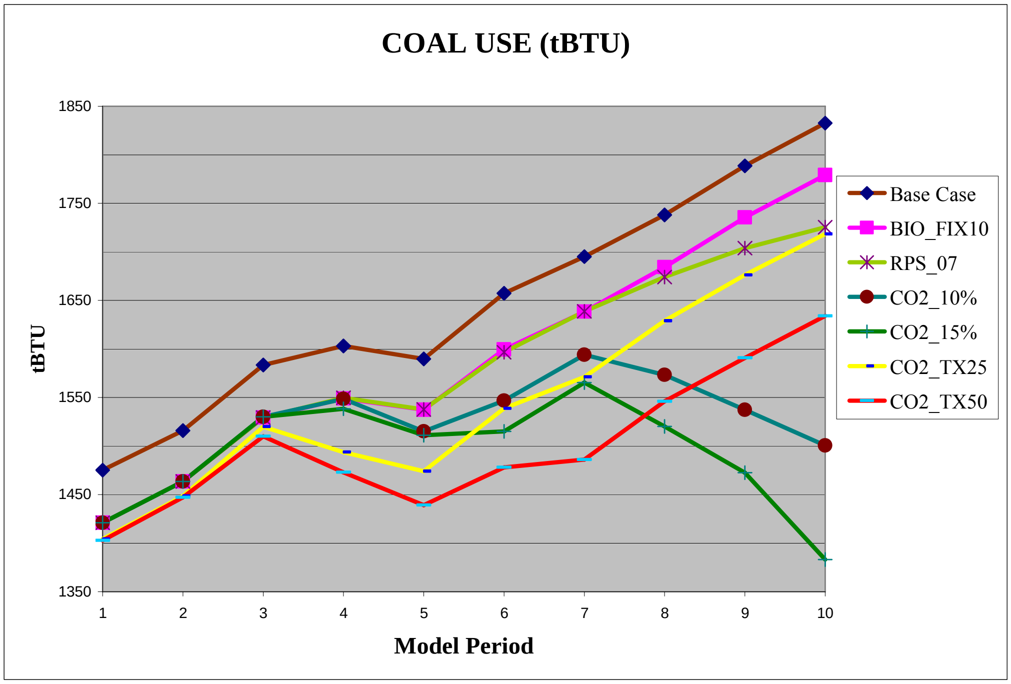


Figure 24. Level of Coal Use under Various Model Scenarios

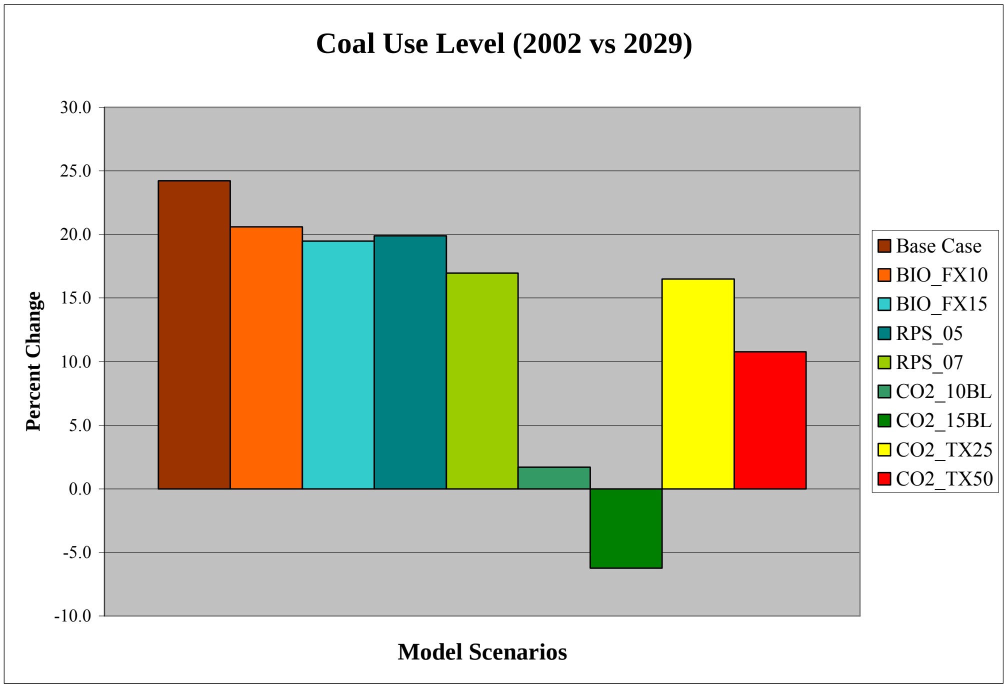


Figure 25. Percentage Change in Level of Coal Use from 2002 to 2029

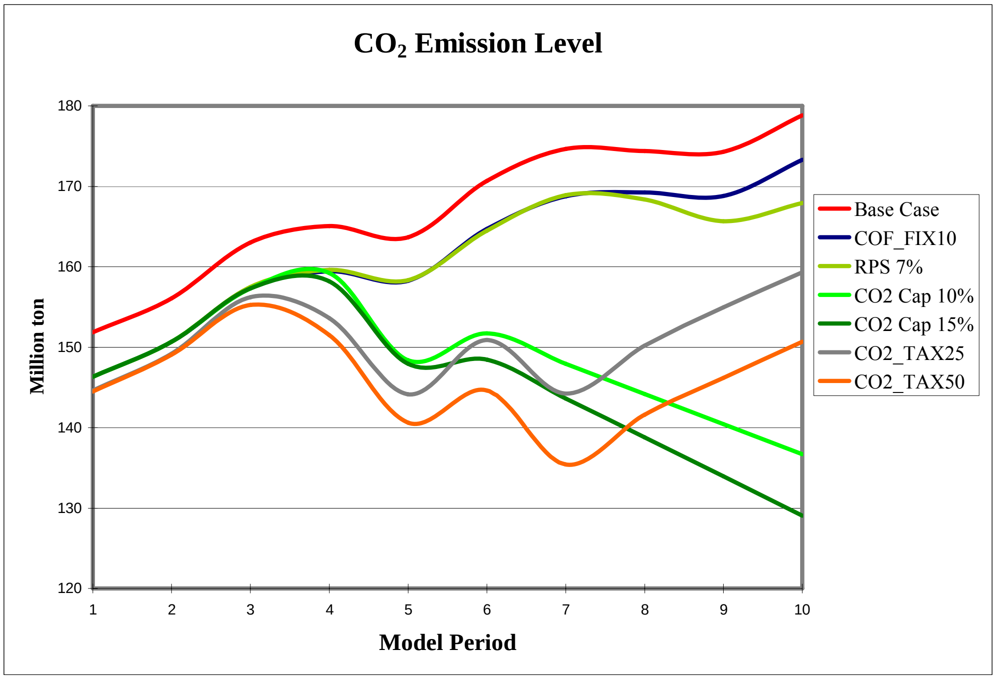


Figure 26. Level of CO$_2$ Emissions under Various Model Scenarios

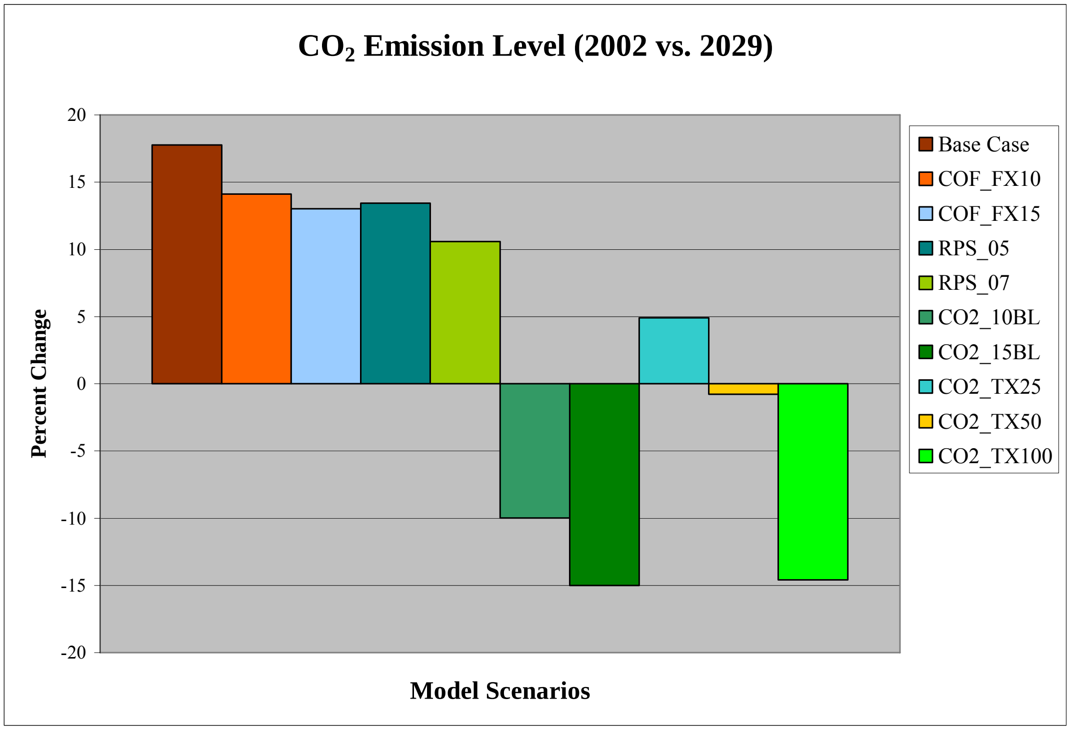


Figure 27. Percentage Change in CO_2 Emission Level from 2002 to 2029

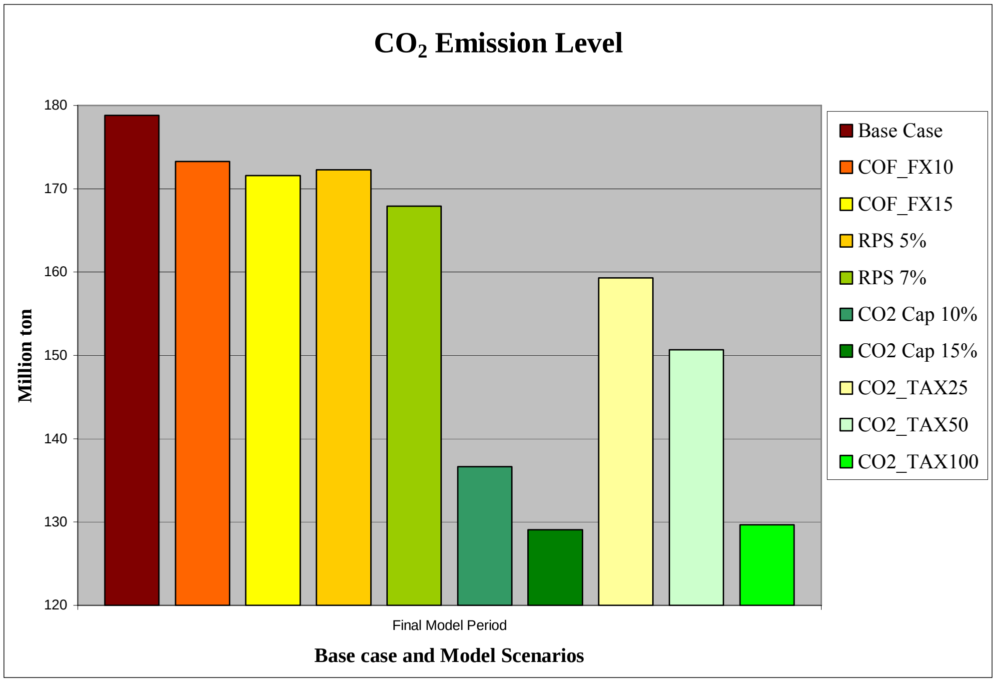


Figure 28. Comparison of CO$_2$ Emission Levels at the end of Model Period

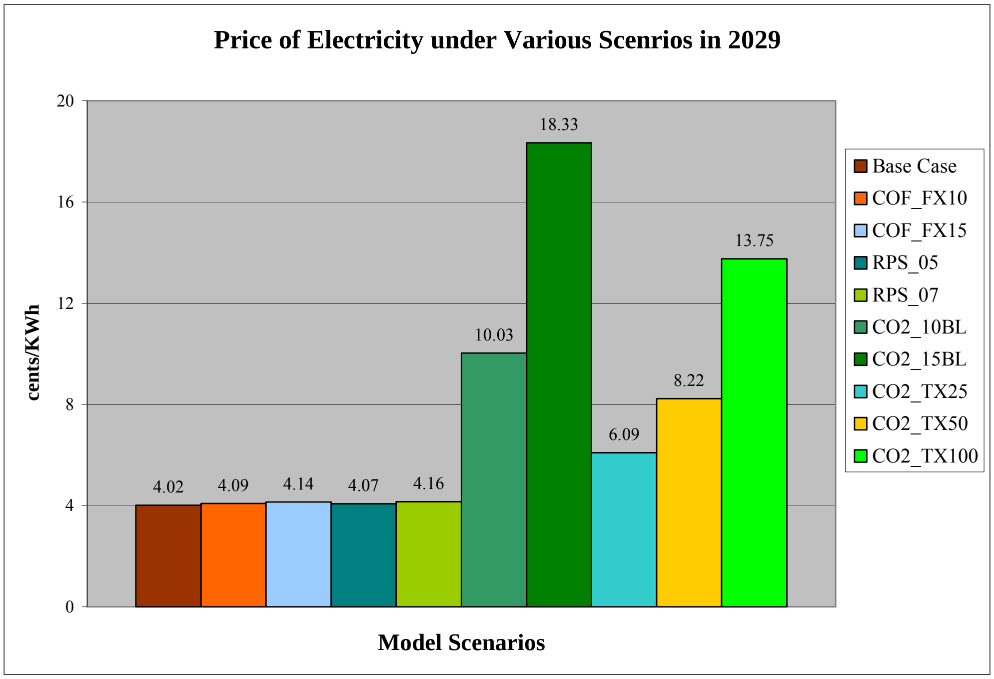


Figure 29. Price of Electricity (cents/KWh) in Model Year 2029

CHAPTER 5

SUMMARY AND CONCLUSION

The latest reports from the Intergovernmental Panel on Climate Change (IPCC) have indicated that human activities are directly responsible for a significant portion of global warming trends (IPCC, 2007). Similar reviews published in recent years from the Natural Resources Defense Council, Pew Center on Global Climate