Fall 2007

# Analysis of the holistic impact of the hydrogen economy on the coal industry

Shannon Perry Lusk

ANALYSIS OF THE HOLISTIC IMPACT OF THE HYDROGEN ECONOMY ON THE COAL INDUSTRY

by

SHANNON PERRY LUSK

A DISSERTATION

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

in

MINING ENGINEERING

2007

| | |
|---|---|
| R. Larry Grayson, Advisor | Samuel Frimpong |
| Paul Worsey | Derek Apel |

David Enke

## ABSTRACT

As gas prices soar and energy demand continues to grow amidst increasingly stringent environmental regulations and an assortment of global pressures, implementing alternative energy sources while considering their linked economic, environmental and societal impacts becomes a more pressing matter. The Hydrogen Economy has been proposed as an answer to meeting the increasing energy demand for electric power generation and transportation in an environmentally benign way. Based on current hydrogen technology development, the most practical feedstock to fuel the Hydrogen Economy may prove to be coal via hydrogen production at FutureGen plants.

The planned growth of the currently conceived Hydrogen Economy will cause dramatic impacts, some good and some bad, on the economy, the environment, and society, which are interlinked. The goal of this research is to provide tools to inform public policy makers in sorting out policy options related to coal and the Hydrogen Economy. This study examines the impact of a transition to a Hydrogen Economy on the coal industry by creating FutureGen penetration models, forecasting coal MFA's which clearly provide the impact on coal production and associated environmental impacts, and finally formulating a goal programming model that seeks the maximum benefit to society while analyzing the trade-offs between environmental, social, and economical concerns related to coal and the Hydrogen Economy.

**ACKNOWLEDGMENTS**

Thank you, Braden, for first introducing me to the mining industry and sharing your passion for it with me. Thank you for encouraging me to get my Ph.D., supporting my work, and for making all the sacrifices you did.

Thank you, Mom and Dad. Not only did you instill in me the courage, confidence, and convictions that have gotten me where I am, you never doubted me. Furthermore, without all of your help the last three months with Baby K, I know I would not have finished this dissertation.

Thank you, Daniel, for making me tough.

Thank you, Kyle, for making me brave.

I would like to extend my first professional thanks to Dr. Robert L. Davis. He always opened my eyes to new possibilities and told me to keep my learning curve steep.

I would like to thank my advisor, Dr. R. Larry Grayson. Thank you for showing me multiple exciting pathways within the mining industry, as well as sticking with me until the end. I would also like to thank the rest of my committee, especially Dr. Paul Worsey for keeping me in the right ballpark and Dr. David Enke for always being willing to help.

A very special thanks goes to Barb Robertson. Not only did she take care of everything that needed taken care of (including my husband), but she always encouraged me and shared her positive energy.

I would like to thank the U.S. Department of Education in cooperation with UMR for the financial assistance I received via a GAANN Fellowship in Energy Research Linked to Sound Public Policy Making.

Last, but definitely not least, I would like to thank my daughter, Kendrick Susannah, who gave me a new kind of motivation.

# TABLE OF CONTENTS

Page

## LIST OF ILLUSTRATIONS

# LIST OF TABLES

# 1. INTRODUCTION

## 1.1. BACKGROUND OF THE PROBLEM

As gas prices soar and energy demand continues to grow amidst increasingly stringent environmental regulations and an assortment of global pressures, implementing alternative energy sources while considering their linked economic, environmental and societal impacts becomes a more pressing matter. As part of the 'solution', President George W. Bush often speaks of the Hydrogen Economy as the answer to meeting the increasing energy demand for electric power generation and transportation in an environmentally benign way.

Based on current hydrogen technology development, the most practical feedstock to fuel the Hydrogen Economy may prove to be coal, which has been targeted by the Bush Administration as the source of preference. If this scenario becomes practical, then coal would be the likely feedstock for producing hydrogen for transportation and a significant, new distributed power supply network. This scenario also would likely cause a dramatic increase in domestic demand for coal, which stands at 1.2 billion tons of production now and is forecast to grow 60% by 2030 just for electric power generation.

Understanding and predicting the ultimate multiple impacts of the coal-based Hydrogen Economy thus becomes an important study. To be sure, the planned growth of the currently conceived Hydrogen Economy will cause dramatic impacts, some good and possibly some bad, on the economy, the environment, and society, which are interlinked. Thus any analysis of impacts must be holistic in nature, using a systems approach, and focus on the incremental impacts on each aspect combined into a model which can weigh the different priorities for society.

## 1.2. STATEMENT OF THE PROBLEM

The Annual Energy Outlook 2005 (Energy Information Administration, 2005) predicted the world oil price in 2010 to be 25.00 per barrel in 2003 dollars. This amount equates to 26.55 in 2005 dollars. At the end of August 2005, world oil prices were 58.99 per barrel in 2005 dollars (Energy Information Administration, Table 13 World Crude Oil Prices). The Annual Energy Outlook 2005 prediction for the year 2025 was that the world oil price would be only 30.31 per barrel in 2003 dollars, or 32.19 in 2005 dollars (Inflation Calculator, http://www.westegg.com/inflation). For the American people who paid more than $3.00 per gallon of gasoline in September 2005, it is hard to imagine that the gasoline prices will be almost half as much in 2010 as they are now. Through 2025, energy consumption in the United States is projected to increase more rapidly than domestic energy supply, which is estimated to result in 38 percent of U.S. energy consumption to be supplied by imports. In 2003, 27 percent was supplied by imports. In 2025, net petroleum imports, including both crude oil and refined products, are expected to make up 68 percent of domestic demand, compared to 56 percent in 2003. The problem, which is briefly represented by the above numbers and predictions, is that the United States will continue to demand increasingly more energy than domestic sources can supply; the result is increased dependence on foreign energy sources. This lack of energy independence results in the U.S. being subject to fluctuating and unpredictable energy prices. The Annual Energy Outlook 2005 states a few contributing factors to the price uncertainty such as growth of world energy demand overall; concerns about the political and economic instability in the Middle East, Venezuela, Nigeria, and the former Soviet Union; and supply disruptions caused by weather events, such as Hurricane Katrina.

In President George W. Bush's second week in office, he called for the National Energy Policy Development (NEPD) group, which he established, to "develop a national energy policy designed to help the private sector, and as necessary and appropriate, state and local governments, promote dependable, affordable, and environmentally sound production and distribution of energy for the future." (National Energy Policy, 2001) The President's goal of dependable and affordable energy does not correlate to the current state of the U.S. energy supply and costs. The apparent solution to this conundrum is to penetrate a new, reliable energy source and technology into the United States economy to reduce our dependence on foreign oil. The Hydrogen Economy is one such proposed solution. However, the effects of the implementation and utilization of hydrogen energy sources, or any other new energy source for that matter, must be quantified and the impacts on the current energy structure must be assessed. This is an issue that should be addressed before politicians and legislators implement a new energy policy that could directly or indirectly be detrimental to existing economic, environmental, and social situations in the United States. A government that makes well-educated decisions after weighing the priorities and effects of different proposals is imperative in a progressively more uncertain future relative to meeting energy needs and predicting potential impacts of significant changes. Therefore, the government needs to have integrated information and holistic analytical tools available to inform policy decisions. It is the responsibility of government working with industry, academia, and non-government organizations to develop these tools for integrated analysis.

The overall problem analyzed in this dissertation is how a transition to the hydrogen economy will impact the coal industry and its downstream effects on the economy, the environment and society. The subsequent problems to be solved include determining the market penetration for the technology used to produce hydrogen from coal, updating national coal flows to reflect this penetration as well as increased energy demand, and providing a tool for policy-makers to use that can incorporate different priorities for aspects relating to a coal-based hydrogen economy.

## 1.3. OBJECTIVES AND SCOPE OF RESEARCH STUDY

The main objective of this research is to understand and predict the ultimate multiple impacts of a transition to the Hydrogen Economy on the coal industry. The specific objectives are as follows:

1. Develop a market-penetration curve for FutureGen technology.

2. Forecast national coal flows with the predicted FutureGen penetration incorporated.

3. Formulate a goal programming model that incorporates economic, social, and environmental issues relating to the Hydrogen Economy and the coal industry that can be used as a tool by policy-makers in order to allow them to analyze the downstream effects of their priorities.

The scope of the research regarding FutureGen penetration and the forecasted national coal flows will be limited to the timeframe of 2012 to 2052. A sensitivity analysis will be applied to electricity demand estimates within the timeframe to the degree of plus and minus ten and twenty percent from the base case estimate. The scope of the goal programming model will be to provide system constraints based on estimated available electricity capacity as well as the predicted FutureGen penetration, and also to provide goal constraints that represent key economic, environmental, and social issues related to the Hydrogen Economy and the coal industry.

## 1.4. RESEARCH METHODOLOGY

In this research, changing domestic coal flows were first forecast based upon technology-penetration models for FutureGen Plants with the driving force being coal-based electricy demand.  Therefore, the motivation to use FutureGen plants was assumed to be a desire to have emissions-free electricity generation, and the hydrogen produced is a value-added product.  Results of the predicted changes in U.S. coal flows were then used to estimate the incremental economic, environmental, and societal impacts, positive and negative.  Finally results of the holistic incremental analyses were incorporated into a goal programming model formulated to be a useful tool to inform public policy-makers in sorting out policy options related to the coal-based Hydrogen Economy, cognizant of the projected incremental impacts under sensitivity analyses.

## 1.5. SCIENTIFIC AND INDUSTRIAL CONTRIBUTIONS

This dissertation provides two main contributions, and the contributions are as follows:

1. It provides the coal industry with a general overview of how it may be impacted by implementation of the Hydrogen Economy.
2. It provides a scientific tool (the goal programming model) for lawmakers to utilize in order to create sound public policy in regards to this topic.

Other contributions will be made through the research process, such as creating estimates of technology penetration curves of FutureGen type power plants, and predicting the impacts on and changes of coal material flows in the United States.

### 1.6. STRUCTURE OF THE DISSERTATION REPORT

The Dissertation is broken down into seven chapters. The first being this introduction, the second and third chapters are devoted to a critical literature review, and the fourth chapter will cover technology penetration of both the Hydrogen Economy and FutureGen plants. The fifth chapter will address potential changes on the coal material flows in the United States dictated by the predicted penetration of FutureGen plants and the Hydrogen Economy developed in Chapter 4, and the sixth chapter will encompass the formulation and description of the goal programming model. The final chapter, chapter 7, will discuss conclusions as well as areas of potential future research.

# 2. ENERGY LITERATURE REVIEW

## 2.1. OVERALL ENERGY SUPPLY AND DEMAND

In 2004, the current Deputy Secretary-General of the World Energy Council, Jan Murray (Murray, 2004) gave a speech in Sydney, Australia, and spoke of the fundamental questions about energy supply that appear to have no consensual answers or even clear inevitable directions. The six questions, which do not make up an exhaustive list but highlight the larger issues, include the following:

1. Is the peak in world oil production imminent?
2. How widespread will constraints on carbon emissions become?
3. How far down the cost-curve will renewable energies come?
4. Will zero or near-zero emissions fossil fuels systems prove viable and competitive?
5. Will we succeed in having a competition-based electricity industry?
6. Will distributed energy production kill the grid?

The eventual answers to these questions, which only time will tell, will weigh heavily on the actual energy supply and demand in the future.

According to the Annual Energy Outlook 2006 (EIA, 2006), energy consumption in the United States is predicted to increase at an average rate of 1.2% per year between 2004 and 2025. In 2004, U.S. energy consumption was 99.7 quadrillion Btu, and the consumption is estimated to be 127 quadrillion Btu in 2025. The EIA uses its National Energy Modeling System (NEMS) in order to formulate energy supply, demand, and cost predictions that incorporate a range of variables, such as but not limited to current and predicted trends, state laws, government regulations, and new technologies. Due to the complexity of the variables within the model, the predictions have even changed from the Annual Energy Outlook 2005 to the Annual Energy Outlook 2006.

Figure 2.1 illustrates the history and predicted energy consumption by the transportation, industrial, residential, and commercial sectors. While the industrial, residential, and commercial sectors do show an upward trend, the predicted rate of increase is significantly greater in the transportation sector, which lends itself to support the importance and current technology push to create more energy efficient and alternative fuel-powered cars and other transportation.