Change, Resources for the Future, and Union of Concerned Scientists claim that the increased use of fossil fuels and industrial pollution have contributed considerably toward changing the climate systems of our planet. The use of clean and sustainable energy resources will be pivotal to mitigate GHG emissions and reduce their negative impacts on climate change.

In response to growing concerns regarding climate change and to create an environmentally sustainable future, biomass resources have come to the forefront as a clean and renewable energy source, since they have the potential to complement traditional sources of energy such as coal and oil to meet growing energy demands. Among renewable energy sources, biomass is currently a principal supplier of renewable electricity in the U.S.

Biomass energy resources are environmentally clean and carbon neutral with net-zero carbon dioxide (CO_2) emissions since CO_2 is absorbed (or sequestered) from the atmosphere during the plant growth. In addition, biomass energy provides several other environmental and social benefits that include reducing air pollutants, diversifying the rural economic base by complementing farm income, as well as enhancing national energy security. Recognizing such benefits, state and federal legislatures have initiated several key policies in recent years to encourage the use of biomass resources for energy purposes. In the U. S., biomass and other renewables are currently receiving significant policy impetus at the federal, state, county, and even city levels. The Farm Security and Rural Investment Act of 2002 is the first federal farm bill to recognize agriculture as a major stakeholder in the energy security debate and the bill included several policy initiatives to promote the use of biomass energy in the U.S. In 2005, the Energy Policy Act (EPAct 2005) was signed into law that provides major incentives to improve biomass technologies and to boost the use of biopower, biofuels, and bioproducts in the country.

1. Biomass as an Energy Option in Ohio

In view of these policy incentives and the need for Ohio to diversify its power generation mix, the use of biomass resources for electricity generation could become a viable option of providing renewable power in Ohio. Currently, the power industry is heavily based on coal, providing about 90 percent of the state's total electricity while the national average is only 50 percent. The burning of coal for electricity generation results in substantial greenhouse gas (GHG) emissions and environmental pollutants which are directly linked to global warming and acid rain. Ohio needs to diversify its power industry's fuel mix and consider alternative sources of energy to meet growing demands for electricity. With the current push towards biomass and renewable energy in the U.S. and the growing environmental concerns related to Ohio's heavy coal use, this dissertation research aimed to highlight key economic, environmental, and policy issues related to power generation in Ohio over a long term future.

The biomass research in Ohio to date has focused on database development on biomass feedstock, in regional or individual studies. These include a recent study conducted by The Ohio State University research team which created an inventory of potential biomass feedstock in the state (Jeanty, Hitzhusen, *et.al.* 2005). Similarly, the Oak Ridge National

Laboratory has projected data on potential energy crops, while the National Renewable Energy Laboratory estimated availability of various biomass feedstocks at the county level in Ohio. A report released by The Ohio Biomass Energy Program proposes biomass utilization for energy purpose and uses a linear programming model to identify potential sites for biomass energy projects in Ohio (Shakya and Southgate, 1996). The study also provided an overview of existing biomass power plants within the wood manufacturing and paper industry. In the power sector, American Electric Power (AEP) conducted a pilot biomass cofiring test project in one of their power plants. Although the test was successful, none of the coal power plants are currently cofiring biomass in Ohio (personal interview with AEP staff, 2006). While these studies provide valuable data to analyze the availability of biomass feedstock in Ohio, there seems to be an important research need on the prospect of using biomass feedstock for power generation.

Building on the available data and previous studies conducted on biomass resources in the state, this dissertation research therefore serves as one of the first comprehensive models to examine the prospect of biomass feedstock for electricity generation in Ohio. Specifically, the model utilizes a substantial amount of data to analyze key economic, environmental and policy issues related to biomass as a viable source of clean energy in Ohio. It is hoped that the results of the study will be useful to energy consumers, power industry professionals, state government officials, and the Ohio legislature.

2. OH-MARKAL Model: Strengths and its Limitations

For its research goals, this study developed a dynamic linear programming model (OH-MARKAL) with an objective to contribute to Ohio's energy planning. The model assessed the current use of energy, its growing future demand, as well as its potential economic and environmental consequences for Ohio. The MARKAL (MARKet ALlocation) model was selected as the most effective economic model framework, as it provides a technology-rich basis for estimating energy and environmental issues over a multi-period horizon. The MARKAL model has been specifically developed and employed for assessing a wide range of energy and environmental policies. It is a flexible, verifiable, and adaptable methodology that has been successfully used around the world (at local, regional, national and global levels) for assessing a broad range of planning and policy issues.

Like any other economic model, MARKAL also has its limitations. It is a linear programming model with an enormous requirement of data and model specifications. One of the limitations is the assumption of "perfect information" and foresight that will not allow incorporating uncertainty in the analysis. The dynamic nature of this model implies that the past decisions and future constraints are included in the decision process, thus making such changes limited to only those that are both economically and technically viable.

Another equally important limitation of this model to consider is that a number of key assumptions must be made, such as the growth in energy demand and technology improvement. The changes in energy demand due to efficiency improvements and economic behaviors are often difficult to specify in the model. However, generalized assumptions for future technology and efficiency improvements can be made and incorporated in the model to be tested further by sensitivity analyses. Similarly, uncertainties in the model can also be evaluated by developing various model scenarios. Once the model is well specified and the calibration is done, the multiple model scenario runs can be accomplished with relative ease.

At the international level, MARKAL is considered one of the most widely used "bottom-up" models among the economic models used in energy, environment, and climate change policy analyses (www.etsap.org). One of the key reasons for the model's implementation in this study was based on the success of the MARKAL model in the Northeastern states to evaluate similar energy and environmental issues. Recently, the framework was used by the Northeast States for Coordinated Air Use Management

(NESCAUM), where the model was adapted as a New England MARKAL (NE-MARKAL) that includes nine New England states. Similarly, the proposed OH-MARKAL may also be expanded to a Midwest (MW-MARKAL) by including other Midwest states to undertake research projects at the regional level.

In developing OH-MARKAL as an empirical model, this research analysis specifically evaluated biomass cofiring as an option in selected coal power plants (both existing and new) to generate commercial electricity. Cofiring utilizes the existing infrastructure, thus making it the most attractive and easily implemented option of utilizing biomass energy resources, with an objective of replacing non-renewable fuel (coal) with renewable and clean fuel (biomass). This study addressed the two key energy and environmental issues for Ohio. The first issue is the importance of diversifying the fuel resource base for the power industry, rather than primarily relying on coal. The second is the need to increase the use of biomass and other renewable resources in Ohio, since the current use is minimal as compared to other Midwest states. As a major agricultural state and in using biomass energy, Ohio can realize benefits for its environment, energy consumers, and the farming communities.