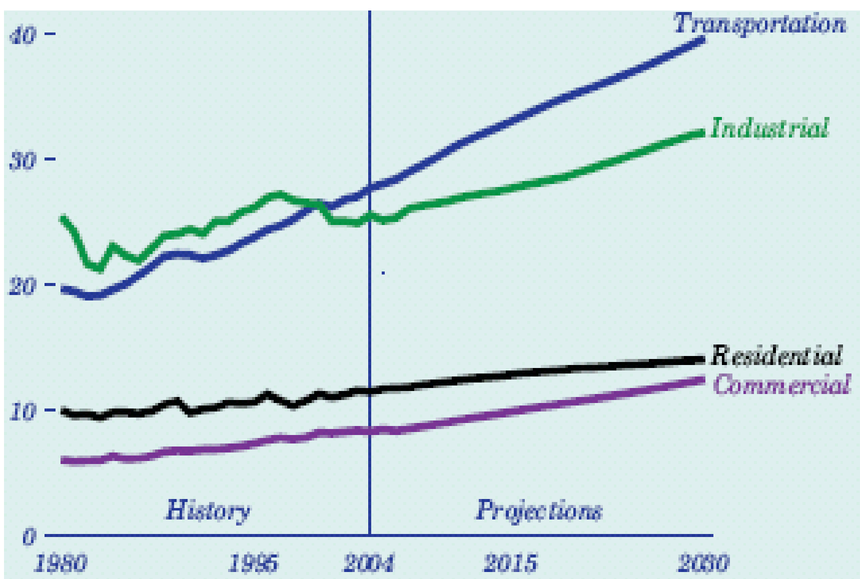



Figure 2.1 Delivered Energy Consumption by Sector, 1980-2030 (quadrillion Btu) (EIA, 2006).

The EIA (EIA, 2006) produced predictions that broke the energy consumption down into fuel type as illustrated in Figure 2.2.

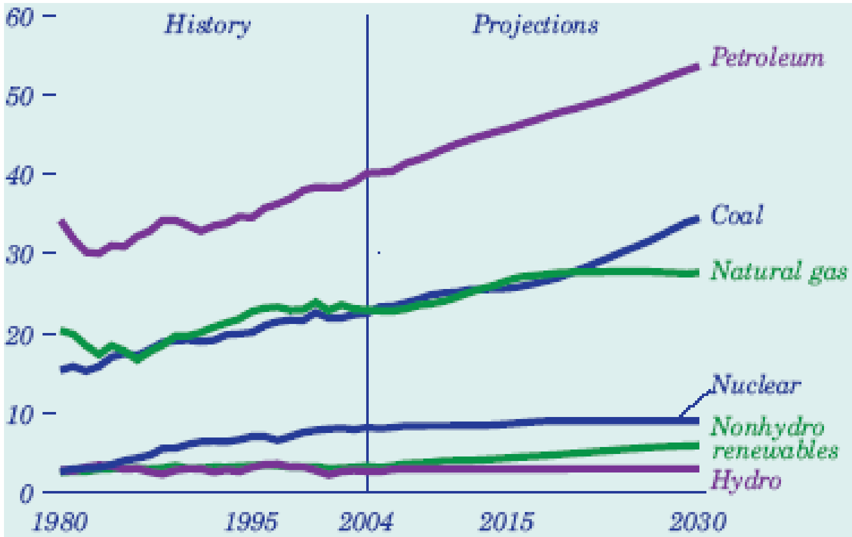



Figure 2.2 Energy Consumption by Fuel, 1980-2030 (quadrillion Btu) (EIA, 2006).

On the supply side, the AEO 2006 makes predictions on energy supply by fuel type. Figure 2.3 shows the amount of individual energy sources supplied by the U.S.

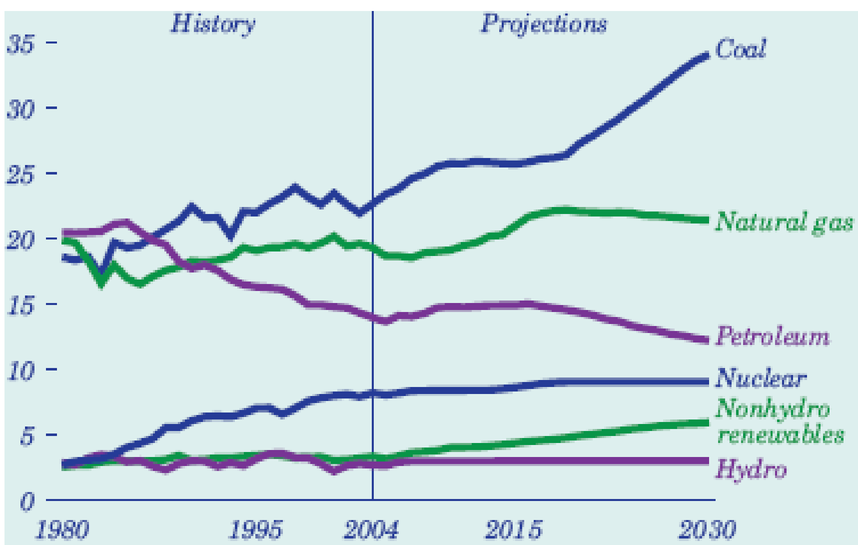



Figure 2.3 Energy Production by Fuel, 1980-2030 (quadrillion Btu) (EIA, 2006).

Figure 2.4 clearly illustrates the predicted gap between the amount of energy produced in the United States and the amount of energy consumed. Imported energy is slotted to fill the gap.

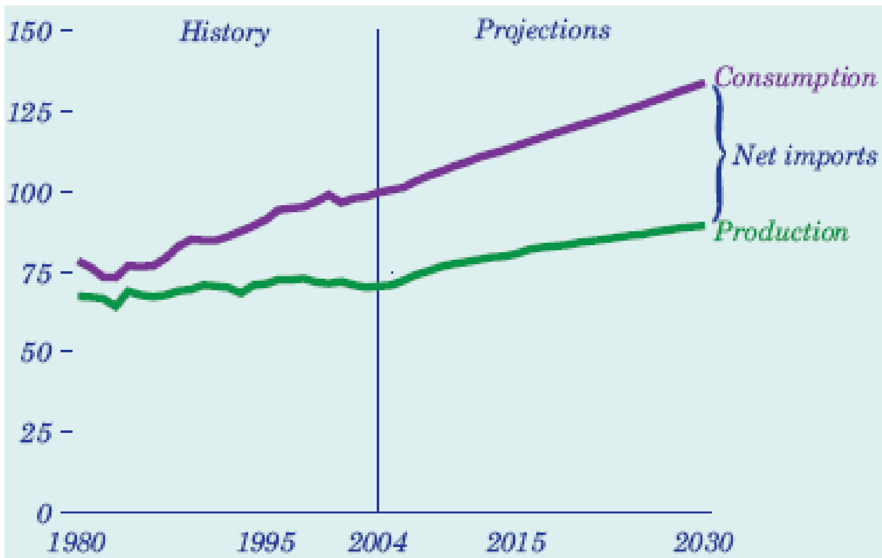



Figure 2.4 Total Energy Production and Consumption, 1980-2030 (quadrillion Btu) (EIA, 2006).

**2.1.1. Imported Oil.** In 2000, 55 percent of the United States' gross oil imports came from four main countries—Canada (15%), Saudi Arabia (14%), Venezuela (14%), and Mexico (12%) (NEP, 2001). In 2004, the top four countries were the same except the percentages changed to 16, 15, 13, and 16, respectively. Mexico jumped to be one of the top two importers and Venezuela fell to the fourth position (EIA, 2006). Overall, the United States currently imports about two-thirds of the oil it consumes.

**2.1.2. Energy Security.** In the 2001 NEP, the NEPD recommended that "…the President make energy security a priority of our trade and foreign policy." A similar call was given during the 1973 Arab oil embargo when President Nixon launched Project Independence. This call was repeated during the administrations of Ford, Carter, Reagan, and the first President Bush.

Maintaining energy security will be paramount in ensuring economic stability in the United States. The first step will be for the U.S. to use its own resources to produce, process, and transport the energy resources we need efficiently and in an environmentally sustainable fashion. In order to increase national energy security, the United States will need to lower its dependence on foreign oil. In order to do so, it will have to reduce oil consumption and gain the flexibility to accommodate oil or other energy disruptions, both domestically and internationally (NEP, 2001).

In 2020, it is projected that Persian Gulf[1] oil producers will supply between 54 and 67 percent of the world's oil (National Energy Policy, 2001). (The Persian Gulf oil producers include Behrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates.) This statistic should raise concerns since the United States imports about two-thirds of its oil and undoubtedly a growing percentage will be coming from the Persian Gulf, which houses much political unrest.

---

[1] (The Persian Gulf oil producers include Behrain, Iran, Iraq, Kuwait, Qatar, Saudi Arabia, and the United Arab Emirates.)

The article by Peter Kiernan in the *World Politics Watch* (Kiernan, 2006) highlights the fact that 15 of the 19 hijackers on 9-11 were from Saudi Arabia. This appears to support a growing argument in America that the United States' dependence on foreign oil is basically funding regimes that do not mesh with America's interests and fund terrorist organizations. Therefore, not only is America's security threatened by requiring energy imports to meet demand, America could be supplying money to terrorists who wish to harm Americans and their interests. By being energy self-sufficient, this risk would be alleviated.

## 2.2. ELECTRICITY SUPPLY AND DEMAND PREDICTIONS

According to the 2006 Annual Energy Outlook, petroleum and electricity will lead the growth in energy consumption. Electricity consumption, i.e. electric power generators and on-site generation, is predicted to increase at an average of 1.6% per year through 2025. In 2004, the United States consumed 3,729 billion kilowatts of electricity, and in 2025, the prediction is that 5,208 billion kilowatts will be demanded (EIA, 2006).

Figure 2.5 illustrates the sources of electricity generation and the extent to which they are predicted to change through 2030.

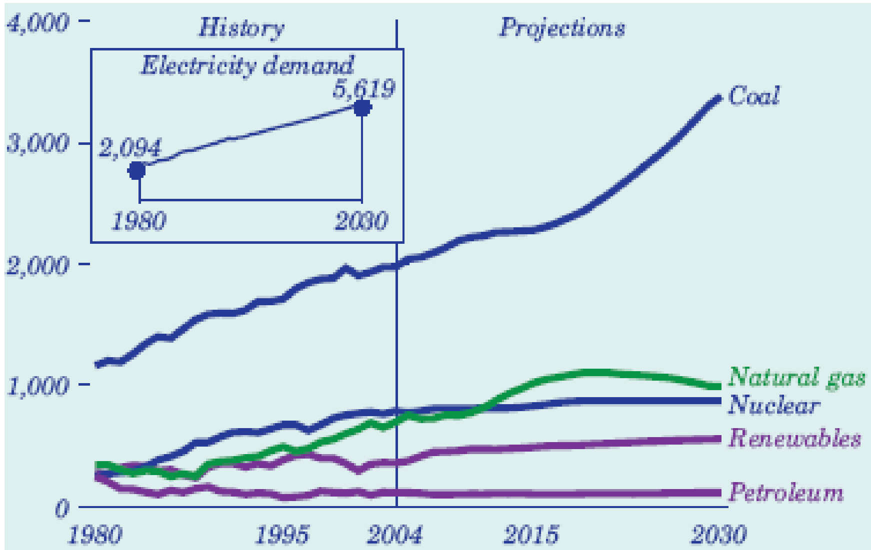



Figure 2.5 Electricity Generation by Fuel, 1980-2030 (billion kilowatthours) (EIA, 2006).

Coal, as a fuel source for electricity, has steadily increased since 1980 and is predicted to do so at approximately the same rate through about 2015. At this point, coal use for electricity increases at an even greater rate. In the past, natural gas has also increased as a fuel source for electricity, but after a small spike around 2015, it is predicted to decrease in use for electricity.

Natural gas and coal are predicted to meet most needs for new electricity supply. Figure 2.6 shows the comparison of fuel type used for electricity generation in 2004 and 2030. Coal outpaces all the others significantly. It is interesting to note that even though natural gas is second for supplying future electricity, nuclear is a close third.

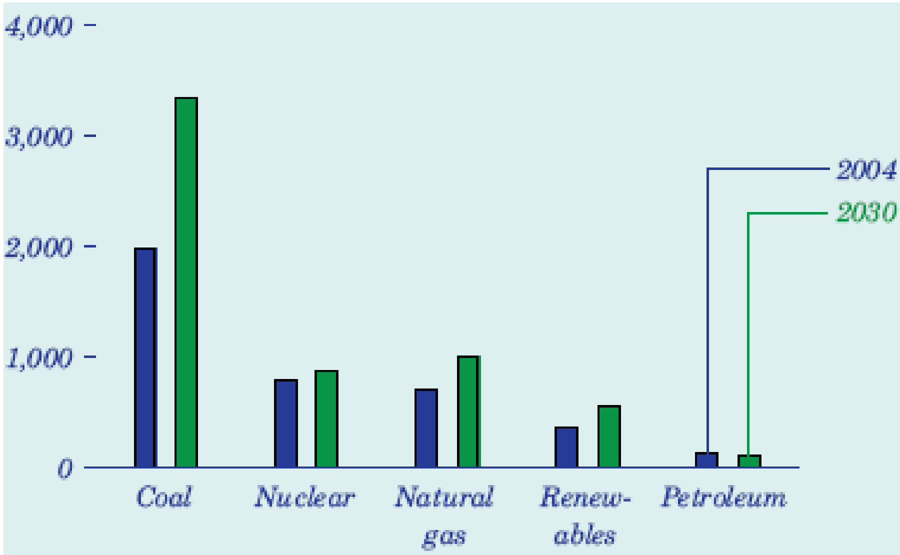



Figure 2.6 Electricity Generation by Fuel, 2004 and 2030 (billion kilowatthours) (EIA, 2006).

**2.3. ELECTRICITY PRODUCTION**

The AEO 2006 examined a variety of technologies that could contribute to electricity production, although they may not be economically feasible today. Depending on new innovations, advancement of current ideas, technological improvements, and the energy market, some of these electricity sources may prove to be significant in the future.

**2.3.1. Advanced Coal Power.** The Department of Energy's FutureGen product embodies advanced coal power. President Bush (2003) announced that the United States would fund a $1 billion, 10-year project that would create the world's first coal-based, zero-emissions electricity and hydrogen power plant. The goal is to utilize coal without having the regularly associated negative environmental effects, such as greenhouse gas emissions. Coal gasification technology, integrated with combined-cycle electricity generation and carbon dioxide sequestration, will be incorporated into the FutureGen project. This opportunity will exist as a research project, and thus, relevant future technologies will have the opportunity to be tested (DOE, 2006).

**2.3.2. Advanced Fuel Cells.** Fuel cells are powered by a supply of hydrogen which is broken down into free protons and electrons within the cell. The operation of fuel cells is much like batteries except fuel cells do not lose their charge. Several different types of fuel cells exist such as phosphoric acid fuel cells and molten carbonate fuel cells. The types are differentiated based on the materials used and the temperature at which they operate. Fuel cells are envisioned to connect to the electricity grid, as well as, to be used on a smaller scale, for example in cars. The only byproduct of fuel cells is water which creates a tremendous environmental benefit. However, fuel cells are very cost-prohibitive (AEO, 2006). Hydrogen fuel cells will be discussed further in chapter 3.

**2.3.3. Renewables.** Renewable energy sources gain most of their favor through comparison to fossil fuels. Where fossil fuels are finite, renewables are considered infinite. Renewables also tend to be much more environmentally friendly by producing fewer negative emissions. On the downside, renewables currently only supply a fraction of the electricity demanded in the United States. In 2003, renewables accounted for 9.3% of U.S. electricity generation, and hydropower accounted for 77% of the renewable generation. Therefore, the remaining renewables—wind, geothermal, solar, and wood/municipal solid waste (MSW) accounted for a total of only 2.2% of U.S. electricity generation (Darmstadter, 2005).

Another factor to consider when examining renewables is their availability in different regions. Solar panels might be great in Panama City Beach, but they will be far less effective in Seattle.

**2.3.4. Hydrogen.** Hydrogen is an energy carrier, much like electricity, and can be used to produce electricity. There is a strong support for working towards a hydrogen economy. A hydrogen economy sounds ideal since the only byproduct from using hydrogen as an energy source is water, which is great for the environment. Furthermore, hydrogen is abundant on earth. The problem is that hydrogen in its elemental form ($H_2$) does not exist in significant quantities on the earth. Therefore, energy must be expended to separate hydrogen from other molecules, and this process takes energy. The energy and environmental balance of the process of obtaining and using the hydrogen as an energy source must be taken into account. Current hydrogen technologies are also expensive, and thus, they are not yet feasible in today's energy market (AEO, 2006).

**2.3.5. Nuclear.** Nuclear power involves harnessing the energy that results from the splitting of atoms and currently accounts for about one-fifth of the United States' electricity. Nuclear power is the most controversial energy source in the U.S. However, nuclear power is gaining support due to the urgency to free America of foreign oil dependence as well as to decrease greenhouse gas emissions that result from coal-fired power plants. Nuclear power is free from some of the serious pollution problems associated with coal; however, there is a new dimension of safety concerns and high operation costs. No new nuclear power plants have been built in America since the 1970's, but the tide appears to be turning with a push for new nuclear power plants (Portney, 2005).

The realized costs of advanced nuclear power plants whose designs have been certified by the U.S. Nuclear Regulatory Commission (NRC) or exist elsewhere in the world were incorporated into the costs assumptions of the AEO 2006 model. More specifically the advanced plants will have the generation 3 light-water reactors (LWRs) (AEO, 2006).

## 2.4. COAL'S ROLE IN MEETING DEMAND

Not only is it a matter of concern that the United States consumes more energy than it produces, but it is also significant that rapidly developing countries, such as China, are putting an added demand on oil supply that could end up costing Americans another 38 cents per gallon in five years, according to the Congressional Budget Office (Roberts, 2006). This statistic is yet another push towards obtaining a domestic energy supply. The most abundant domestic energy supply the United States has is coal.

The problem with coal is that it is dirty. In the 1990's, the electric power sector started turning towards natural gas since it is cleaner-burning than coal. However, due to natural gas prices almost doubling since 1999, the pendulum is swinging back towards coal (Anderson, 2005).

Coal currently produces more than half of the electricity used in the United States. The United States alone produces over 1 billion tons of coal, which is 35% of the world's coal supply, and is the number two coal producer in the world. There are enough coal reserves in the U.S. to last another 250 years if coal usage continues at the same rate. It is interesting that the U.S. coal deposits contain more energy than all of the world's oil reserves (Coal News, 2006).

James Roberts, President and CEO of Foundation Coal Corporation and Vice Chairman of the National Mining Association (NMA), testified before a Senate Committee on energy and natural resources. He spoke to the fact that coal is meeting current U.S. electricity demands and is poised to play a significant role in the future, for example, in the Hydrogen Economy. The future role will need to be a cleaner, more environmentally friendly one.

A nearer, cleaner use of coal will be through alternative fuels such as coal-to-liquid transportation fuels and coal-derived natural gas substitutes. The liquefaction and gasification technologies already exist in oil-deprived countries, such as South Africa, who have coal reserves. As much as 60% of South Africa's transportation fuels have been supplied by liquefied coal. Since the technologies exist, the research and development dollars required of new innovations will not be necessary. The challenge will be to find early adopters into the market from the private sector. Roberts believes the government will need to intervene in order to ensure that coal liquefaction and gasification technologies have a chance to penetrate and survive in the energy market. He is concerned that the oil producers may play with the market in order to keep oil prices low enough to deter and defeat alternative fuels when they gain strength. This is why Roberts feels the U.S. Government should ensure that coal liquefaction and gasification technologies are realized in the United States (Roberts, 2006).

AEO 2006 also projects coal production to significantly increase. It estimated that coal production would increase 1.1% per year to 2015 as a few new coal-fired plants are added, and then 2.0% per year from 2015 to 2030 as more coal-fired plants are added along with several coal-to-liquid plants are brought online. Figure 2.7 shows the coal projections by region (AEO, 2006).

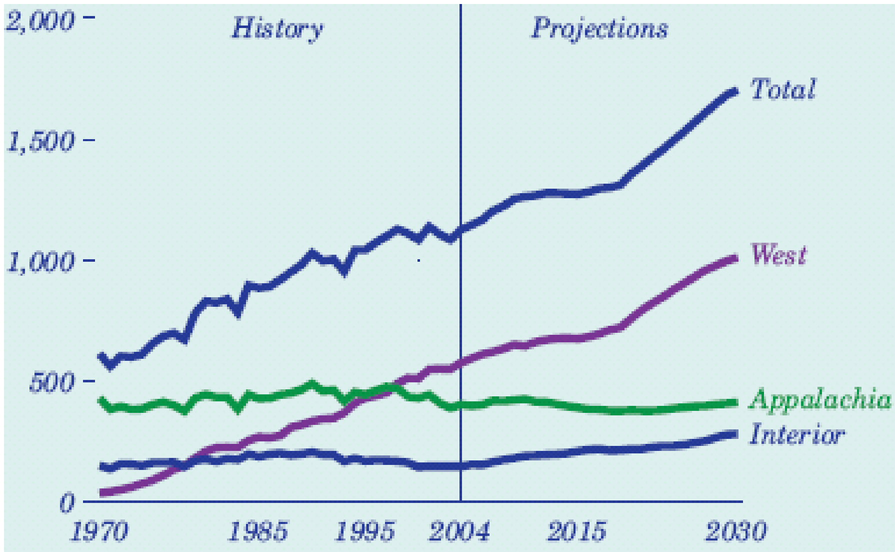



Figure 2.7 Coal Production by Region, 1970-2030 (million short tons) (EIA, 2006)

The model took into account two new pieces of environmental legislation, enacted in 2005, that would impact coal. They are the EPA's Clean Air Interstate Rule (CAIR) and Clean Air Mercury Rule (CAMR). These new laws tighten restrictions on emissions of $SO_2$ and $NO_X$ and address for the first time mercury emissions from power plants. These new regulations will increase the cost of coal-fired generation but are not expected to have a substantial impact on the amount of coal production (AEO, 2006).

**2.5. THE HYDROGEN ECONOMY**

Non-oil energy technologies, also known as alternative energy sources, will be necessary in order to decrease America's dependence on foreign oil. Secretary Samuel Bodman, the U.S. Energy Chief, believes that as oil supplies are diminished, the rising cost of oil will be harmful to the economy of the United States as well as developing countries around the world. Therefore, he feels it is imperative that the U.S. along with other countries develop viable alternative energy sources. This mission will require significant intellectual and financial resources. The high cost of oil enables the alternative sources to be competitive (Zwaniecki, 2006).

Robert Ebel, an energy expert who is the director of the energy program at the Center for Strategic and International Studies in Washington, believes that governments will have to take the lead in order to provide market incentives to alternative energy participants. Furthermore, Secretary Bodman pinpoints the necessity of the oil-producing countries to perceive alternative energy sources as an opportunity for economic diversification as opposed to a threat, because the oil producers must not engage in market distorting practices, such as rationing of oil, if the alternative energy sources are to survive (Zwaniecki, 2006).

The Hydrogen Economy is an alternative energy plan. A $1.2 billion hydrogen initiative was introduced by the U.S. Government in 2003 with the intent to create a hydrogen economy in the U.S. The initiative's main objectives are to reverse dependence on foreign oil by providing an attractive energy alternative, reduce greenhouse gas emissions since hydrogen burns cleanly, and develop commercially viable hydrogen fuels and technologies so that the Hydrogen Economy can be realized (Newell, 2005).

Hydrogen is domestically abundant, but it does not exist naturally in its elemental form ($H_2$) in significant quantities on the earth. Therefore, the $H_2$ must be produced from hydrogen-containing substances which, to date, is an expensive endeavor. Furthermore, new infrastructure and technologies will be required to deliver, store, and use the hydrogen, which is costly.

**2.5.1. Production Methods.** Hydrogen must be separated from hydrogen-containing compounds because hydrogen is termed an "energy carrier" as opposed to an energy source. There are several methods for producing hydrogen. The three generic categories for hydrogen production technologies are thermochemical production, electrolytic production, and photolytic production technologies. Hydrogen.com[2] lists the following, more specific, main production methods (www.hydrogen.com, 2006):

- Steam reforming converts methane (and other hydrocarbons in natural gas) into hydrogen and carbon monoxide by reaction with steam over a nickel catalyst
- Electrolysis uses electrical current to split water into hydrogen at the cathode (-) and oxygen at the anode (+)
- Steam electrolysis (a variation on conventional electrolysis) uses heat instead of electricity to provide some of the energy needed to split water, making the process more energy efficient
- Thermochemical water splitting uses chemicals and heat in multiple steps to split water into its component parts
- Photoelectrochemical systems use semi-conducting materials (like photovoltaics) to split water using sunlight
- Photobiological systems use microorganisms to split water using sunlight
- Biological systems use microbes to break down a variety of biomass feedstocks into hydrogen
- Thermal water splitting uses a high temperature (approximately 1000°C) to split water
- Gasification uses heat to break down biomass or coal into a gas from which pure hydrogen can be generated.

Once hydrogen is produced, it can be used on site or distributed. Hydrogen can be stored as a liquid, gas, or chemical compound. Hydrogen can then be converted to energy by familiar-sounding combustion in turbines and engines or by fuel cells (Research Reports International, 2004).

---

[2] Hydrogen.com is a website committed to hydrogen as an energy source.

**2.5.2. Feed Stocks.** In the United States, approximately nine million tons of hydrogen are produced each year. About 3 million tons of this hydrogen is used to manufacture ammonia, and the remainder of the hydrogen is used in petroleum refining. Fossil fuels, which contain carbon and hydrogen, make up the primarily utilized feed stocks for hydrogen and include natural gas, coal, and oil (Newell, 2005).