3. Policy Implications and Recommendations for Future Research

The study developed four model scenarios to analyze economic and environmental issues related to biomass cofiring in Ohio. The results of the base case scenario without any policy changes or the business-as-usual case, indicate that coal power plants will not use biomass feedstock for cofiring as expected, because biomass is more expensive than coal and the preferred choice will be coal over biomass to generate electricity. The results further demonstrate that CO_2 emission levels will increase by 18 percent by 2029 as compared to 2002 levels, if the current fuel mix remains unchanged for electricity generation. Under the base case scenario, new biomass power plants will start generating electricity to meet the growing electricity demand that is not met by coal power plants by the model year 2020 due to their capacity limit. This is the main reason for the increase in renewable electricity generation from 0.4 percent in 2002 to 2.17 percent in 2029. Otherwise, biomass feedstock will not generally be used to generate electricity under this business-as-usual case.

The model results suggest that policy interventions are necessary to make biomass co-firing competitive with coal. It needs to be underscored here that the social costs of coal based electricity generation are not fully reflected in their market prices. The renewable sources of energy could become economically competitive with fossil fuels, if the social costs and benefits were incorporated in the respective production systems. Various levels of biomass feedstock use in existing cofiring power plants occur under the RPS, CO_2 caps and taxes scenarios in order to meet the constraint imposed by the model. The results from these various scenarios indicate that the proposed biomass cofiring in selected cofiring coal power plants and new biomass plants can achieve about 7.44 percent generation of renewable electricity in Ohio. The 7 percent level of renewable electricity from biomass reduces the CO_2 emissions by 6 percent. The biomass feedstock supply at Ohio's regional level is sufficient to meet this 7 percent level of electricity generation from cofiring and proposed new biomass plants.

The marginal prices of electricity do not vary much between the base case vs. a RPS of 7 percent level scenarios. Therefore, Ohio can reduce CO_2 emissions by 6 percent without significant increase in electricity price. However, it appears that the marginal price of electricity increases by more than four fold, once the model is constrained to reduce CO_2 emissions by 15 percent in 2029 as compared to 2002 level. The reason for this high price of electricity is due to capacity limitation of biomass and cofiring coal power plants to generate more than 7.44 percent of renewable electricity from biomass sources. Thus, the model was constrained to use more expensive natural gas to replace coal, in order to achieve a 15 percent reduction on CO_2 emissions. The model also shows that a CO_2 tax of $100 per ton results in CO_2 emissions close to 15 percent below the 2002 level by the end of model period. With the current data specifications of the model, it is not feasible to generate more than 7.44 percent of renewable electricity and achieve more than 15 percent reduction of CO_2 emissions level.

This study analyzed biomass cofiring as an option to generate renewable electricity in Ohio. This model can be extended in future research work by including additional renewable resources like wind, solar, and hydro power to examine complete renewable electricity potential for Ohio. If a policy initiative is to increase renewable electricity generation in the state, the RPS can be a potential policy option to generate the desired level of renewable electricity in Ohio. The current model specifications on cofiring and new biomass power plants indicated that the biomass feedstock could provide about 7 percent of renewable electricity in Ohio.

To achieve higher RPS levels, Ohio needs to include other sources of renewable energy such as wind, solar, or hydro into its electricity generation mix. However, if a policy goal is directed towards achieving a certain level of reductions in CO_2 emissions, either a CO_2 cap-and-trade or tax options should be considered in Ohio. While it is beyond the scope of this study to compare the benefits between cap-and-trade and tax options, recent studies suggest that a carbon tax may be a better policy option over cap and trade. Therefore, it is recommended that both policy options should be carefully examined before implementing a carbon policy in Ohio. Once the detailed administrative costs associated with both policies are estimated and identified, the OH-MARAKL model can be used to develop various scenarios for comparative analyses of cap-and-trade vs. carbon tax policy.