**2.5.2.1 Natural Gas.** As mentioned above, natural gas is currently the most popular feed stock for hydrogen. It currently accounts for 48% of the world's hydrogen (hydrogen.com, 2006) and approximately 95% of the United States' hydrogen. The hydrogen is produced through catalytic steam reforming, which is a relatively cost-effective process. The methane-steam reforming chemical equation is illustrated in equation 2.1 (DOE Hydrogen Production, 2006).

$$CH_4 + H_2O \text{ (+heat)} \rightarrow CO + 3H_2 \qquad (2.1)$$

Hydrogen can also be produced from natural gas via partial oxidation. In partial oxidation, oxygen is introduced, but not in amounts great enough to completely oxidize the hydrocarbons to carbon dioxide and water as illustrated in equation 2.2 (DOE EERE, 2006).

$$CH_4 + \tfrac{1}{2}O_2 \rightarrow CO + 2H_2 \text{ (+heat)} \qquad (2.2)$$

Using natural gas as a feed stock for hydrogen is cheaper than producing hydrogen from electrolysis. However, the cost associated with the natural gas will, of course, depend on the price of natural gas which is on the ascent. Even at current prices, hydrogen produced from natural gas produces usable energy that is still two to four times more expensive than energy from gasoline (Newell, 2005).

Natural gas is favorable for use as a feed stock since the infrastructure to transport natural gas is already in place. Current analysis estimate that using natural gas to transition into the hydrogen economy will increase natural gas demand by less than 5% (DOE EERE, 2006). However, relying on natural gas as feed stock does not address the concerns of greenhouse gas emissions or national security issues. Furthermore, other markets, such as residential heating and cooking, industrial uses, and electricity generation, currently demand a large amount of natural gas and will dominate over demand for natural gas to produce hydrogen.

**2.5.2.2 Oil.** Distillates and heavy fuel oils have been proven to be a successful feed stock for hydrogen production plants in oil refineries and facilities (RRI, 2004). Hydrogen produced from oil makes up approximately 30% of the world's hydrogen production (hydrogen.com, 2006). Using oil as a feed stock has the same main negatives as natural gas; the greenhouse gas emissions are still a problem, as well as, national security issues since this feed stock still depends on foreign oil sources.

**2.5.2.3 Coal.** Coal as a feed stock for hydrogen currently accounts for 18% of the world's hydrogen production (www.hydrogen.com, 2006). Coal is an attractive feed stock for the United States, since the U.S. has more coal than any other country in the world. When the DOE's Office of Fossil Energy names coal as its number one strategy for fueling the Hydrogen Economy, it does not include the use of coal-produced electricity to separate hydrogen from hydrogen-containing compounds. Instead, it is referring to coal gasification.

The coal gasification process involves a gasifier unit, which is used to break the coal down by applying heat under pressure in the presence of steam and a controlled amount of oxygen into a gaseous mixture of hydrogen, carbon monoxide, carbon dioxide, and other compounds. The gasifier creates an environment that encourages and supports chemical reactions that create a synthesis gas (syngas) from the coal. Synthesis gas is primarily made up of hydrogen, carbon monoxide, and carbon dioxide. These gases can be separated and sequestered, as opposed to being released into the atmosphere. The DOE's FutureGen project is based on this technology—a coal-based, zero-emissions power plant (DOE EERE, 2006).

Coal gasification is a promising feed stock for the Hydrogen Economy. It is domestically abundant which will aid in alleviating America's dependence on foreign oil. Also, since coal gasification allows gases to be separated and sequestered, the greenhouse gas emissions can be eliminated by capturing them before they enter the atmosphere. The Department of Energy is touting coal as the feed stock of choice.

**2.5.2.4 Renewables.** Renewable sources are being considered as a feed stock since they would produce fewer negative environmental impacts. The key areas that the DOE is researching include electrolysis, thermochemical conversion of biomass, photolytic and fermentative micro-organism systems, photoelectrochemical systems, and high-temperature chemical-cycle water splitting (DOE Hydrogen Production, 2006).

The most advanced in terms of near commercialization and popularity is biomass utilization. Biomass is a renewable organic resource and includes everything from agricultural waste, to crops, to organic municipal solid waste, to forest residues. The biomass can be put into gasifiers that create a syngas made up of carbon monoxide, carbon dioxide, and hydrogen. The gases can be separated and captured. Another option is to use biomass to create liquid fuels, such as ethanol. This renewable liquid fuel can then be used in steam reforming, much like as for natural gas, in order to create hydrogen. A unique benefit to using biomass is that carbon dioxide is removed from the air when the crops that will be used for biomass are grown (DOE EERE, 2006).

Although renewables are more environmentally friendly, the capital costs associated with the equipment and necessary technologies are still high. Furthermore, the process is thermodynamically inefficient and again more expensive than other hydrogen-producing technologies. Other concerns that should be addressed before a biomass feed stock is relied upon is the added demand that would be placed on land and agricultural goods and services that are already demanded for food, recreation, and conservation (Research Reports International, 2004).

**2.5.2.5 Nuclear.** The Department of Energy lists nuclear power as a possible feed stock for the hydrogen economy. The Office of Nuclear Energy is funding research that will study commercial-scale hydrogen production using heat from the nuclear process.

**2.5.3. Fuel Cells.** Sir William Grove, a Welsh judge and gentleman scientist, built the first fuel cell in 1839. However, serious consideration and application were not given until the 1960's when the U.S. Space Program chose fuel cells over nuclear or solar power for spacecraft. Fuel cells provided power for the Gemini and Apollo projects and still provide electricity and water for modern spacecraft (fuelcells.org, 2006).

As previously mentioned, fuel cells are the technology of choice to convert the hydrogen into an energy source. Unlike traditional engines which rely on combustion, fuel cells rely on a chemical process to create the energy, in the form of heat and electricity. Fuel cells behave like a battery, except they never need recharging. As long as a fuel source is supplied, such as hydrogen, the fuel cell will operate.

A fuel cell is made up of an electrolyte with two electrodes around it. Hydrogen fuel is introduced to the anode of the fuel cell, and oxygen or air is introduced to the fuel cell via the cathode. A catalyst then initiates the process by which the hydrogen atoms split into a proton and an electron. The proton passes through the electrolyte while the electrons create a separate current that can be utilized before returning to the cathode. At this point, the electrons are reunited with the hydrogen and oxygen to form water (fuelcells.org, 2006).

The Rocky Mountain Institute (RMI) began as a small venture in 1982 dedicated to energy policy and has since grown to a research institution with a six million dollar annual budget. RMI produced Table 4.1 which shows the different fuel cell types with the electrolyte, anode gas, cathode gas, temperature, and efficiency descriptions. Fuel cells are differentiated based on their electrolyte type. The material properties of the electrolyte dictate the conditions under which the fuel cell will work and in turn, therefore dictates the fuel cells benefits and shortcomings (RMI, 2006).

Table 2.1 Types of Fuel Cells

| Fuel Cell Type | Electrolyte | Anode Gas | Cathode Gas | Temperature | Efficiency |
|---|---|---|---|---|---|
| **Proton Exchange Membrane (PEM)** | solid polymer membrane | hydrogen | pure or atmospheric oxygen | 75°C (180°F) | 35–60% |
| **Alkaline (AFC)** | potassium hydroxide | hydrogen | pure oxygen | below 80°C | 50–70% |
| **Direct Methanol (DMFC)** | solid polymer membrane | methanol solution in water | atmospheric oxygen | 75°C (180°F) | 35–40% |
| **Phosphoric Acid (PAFC)** | Phosphorous | hydrogen | atmospheric oxygen | 210°C (400°F) | 35–50% |
| **Molten Carbonate (MCFC)** | Alkali-Carbonates | hydrogen, methane | atmospheric oxygen | 650°C (1200°F) | 40–55% |
| **Solid Oxide (SOFC)** | Ceramic Oxide | hydrogen, methane | atmospheric oxygen | 800–1000°C (1500–1800°F) | 45–60% |

The useful applications of a fuel cell are determined based on characteristics, such as the ones listed in Table 4.1. The useful applications include stationary, residential, transportation, portable power, and landfill/wastewater treatment. The U.S. Department of Energy's Hydrogen Program is focused on using fuel cells to convert hydrogen to electrical or thermal power, and more specifically, the emphasis of the research is intended for the use of hydrogen to power vehicles via PEM fuel cells, for auxillary power units on vehicles, or for stationary applications. DOE is also conducting research on PAFC, MCFC, and SOFC fuel cells, but this research does not fall under the Hydrogen Initiative since the utilization of these fuel cells is geared towards stationary power as opposed to transportation (DOE Hydrogen Program, 2006).

The National Renewable Energy Laboratory (NREL) supports the DOE's initiatives and recognizes that a key component of realizing robust fuel cells is to have adequate testing of the fuel cells and their materials. The NREL has formulated some test systems, such as ADVISOR for analyzing vehicle systems with fuel cells and HOMER (Hybrid Optimization Model for Electric Renewables) for evaluating stationary fuel cells. These tests are used to test the robustness of the fuel cell systems, as well as, target key areas, such as optimizing water and thermal management in extreme weather conditions. HOMER also can run sensitivity analyses that evaluate the impacts of changing material/technology costs, availability, and policy decisions (NREL, 2006).

## 2.6. CARBON CAPTURE AND SEQUESTRATION (CCS)

Three different types of locations have been identified for CCS. The locations are geological (underground reservoirs), such as depleted oil and gas fields, saline aquifers, and unmineable coal beds; terrestrial, such as trees, grasses, soil, and algae; and dissolved in deep oceans. Several public-private sector relationships have been established across the nation in order to examine and research the necessary technologies, regulations, and infrastructure required in order to implement CCS in different regions. This initiative is divided into three phases. The characterization phase involved identifying and characterizing opportunities for CCS and collecting the capital to perform the tests; this phase took place from 2003 to 2005. The second and current phase is the validation phase which is scheduled from 2005-2009. The main goal of this phase is to validate CCS technologies in promising regions via field tests. Geological and terrestrial field tests are included in this phase and have been done. The final phase is the deployment phase (2008-2017) which will involve executing large-scale CCS projects which are representative of the CCS potential for given regions (Litynski, 2007.)

Many co-benefits have been identified in conjunction with CCS. Some of these co-benefits are improved soil and water quality, restoration of degraded ecosystems, increased plant and crop productivity, and enhanced oil recovery. However, possible problems also exist, such as developing and implementing the regulatory policies that must accompany CCS (Vine, 2004.) Furthermore, as CCS technologies are relatively new, the downstream effects, both good and bad, of the sequestration are not yet fully understood. Work is being done in order to develop tools and understanding of these downstream effects. One such example is modeling performed by the NETL that used a one-dimensional reactive mass-transport model to predict the long-term chemical behavior of a deep saline aquifer following carbon dioxide sequestration. This model showed that the carbon dioxide injected into brine caused a sharp drop in pH, which resulted in the acidic brine reacting aggressively with aquifer minerals (Strazisar, 2006.)

# 3. LITERATURE REVIEW OF MATERIAL FLOW ACCOUNTING AND ANALYSIS, TECHNOLOGY MARKET PENETRATION, AND GOAL PROGRAMMING

## 3.1. MATERIAL FLOW ACCOUNTING AND ANALYSIS

Since the beginning of mankind, humans have used wide ranges of materials for a variety of purposes and then discarded them when finished. As the number of people on earth has increased and as technology has advanced, the amount of materials flowing through the human environment has grown significantly. This has caused growing concern globally due to not only the shear mass of the materials but also due to the hazards associated with them and the amount, often limited, of the material or resource available. As a result, there has been a movement forming to create and maintain material flow accounts, much like economic accounts, that would be available for review and analysis. A material flow account would account for a material from its entrance into the defined environment to its eventual waste or exit from the defined environment.

**3.1.1. Description of Material Flow Accounts and Analysis.** According to the National Research Council (NRC) Committee on Material Flows Accounting of Natural Resources, Products, and Residuals, material flows accounting is a method for tracking a material's movement into and out of an environment, previously defined, as well as accumulations of stocks within the environment or economy. The environment could be as small as a user-defined region to larger scales, such as nationally or globally (NRC, 2004).

According to Brunner and Rechberger (2004), material flow analysis (MFA) is "a systematic assessment of the flows and stocks of materials within a system defined in space and time." This material flow analysis definition appears to be very close to the material flow accounting definition. The main distinction is that material flow analysis deals with specific problems, regions, or materials, which involves a more focused approach. In analysis, a problem or concern has been identified and a solution is being sought. For example, a use of material flow analysis would be to locate and clean up all the arsenic in a defined region. This would be impossible without accurate material flow accounts of arsenic, but the material flow of arsenic is not useful if it is not being reviewed for a specific purpose. Therefore, material flow accounting and analysis are not the same, but are intertwined since analysis would not prove useful unless good, accurate accounts are available (NRC, 2004). Material flow analyses are even more useful if selected materials are targeted based on identified public policy needs, accounts are developed, and analyses are done to track their flows and impacts.

Three rules govern a material flow analysis. The three rules are as follows (Eurostat, 2001):

1. The first law of thermodynamics,
2. Total Inputs=Net Accumulation + Total Outputs, and
3. All flows have an origin and a destination.

The first law of thermodynamics states that matter is neither created nor destroyed by any physical transformation. Therefore, if a material enters the defined environment, it either has to be in the environment or it has to exit the environment. This law is applicable to the three main categories of material flow analysis—inputs, accumulation, and outputs (Eurostat, 2001).

Developing a material flow analysis involves several procedures. The first is to select the substance or material to be the subject of the MFA. This selection will be dependent on the scope or goals of the study, the grade of precision desired, and the financial and human resources available for the MFA study. The second step involves defining the system in space and time, in other words, defining the environment for the study. The environment's limits can be thought of as a boundary, and the boundary will be dependent on the extent of the project and possibly physical characteristics of the material being studied (Brunner et al; 2004).

After the boundary has been selected, the relevant flows, stocks, and processes must be identified. The flows, stocks, and processes to be incorporated into the model will be chosen based on the objectives, both type and breadth, of the MFA study. Based on the mass-balance principle, the inputs of all mass into a system or process has to equal the mass output plus the mass stored. The storage term accounts for material that is accumulated or depleted within the system (Brunner et al., 2004).

$$\sum_{k_i} \dot{m}_{input} = \sum_{k_o} \dot{m}_{output} + m_{storage} \quad (3.1)$$

where:

$k_i$ = substances input into the system

$k_o$ = substances output from the system

In order to have accurate material flow accounts, the flows within systems and processes must be accurately determined. This leads us to the next step which is the determination of mass flows, stocks, and concentrations. Actual measurements are usually not performed for flows, stocks, and concentrations of materials. Instead, existing data is studied and compiled in order to represent reality. If actual measurements are to be taken, the flows, stocks, and concentrations are usually broken down into smaller more manageable subcomponents. Again, the amount of effort and detail put into this step will be dependent on the objectives and even more so on the resources available for the study (Brunner et al., 2004). Next, an assessment of the total material flows and stocks is performed. "The substance flows (X) that are induced by the flows of goods can be directly calculated from the mass flows of goods (m) and the substance concentrations (c) in these goods, as follows" (Brunner et al., 2004):

$$X_{ij} = m_i * c_{ij} \tag{3.2}$$

where:

i = 1, ..., k as the index for goods

j = 1, ..., n as the index for substances

It is important to note that the error associated with a material balance is rarely less than ten percent of the total flow. Therefore, it is important to review the available data against the objectives of the study in order to determine the usefulness of the results.

The last step of an MFA is to present the results. It is imperative that the results are presented clearly, concisely, and in a manner that is understandable to the intended audience. The two main audiences for MFA's are the technically-minded scientists and policy-makers. Therefore, a comprehensive technical report and a lucid executive summary should be delivered for each MFA (Brunner et al., 2004).

**3.1.2. Uses of Material Flow Accounts and Analysis.** Material flow databases and analyses have already proven useful within U.S. government agencies, as well as, within private organizations. However, their potential is not yet widely understood, appreciated, or realized. Furthermore, the available data is not being used as effectively as it potentially could be if a consistent framework and system were developed in order to collect, analyze, distribute, and organize material flow data. Implementing this type of formal economy-wide material flows accounting system and a national input-output table would likely produce a range of benefits, such as the following (NRC, 2004):

- Federal and state agencies would gain better information on the sources and uses of the mineral and renewable resources within their responsibilities.
- In the pursuit of continuous improvement of economic and environmental performances, corporations would have better information on current and potential supplies of the materials they use, on potential positive and negative environmental impacts of the materials, and on substitutes they could use to supplant undesirable materials in their systems and processes.
- Users of material accounts would be able to track sources, flows, and dispositions of materials to determine more effective strategies for improving environmental and economic performances as well as efficiency of resource use.
- National security strategists would have better data on the sources of materials critical to the U.S. economy and to national security—from energy materials, to rare metals, to widely used material resources.

In support of MFAs, the Environmental Protection Agency (EPA) stated that there are three major public-policy areas in which the federal government's current responsibilities could benefit if regularly assembled MFAs were available. The three major public-policy areas are as follows (EPA, 2004):

- International Trade: Economic trade, national security, and technological development can all be improved by enhancing our understanding of the material basis of the economy.
- Natural Resources: By enriching system-wide, life-cycle information on the status and trends of materials sources and uses and other aspects of supply and demand, natural resource policy can be improved.
- Environment: The environmental policy can be improved by identifying categories of pollution sources, developing materials-based and product-based environmental strategies, and promoting reuse of what is currently discarded.

The Merriam-Webster online dictionary defines sustainability as "of, relating to, or being a method of harvesting or using a resource so that the resource is not depleted or permanently damaged." Taking this definition a step further, Graedel and Allenby (2003) define sustainability, "In the context of industrial ecology, the state in which humans living on Earth are able to meet their needs over time while nurturing planetary life-support systems." From these definitions, it is apparent that a formal MFA system in the United States could act as a useful tool in improving the country's sustainability.

**3.1.3. Coal Material Flow Accounting and Analysis.** Warneke (2004) developed a balanced material flow of coal for the United States using data from 2001. He improved upon the first U.S. coal material flow analysis created by Ayres and Ayres (1998) by adding and analyzing available and updated transparent data. The system boundary was defined by the borders and surface of the country; in other words, once coal enters the country's borders or is extracted from a mine in the United States, the coal is counted in the system (Warneke, 2004).

Figure 3.1 shows the graphical presentation of Warneke's coal MFA.

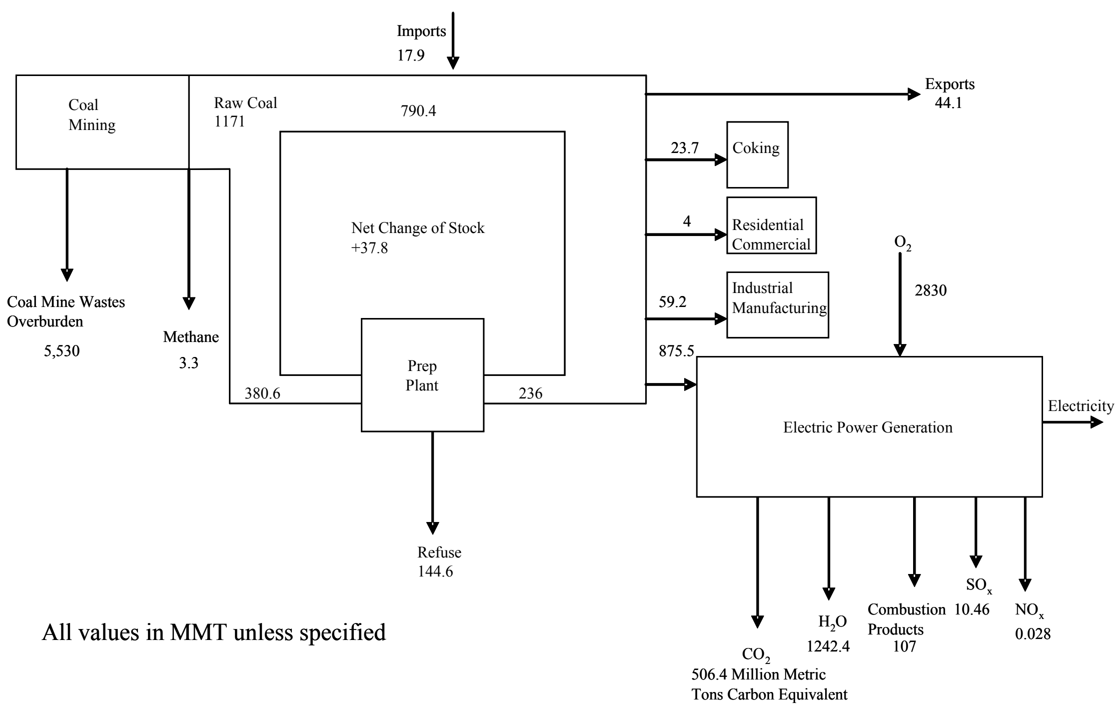



Figure 3.1 Depicts the balanced material flow of coal that was developed using the best available information (Warneke, 2004).

**3.1.4. Hydrogen Produced From Coal.** The latest Annual Coal Report shows that coal produced in the U.S. is used by electric power plants, coke plants, other industrial plants, and residential/commercial applications (EIA, 2005). In data released on December 20, 2006 by the EIA on U.S. Coal Consumption by End-Use Sector, the end-uses include only the above mentioned categories (EIA, 2006). This is noteworthy because it illustrates that hydrogen is not currently being produced from coal in any significant quantity.

Hydrogen can be produced from coal via coal gasification and subsequent separation of the hydrogen from the syngas, and research and development is being performed on these technologies to produce hydrogen from coal. However, these technologies have yet to be commercialized. Currently, coal gasification is mainly being used to produce ammonia for fertilizer (DOE, 2007). Dakota Gasification Company operates the Great Plains Synfuels Plant in North Dakota. It creates synthetic natural gas, fertilizers, solvents, phenol, carbon dioxide, and other chemicals. Again, the issue of importance is that coal is not currently being used to produce hydrogen.

## 3.2. KEY COAL INDICATORS AND RELATED ISSUES

Indicators are used to simplify and quantify vast amounts of data about a particular issue. Through this simplification and quantification, the trends of the issue can be measured and tracked more easily than if the data was not encompassed by an indicator.

In order for indicators to be effective, they must have the characteristics of measurability, analytic validity, cost effectiveness, and simplicity. Indicators must also be relevant to the issue and to key policy and legislation. In other words, successful indicators should be able to directly measure progress against policy goals (New Zealand Ministry for the Environment, 2000).

In 2004, Warneke developed a comprehensive set of indicators for the coal industry. He divided the indicators into seven main categories: economic, environmental, social, economic-environmental, economic-social, environmental-social, and economic-environmental-social. See Appendix A for more detailed information.

Warneke selected a list of key coal indicators out of the comprehensive lists found in Appendix A. The final selection of the key indicators are meant to be "a quick reference to get the pulse of the industry's impact." The criteria used follow (Warneke, 2004):

- Indicators must pertain to the coal industry.
- Indicators must be of national scope.
- Indicators must provide a basis of comparison to other energy sources.
- Indicators addressing all inputs and outputs of the MFA accounting of coal must be included.
- Indicators must be capable of being linked to various models for forecasting and other various uses.

Warneke wanted to provide a more manageable set of indicators that could be used by policy-makers and society to easily obtain a transparent view of the coal industry and its impacts on the economic health, environmental health, and the quality of life in the U.S. The fifteen core coal indicators selected are the following (Warneke, 2004):

- Global warming emissions
- Acidifying emissions

- Water quality
- Land disturbed
- Land reclaimed
- Cost of electricity
- Coal production
- Coal consumption
- kWh produced by coal
- Reserves
- Heavy metals
- Worker health
- Public awareness of coal's usage
- Company sustainable community spending
- Clean coal spending

**3.3. TECHNOLOGY MARKET PENETRATION**

Technologies vary greatly. However, the manner in which technologies evolve is similar, regardless of what the technology is. According to Graedel and Allenby, "At all scales, technology tends to exhibit the familiar logistic growth pattern: it begins in research, invention, and innovation; experiences exponential growth as it is introduced into the market; peaks at market saturation; and is usually replaced by a newer technology as the original becomes obsolete." This growth pattern holds true for popular inventions such as electricity, color television, air conditioning, and computers, just to name a few (Graedel et al., 2003).

Raymond Kurzweil, a highly acclaimed author, scientist, and futurist, is well-known for his advances in artificial intelligence as well as his technology penetration prediction models. He expands upon Moore's Law, which is the name given to the trend of the semiconductor industry doubling the price and performance of its products approximately every eighteen months, which encompasses an example of disruptive technologies (Burgelman et al., 2004). Kurzweil extended Moore's Law to include technologies available before the integrated circuit to future computing technologies. Kurzweil believes that anytime a current technology hits a barrier that a new technology will be invented that overcomes the barrier and promotes a paradigm shift (Raymond Kurzweil, 2007). Kurzweil elaborates on exponential growth in technology resulting from a cascade of "s" curves, "There is an s curve for each paradigm: very slow, almost flat, initial growth until acceptance, then a period of rapid penetration and exponential growth, then a flattening out as the particular paradigm reaches its limits (Kurzweil, 2001)." This concurs with Graedel and Allenby's take on technology evolution.