The DOE/EIA report on biomass feedstock roadmap indicates that biomass will provide 5 percent of the nation's power, 20 percent of transportation fuels, and 25 percent of chemicals by 2030 (Haq, 2004). Hence, an important future research consideration for biomass feedstock will be to examine its optimal use for energy purposes such as for power or biofuels by taking all the economic and environmental aspects into account. As various biomass power and biofuel technologies mature, competition for the biomass feedstock supply for its different energy uses is bound to happen. The research that identifies the most efficient use of biomass feedstock will be able to help formulate appropriate policy incentives for suitable future biomass energy technologies.

Any potential carbon policy for Ohio will have a significant impact on the coal and power industries. Ohio's reliance on coal will continue to play an integral part in electricity generation. Hence, in addition to successfully developing renewable energy resources which will undoubtedly contribute toward increased renewable electricity generation and mitigate CO_2 emissions, Ohio will have to consider and invest in clean coal technologies. Furthermore, carbon sequestration as a future option to reduce CO_2 emissions needs to be taken into account as well. American Electric Power (AEP) has recently announced that it will capture and store the CO_2 underground instead of emitting into the atmosphere from two of its existing coal-fired plants in West Virginia and Oklahoma (The Columbus Dispatch, March 16, 2007). It is encouraging to see that power companies like AEP have begun to address the issue of global warming.

Since a large percentage of Ohio's energy supply is coal-based, it is important for Ohio to become a leader in clean coal technologies and carbon sequestration. Similar to what AEP is doing in West Virginia and Oklahoma, power companies in Ohio will need to implement aggressive projects to combat global warming. In addition, Ohio should consider providing significant impetus on energy conservation and developing new energy efficient technologies. To conduct comprehensive economic and environmental analyses of Ohio's energy future, the research should also include energy conservation, efficiency improvements, clean coal technologies and carbon sequestration, in addition to renewable energy options in Ohio. The current OH-MARKAL can be effectively extended to undertake such projects, especially since the major data needed and model specifications for the Ohio power sector including biomass resources in Ohio has been accomplished by this study. As noted earlier, the balance between energy and environment is complex and there is no single solution for it. Hence, Ohio's energy strategy should include a mix of domestic renewable energy options, energy efficiency, clean coal technology, and carbon sequestration options.

Other states in the U.S. are already working toward more extensive goals of RPS and CO_2 caps, hence Ohio should probably also need to increase efforts of achieving more renewable electricity and reducing CO_2 emissions further than what is shown feasible by this model. From the results of this study, it can be concluded that Ohio can comfortably set and achieve a moderate goal of a 10 percent RPS by year 2029, resulting in approximately 10 percent reduction of CO_2 emissions as compared to the 2002 level. However, the more aggressive goal for Ohio might be to achieve a 15 percent RPS level by 2029 with 15 percent reduction in CO_2 emissions in comparison to the existing and future energy policies/proposals of its neighboring states. However, success towards this higher goal of RPS will depend on the development of other renewable energy resources like wind, solar, and hydro in Ohio. It would seem prudent for Ohio to become proactive to reduce CO_2 emissions so that it will be ready to deal with any future federal mandates, otherwise the consequences could be too expensive for the state's economy.

4. Potential Future Use of OH-MARKAL

The OH-MARKAL model is a comprehensive power sector model for Ohio and the model may be used effectively in the state's energy planning for the power industry . The model can also serve as an excellent tool for Ohio's policy considerations, since it evaluates the economic and environmental consequences of any policy changes. The model can also be extended and applied to any new policy analyses as the state moves forward to its better energy and environmental future.

The next step for the OH-MARKAL model, is to include other sectors in the model, such as transportation, industrial, commercial, and residential sectors, so that the model can evaluate the entire energy issues for the state in addition to its power sector. This model is based on the MARKAL framework, which is also successfully adapted by the Northeast State for Coordinated Air Use Management (NESCAUM) to develop a New England MARKAL (NE-MARKAL) that includes nine New England states. The primary objective in developing NE-MARKAL was to conduct various energy and environmental policy simulations with a special focus on energy services and improving air quality at the regional level. Similarly, the OH-MARKAL model can also be expanded to a Midwest MARKAL (MW-MARKAL) by including other Midwest states. Since the use, trade and environmental impact of energy go beyond state boundaries, the future hope is to use both the MW-MARKAL and NE-MARKAL together for multi-regional energy, environmental, and policy evaluations.

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