Technology does grow exponentially. However, the exponents vary, and the challenge is to determine what the exponent will be for a given technology. Kurzweil estimates that the annual exponent of growth for information-based industries is 2 or more. However, growth is slower in industries that are not information-based, such as transportation and energy technologies (Kurzweil, 2001).

**3.3.1. Market Penetration of Existing Technologies.** Graedel and Allenby supplied a graph which is represented in Figure 4.1 showing the U.S. consumer technology penetration rates of a variety of technologies. The resultant trends support the exponential nature of idealized technology lifecycles (Graedel et al., 2003).

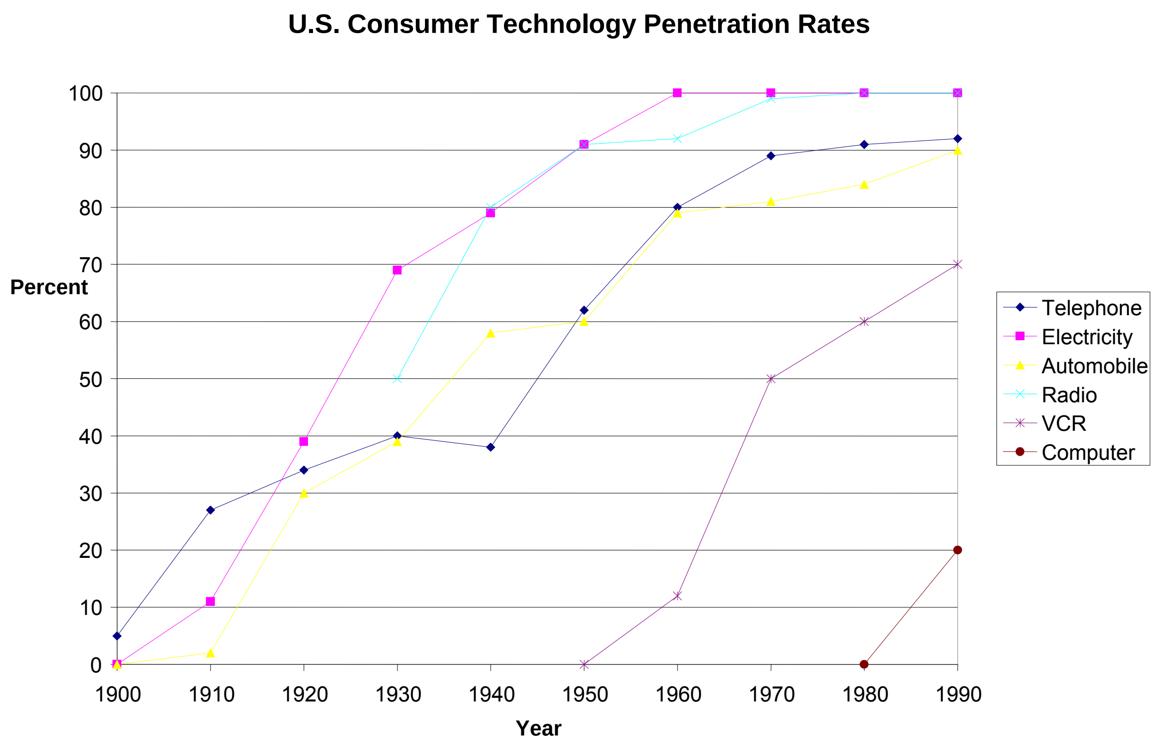



Figure 3.2 Consumer Technology Penetration Rates (Graedel et al., 2003).

Kurzweil also created a Mass Use of Inventions graph showing the number of years it took until one-fourth of the U.S. population used a given technology. This graph, shown in Figure 3.3, clearly illustrates the trend of technological inventions penetrating more quickly as time progresses. For example, the television took almost thirty years before it was used by one-fourth of the U.S. population in 1926, compared to only the seven years it took for the web to be used by one-fourth the U.S. population in 1992.

Again, Figure 3.3 further represents the exponential growth characteristic of technologies (Kurzweil, 2007).

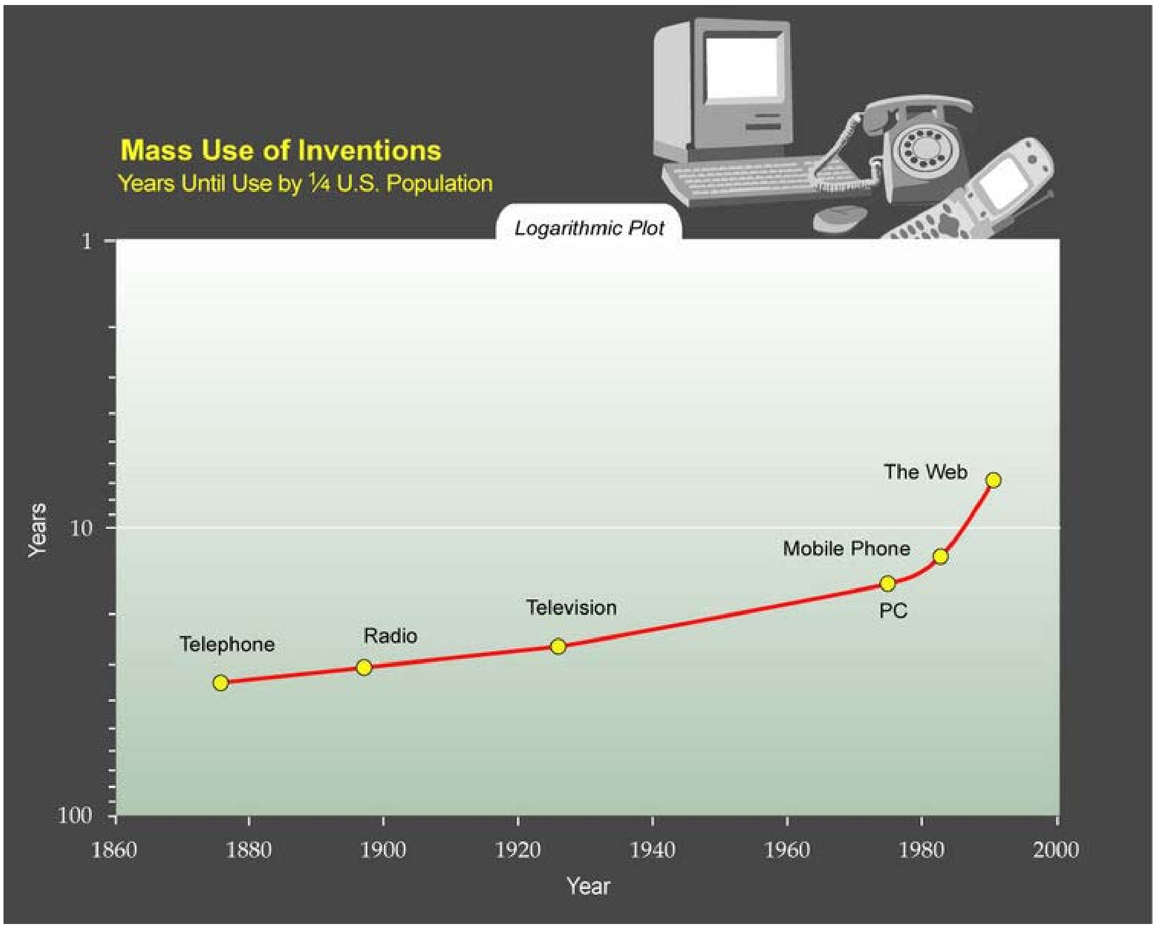



Figure 3.3 Mass Use of Inventions.

**3.3.2. FutureGen Planning.** The FutureGen Alliance[3] supplies Figure 3.4 which shows the timeline for establishing the first FutureGen plant. According to this timeline, full-scale plant operations should occur in year 2013.

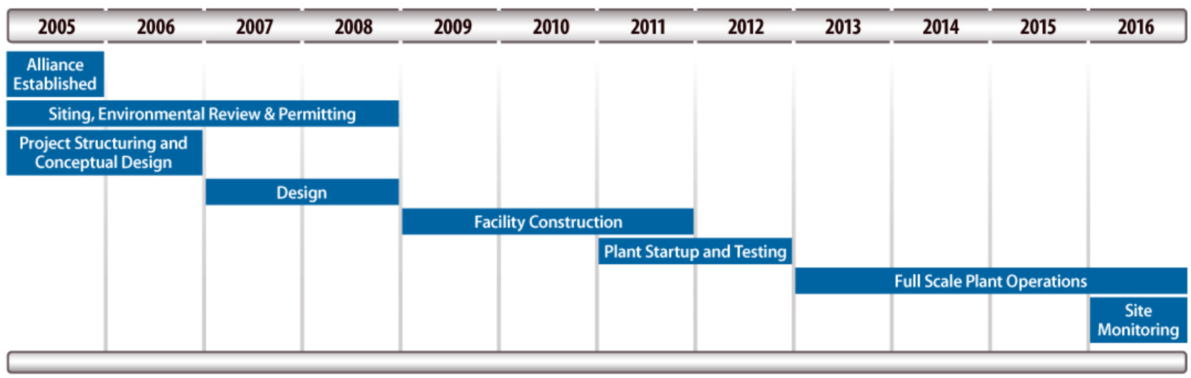



Figure 3.4 FutureGen Timeline (FutureGen, 2007).

The U.S. Department of Energy's Hydrogen Posture Plan graphically laid out the government's and industry's role in transitioning to the Hydrogen Economy. Figure 3.5 displays this.

[3] The FutureGen Alliance is a non-profit international consortium that has teamed with the U.S. Department of Energy to design and construct the FutureGen plant.

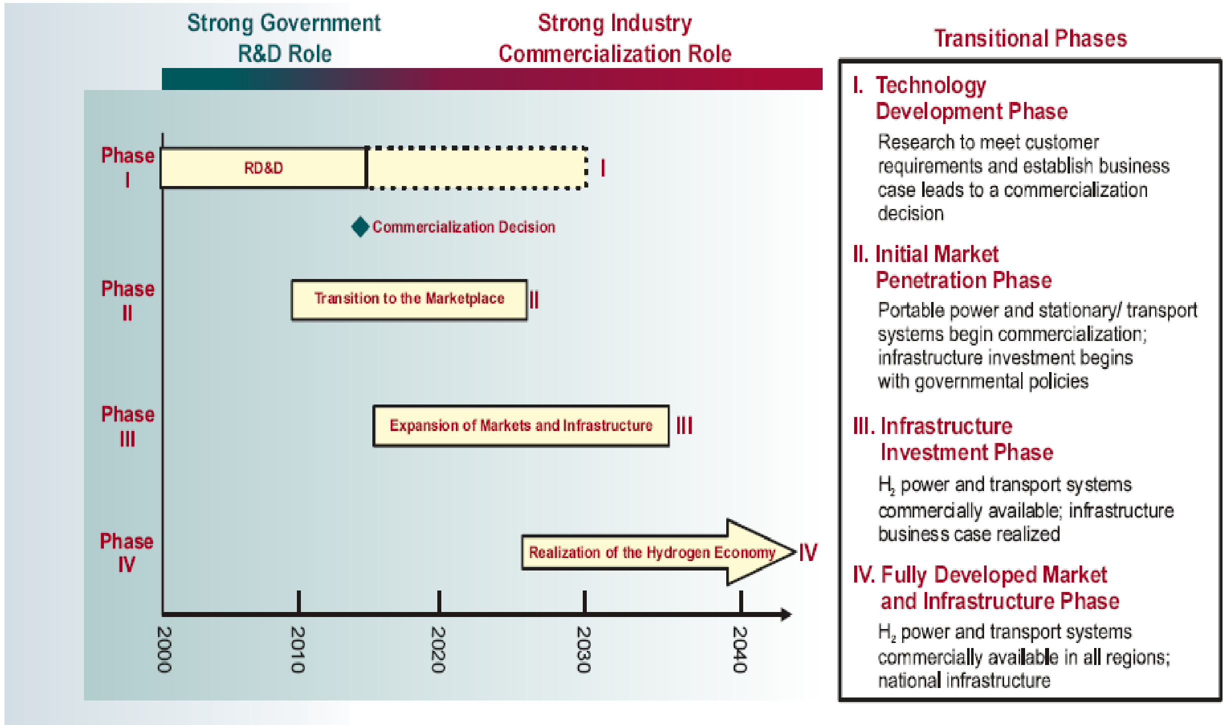



Figure 3.5 Government-Industry Roles in the Transition to a Hydrogen Economy (DOE, 2004).

Comparing Figures 3.4 and 3.5, year 2013, when the first FutureGen Plant will begin full-scale plant operations coincides with the Hydrogen Posture Plan's designated "Commercialization Decision" as well as the beginning of phase three which is "Expansion of Markets and Infrastructure." Therefore, the two charts seem to coincide with planning estimates.

According to Figure 3.5, realization of the hydrogen economy will start to take place around the year 2025. Before this can happen, the "chasm" of the technology adoption life cycle must be crossed. Figure 3.6 was adapted from Exhibit 3 on page 365 of the fourth edition of Strategic Management of Technology and Innovation.

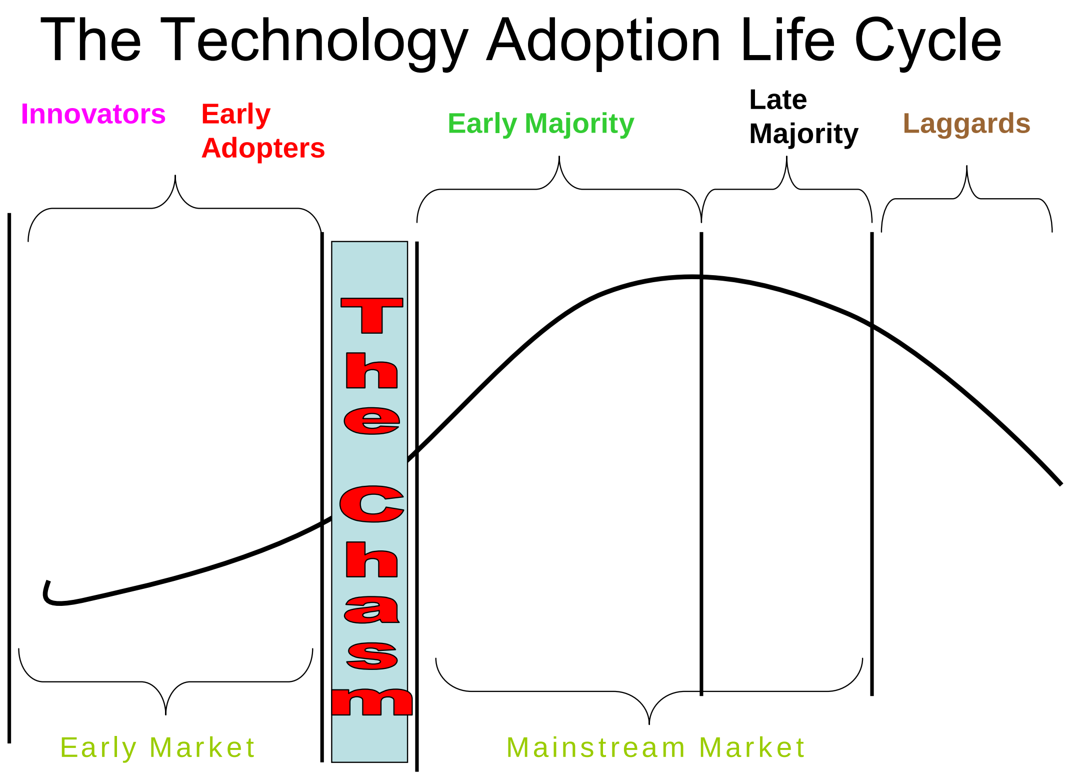



Figure 3.6 The Technology Adoption Life Cycle (Burgelman et al., 2004).

Figure 3.6 is yet another example describing how technologies penetrate the market. From the beginning to the mainstream market, the "s" curve is apparent as well as exponential growth. Again, the key is to cross the chasm. This feat usually occurs by an industry or manufacturer finding a niche market within a given technology. The technology is then designed to fit the needs and desires of that niche market. As a result, a whole product is produced that fits 100% of the needs of a niche group of people. The purpose of a "whole product" is a product that wholly fits all the needs and desires of a certain group. Experience has shown that creating a product that meets some of the needs of multiple groups does not result in any of the groups adopting the product. Therefore, crossing the chasm is the first step into the mainstream market. Although a niche is a smaller group, penetrating this group provides some momentum and resources to build upon the technology in order to create products that meet even more people's needs within the mainstream market (Burgelman et al., 2004).

The Hydrogen Economy is just on the cusp of the "early adopters" phase. Hydrogen-powered transportation appears to be the Hydrogen Economy's first niche market, since many car companies already have prototypes of fuel cell-powered cars. The major car companies such as DaimlerChrysler, Ford, General Motors, Honda, Hyundai, Nissan, Toyota, and Volkswagen all have fuel-cell vehicles, some are as far into design as having a sixth generation model. In California, Governor Schwarzenegger has developed a Hydrogen Highway Network Action Plan (CaH2Net). The goal of this plan is that everyone would have access to hydrogen fuel along California's major highways, more specifically there would be a hydrogen fueling station every twenty miles. In active support, fuel -ell vehicles have been introduced into the government's fleet. There are currently 23 hydrogen fueling stations in operation in California and fourteen more are in the planning phase. Through this program, Governor Schwarzenegger and supporters of the California Fuel Cell Partnership hope to promote awareness and commercialization of fuel-cell vehicles in order to achieve a cleaner, more sustainable future (California, 2007).

### 3.4. GOAL PROGRAMMING

Goal programming is a branch of multiple objective programming and is primarily an extension of linear programming to handle multiple, often conflicting objective measures. The highest priorities are satisfied first and then the lower priorities are addressed. The objective function searches to minimize deviations away from a predefined goal or target. Charnes, Cooper, and Furguson were the first to use goal programming (Charnes, 1955.) Application of goal programming to engineering problems was first performed by Ignizio, in regards to antenna placement on the second stage of the Saturn V. Goal programming was popularized by applications performed by Ignizio (1976), Lee (1972), and later Romero (1991).

#### 3.4.1. Historical Applications in Economic Trade-Offs and Policy-Making

Early applications of goal programming dealt with economic trade-off applications. Goal programming has been applied more widely into areas such as policy-making. Goal programming can be applied in economic trade-off applications in a wide variety of areas such as portfolio profit maximization to simply managing a budget. For example, goal programming can be utilized to optimize IT investment decisions within a company. Furthermore, this type of model will show the economic trade-offs, such as foregoing maintenance or upgrades resulting in earlier replacement of equipment (Schniederjans, 2003.) Another application involves using goal programming to optimize house/property purchasing decisions. This example obviously illustrates the power of user-selected goals or preferences within the model (Schniederjans, 1995.)

Asset management can also be aided with goal programming. The objective is to preserve the long-term value of physical assets in the most cost-effective way. Careful planning, preventive maintenance, and resource management are emphasized. The New York State Department of Transportation (NYSDOT) implemented a Transportation Asset Management (TAM) System that utilizes goal programming to conduct economic tradeoff analysis to compare dollar value to customer benefits to investment costs among competing investment options. This system aids the NYSDOT in making decisions on not only what highway projects should be funded, but also in developing guidelines for items such as design, construction, and maintenance standards (FHWA, 2007.) This example shows that goal programming applications that evaluate economic tradeoffs can lend themselves easily to aiding with policy-making decisions. The policy-making decisions in the example are signified by the resulting standards in design, construction, and maintenance of the roadway projects undertaken and managed by the NYSDOT.

Bioeconomic models can also employ goal programming. For example, a model was created for common fisheries in the English Channel that incorporated the multiple objectives of maximizing overall economic profits, maintaining employment and insuring stable relations between France and the UK Fisheries policy could then be developed that promoted the well-being of the multiple objectives (Pascoe, 2001.)

**3.4.2. Goal Programming Algorithms.** The simplex algorithm is a popular algorithm for solving linear programs, including goal programming models. Variations of the simplex algorithm, such as Lee's modified simplex and the dual simplex, have been developed to address specific situations (Olson, 1984). The simplex algorithm is the central computational element for mathematical programming systems, which are computerized procedures for solving linear programs. Due to the widespread proliferation of linear programming applications, these computer programs are also widespread due to the ability to provide solutions to problems with many constraints in a reasonable amount of computational time. The simplex method has been proven to work well in practice.  It has also proved to be very efficient with efficiency measured by the number of iterations required (Gass, 1995.)

# 4. PENETRATION MODELS OF FUTUREGEN

A unique contribution of this research is the development of market penetration models for FutureGen plants. The importance of this contribution arose when first examining how the Hydogen Economy would impact the coal industry. Before possible increased demand for coal, the initial impact is the transition from the traditional use of coal in coal-fired power plants to plants with the ability to produce hydrogen, such as FutureGen plants. In other words, if coal is to be a feedstock for the Hydrogen Economy, then processes must be in place to generate marketable hydrogen for use in the Hydrogen Economy. This transition is key. Realization of the Hydrogen Economy is not a definite, but electricity demand is. For the purposes of this dissertation, the market penetration of the coal-based Hydrogen Economy is assumed to be dependent upon the success and penetration rate of FutureGen plants. The penetration rate of FutureGen is assumed to be dependent on electricity demand, with the driving forces for constructing FutureGen plants being environmental concerns and the ability to produce hydrogen as a value-added product. Once the penetration of FutureGen plants is estimated, the amount of hydrogen that could be created for use in the Hydrogen Economy can be deduced. The option to create hydrogen at FutureGen plants will be incorporated into the goal programming model in Chapter 6.

## 4.1. PENETRATION OF FUTUREGEN PLANT TECHNOLOGIES INTO NEW AND EXISTING COAL-FIRED POWER PLANTS

The objective of this section is to predict the capacity of new FutureGen plants that will be constructed in the 40 years following 2012; 2013 is the year that full-scale plant operations of the first FutureGen plant should occur. The capacity of FutureGen plants will be determined by developing market penetration models for FutureGen plants, and applying these penetration models to the new electricity-capacity market. This market consists of the amount of capacity additions and replacements for a given time period. Therefore, the objective also encompasses estimating the capacity of existing coal-fired power plants that will be replaced or upgraded within this same timeframe[4]. The assumption of this dissertation is that hydrogen demand will not drive FutureGen plant construction, but instead that plants will want to switch to this type of technology since it is better for the environment (fewer emissions) and the hydrogen created is a value-added product. Therefore, the overall amount of coal-fired power plants predicted will be estimated solely on electricity demand.

**4.1.1. New Coal Capacity Additions.** According to the National Energy Technology Laboratory using data derived from the EIA Annual Energy Outlook 2006, 154 GW of new coal capacity will be added by 2030. The graph provided showed capacity additions in five time periods ranging from 2004 through 2030 and the source, i.e. natural gas, coal, or renewables. The coal information has been compiled into Table 4.1 (NETL, 2007).

[4] The timeframe will be from the end of 2012, i.e. the beginning of 2013, to the end of 2052.

Table 4.1 New Coal Capacity Additions

| Time Period | Capacity Additions (GW) | # of 500 MW Plants Added |
|---|---|---|
| 2004-2010<br>(2006-2010) | 12<br>(8.6) | 24<br>(17) |
| 2011-2015<br>(2011-2012)<br>(2013-2015) | 4.5<br>(1.8)<br>(2.7) | 9<br>(4)<br>(5) |
| 2016-2020 | 26.1 | 53 |
| 2021-2025 | 44.5 | 89 |
| 2026-2030 | 66.9 | 134 |

According to this data, the number of coal-fired 500-MW plants added each five-year period increases by approximately 40 plants from the previous five-year period. This extrapolation begins with the 2011-2015 time period since the timeframe this dissertation is concerned with (2012-2052) begins in this time period. Taking this a step further, the number of 500-MW coal-fired power plants added in subsequent time frames, based on the addition of approximately forty 500-MW plants per five year period, could be approximated based on the above data as follows:

Table 4.2 Extrapolated New Coal Capacity Additions

| Time Period | Capacity Additions (GW) | # of 500 MW Plants Added |
|---|---|---|
| 2031-2035 | 87.5 | 175 |
| 2036-2040 | 107.5 | 215 |
| 2041-2045 | 127.5 | 255 |
| 2046-2050 | 147.5 | 295 |
| 2051-2052 | 155.5 | 311 |

Therefore, in the timeframe from the end of 2012 (beginning of 2013) to the end of 2052, it is predicted that approximately 1,532 new 500-MW plants will be added, or an additional 766 GW. This extrapolation was not highly scientific, but it is deemed reasonable and appropriate due to the nature of the prediction data presented and also due to the fact that a sensitivity analysis will be done with this estimated data. An area of future work will be to analyze the increase in coal-fired power plants past year 2030. Once these predictions have been made, the information should be able to be easily incorporated into the work of this dissertation.

An important contribution of this research will be to forecast coal MFA's based on increased coal-powered electricity demand, with potential FutureGen penetration. The AEO 2006 estimates that coal production will increase an average of 1.1 % per year from 2004 to 2015, and then will grow even stronger and increase at an average of 2.0% per year from 2015 to 2030. This increased coal production estimate was not incorporated into the electricity demand predictions or model because it would be too restrictive. A goal of the research is to predict the amount of coal that will be required based on electricity demand with FutureGen penetration, and not to base additional capacity capabilities on increased coal production estimates.

**4.1.2. Existing Coal Capacity to be Replaced.** The next step is to determine the amount of existing coal-fired power plants that will be replaced in the 2012-2052 timeframe. Weir International, Inc. distributed "Overview of the United States Coal Mining Industry," which included a list of coal-fired power plants having demonstrated capacity of 100 MW or greater as of July 2006. This list included 346 plants with a combined demonstrated capacity of 288,390 MW (Weir International, Inc. 2006.)

According to the EIA (2005), coal had 1,522 generators with a combined nameplate capacity of 335,892 (EIA, 2006). Performing a loose comparison of these reports, there is a difference of 1,176 plants and 47,502 MW. The discrepancies are most likely due to that fact that Weir's report is from July 2006 and only includes plants with 100 MW and greater capacity, and EIA's report is from 2005 and includes all plants. Also, the comparison is between nameplate capacity (EIA) and demonstrated capacity (Weir.) The total capacity accounted for in the Weir report accounts for 86% of the total capacity identified by EIA. Therefore, the Weir report was originally designated to be used as a basis for estimating the number and capacity of coal-powered electric plants to be replaced in the timeframe 2012-2052. This was deemed appropriate for the purposes of this dissertation since the predictions are estimated based on the best information available and since a sensitivity analysis will be performed in order to account for probable variations from the predictions that will no doubt be realized in the next 40-plus years. Furthermore, the Weir report includes the larger plants, which will be more likely to implement FutureGen-type technologies than smaller plants. However, subsequent detailed information about specific plants named in the Weir Report and their estimated closure and replacement dates were not found. Therefore, the research needed to take a more general approach to estimating replacement capacity throughout the timeframe. The research then went into determining the ages of existing coal-fired power plants in the United States.

According to Pratts UDI Electric Power Plants Data Base, about 50 percent of the United States coal-fired power plants went into operation before 1970 (ASME, 2007.) At this time, the estimated life of a plant was approximately 25 years. However, due to life extensions created by refurbishing boiler parts, upgrading the turbines, adding flue gas cleaning to meet new emission regulations, and the conservative nature of original plant designs, plant life can be and has been demonstrated to reach more than 50 years. According to the IEA Clean Coal Centre, units in operation for more than 25 years account for more than 45% of the plants in operation today (IEA, 2006.)

Aside from these general statistics, there is not information readily available on the estimated closing dates of coal-fired power plants. Therefore, an assumption must be made as to how many plants, or more generally how many MW, will be replaced each year within the designated timeframe of 2012-2052[5]. Therefore, for the purposes of this dissertation, in order to determine the available capacity at the end of year 2012, the previously mentioned EIA capacity of existing coal-fired power plant generators in 2005 (335,892 MW) will be added to the expected capacity additions from 2006 to 2012 (10,400 MW). Therefore, at the beginning of the 2012-2052 timeframe, there is expected to be approximately 346,300 MW total capacity available.

During each year of the timeframe 2012-2052, there will be capacity additions as well as replacement of existing capacity with newer power plants. Due to the vague nature of plant-closing information, it was assumed that 1% of the total capacity available at the end of year 2012 will be replaced each year during the timeframe. In other words, each year there will be coal-fired power plants constructed to create new capacity as well as replace the capacity of plants that will be closing. Over the 40-year timeframe, 40% of the existing capacity at the end of year 2012 will be replaced. This sum meshes with the

---

[5] This area lends itself keenly to future work; the future work being an analysis of existing power plants and the amount of life left and plans for rehabilitation or reconstruction.

general statistics previously mentioned about almost half of the existing power plants today went into operation before 1970. Therefore, it stands to reason that almost half will be replaced during the timeframe used in this dissertation.

One percent of the estimated "existing" capacity of 346,300 MW at the end of year 2012 is 3,463 MW. Over the next forty years, 138,520 MW will be replaced by new power plants. The following chart shows new coal-fired power-plant capacity combined of both new capacity and replacement of existing capacity.

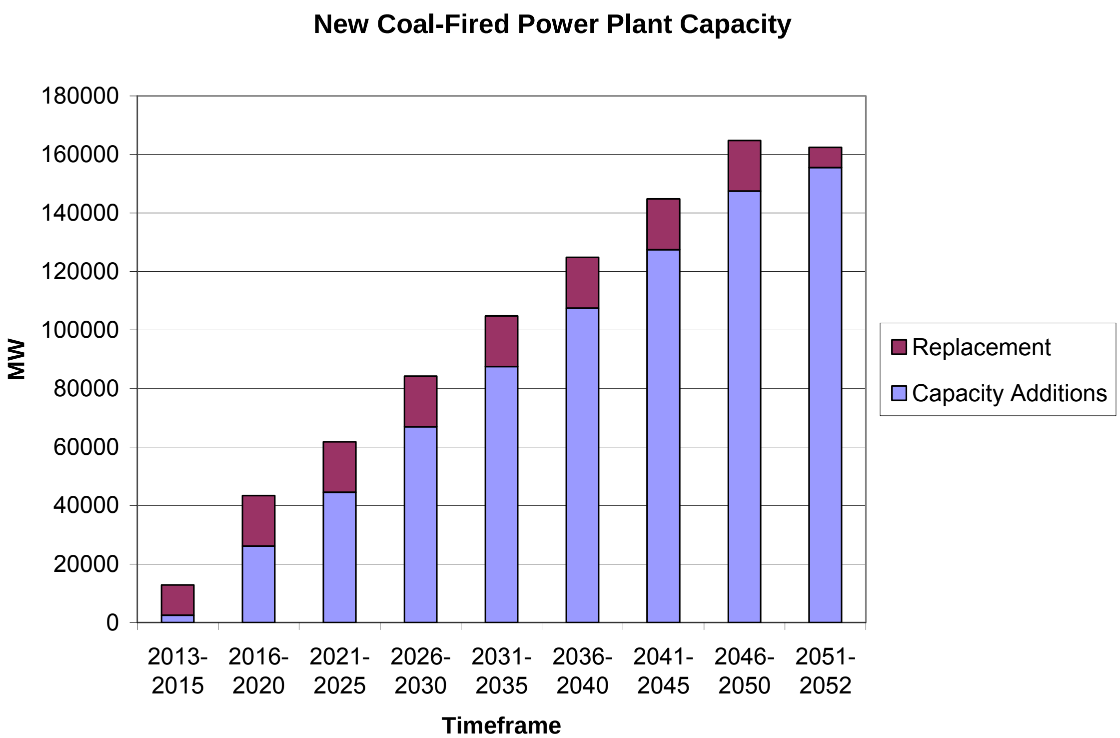



Figure 4.1 New Coal-Fired Power-Plant Capacity

**4.1.3. Megawatt to Metric Tons of Coal Equation for Traditional Electric Power Generation.** In traditional electric power generation from coal, assuming 100%

efficiency, 1 MW of electricity requires 1,306.5 metric tons of coal[6]. Efficiency of 100% was named due to the straight-forward nature of the energy conversions. However, traditional coal-fired power-plant efficiency is not even close to 100%.

In a 2002 presentation at the Annual Gasification Technologies Conference, Dale Simbeck, Vice President Technology SFA Pacific, Inc. commented on the “real” efficiency of typical coal units being about 35%. He continued to discuss the decreases in efficiency that will be caused by modifying existing plants to meet new emissions standards (Simbeck, 2002.)

Information reported by the Energy Information Administration was used to determine approximate average efficiencies of coal-fired power plants in the United States from 2001 to 2005. The efficiency percentages were determined by looking at the coal consumed by electric generation, calculating the amount of electricity that could theoretically be produced from this amount of coal, and then looking at the actual electricity produced from the coal. Refer to Table 4.3.

[6] This is estimated with unit conversions and with the following energy equations: 1 kW-hr = 3.6 MJ; 1 MJ = 0.00004143 metric tons of coal (Energy Calculator, 2007.)

Table 4.3 Coal-Fired Power Plant Calculated Efficiencies

| Year | Coal Consumption by Electric Power Sector EIA Table 7.3 (MMT) | Straight Energy Conversion (MW) | Actual Electricity Generated from Coal EIA Table 8.2b (MW) | Efficiency (actual electricity generated/straight energy conversion) |
|---|---|---|---|---|
| 2001 | 874.9 | 669,636 | 214,932 | 0.321 |
| 2002 | 886.8 | 678,732 | 218,105 | 0.321 |
| 2003 | 911.8 | 697,896 | 222,911 | 0.319 |
| 2004 | 922.0 | 705,673 | 223,425 | 0.317 |
| 2005 | 942.6 | 721,435 | 227,454 | 0.315 |

The resulting percentages of roughly 32% coincide with Dale Simbeck’s approximation of about 35%. Therefore, in this dissertation, an efficiency of 32% will be assumed for traditional coal-fired power plants. Incorporating the efficiency of 32% into the relationship between metric tons of coal and resulting megawatts of electricity, produces the following:

1 MW = (1,306.5 metric tons of coal)/(0.32) = 4,082.8 metric tons of coal.

#### 4.1.4. Megawatt to Metric Tons of Coal Equation for FutureGen Plants.

Using energy conversions already described in previous sections, 1 MW of electricty requires 1,306.5 metric tons of coal. However, the efficiency of FutureGen must be taken into account. According to a 2005 presentation by Dr. Jeff Phillips with the Electric Power Research Institute (EPRI), the net coal to power efficiency of an Integrated Gasification Combined Cycle (IGCC) power plant is 43% (Phillips, 2005). However, in order to estimate the efficiency of a FutureGen plant, IGCC efficiency must be combined with the efficiency cost of carbon dioxide sequestration. According to a 2007 Cost and Performance Baseline for Fossil Energy Plants report by DOE/NETL, net plant efficiencies for three IGCC plants decreased an average of 18.8% when carbon dioxide sequestration was added (NETL, May 2007). Therefore, the efficiency of a FutureGen plant will be estimated to be 35% (43% decreased by 18.8%) in this dissertation.

Incorporating the efficiency of 35% into the relationship between metric tons of coal and resulting megawatts of electricity, produces the following:

1 MW = (1306.5 metric tons of coal)/(0.35) = 3732.9 metric tons of coal.

**4.1.5. Calculation of Hydrogen Produced from a FutureGen Plant.**

According to EPRI, if just 1% of the syngas produced from a 500 MW IGCC plant is used to produced hydrogen, enough hydrogen would be produced to fuel 10,000 vehicles (Holt, 2004). Referring again to Dr. Phillips presentation showing the energy losses of a coal-fueled IGCC plant and incorporating the decrease in efficiency due to carbon dioxide sequestration, approximately 1,140 MW of syngas would be produced in a 500 MW plant. One percent of this amount is 11.4 MW, which is the amount to fuel 10,000 vehicles for one year; 14.25 MW of coal are required in order to produce 11.4 MW of syngas (Phillips, 2005). Since efficiencies are already taken into account, the amount of coal equating to 14.25 MW coal can be found as follows:

14.25 MW coal x (1000kW/MW) x (365 days/yr) x (24hr/day) x (3.6MJ/kW-Hr) x (0.00004143 metric tons of coal/MJ) = 18,618 metric tons of coal (4.1)

The amount of hydrogen to fuel 10,000 vehicles for a year equating to 11.4 MW of syngas can be found as follows:

11.4 MW coal x (1000kW/MW) x (365 days/yr) x (24hr/day) x (3.6MJ/kW-Hr) x
(1 kg $H_2$/130 MJ) = 2,765,465 kg $H_2$ (4.2)

One kilogram of Hydrogen equals 130 MJ (Ramage, 1983). Therefore, 276.5 kg of $H_2$ is required to fuel one car for one year. Using these relationships, equation (4.3) can be found to represent Hydrogen production in a FutureGen plant.

2,765,465 kg $H_2$ / 18,618 metric tons of coal = 149 kg $H_2$ /metric ton of coal (4.3)

From equations (4.1), (4.2), and (4.3), it can be determined that a FutureGen plant consumes 1 MW-yr of electricity to produce 5,531 kg of $H_2$.

**4.1.6. Plant Utilization and Availability.** Plant utilization and availability must also be taken into account. Plants have a demonstrated capacity but do not run at this rate all day, everyday. Therefore, a factor must be applied to the plant capacity in order to predict how much coal will be consumed and how much electricity will be produced based on the estimations of capacity additions and replacements in the timeframe of 2012-2052. Again, utilizing EIA data similarly to Table 4.3, Table 4.4 was created using actual data for the United States in order to get a real estimation of the combined utilization and availability factor. Using the information in Table 4.4, a combined utilization and availability factor of 75% will be selected to be used during the given timeframe of 2012-2052 for traditional coal-fired power plants, i.e. traditional electric power generation.

Table 4.4 Coal-Fired Power Plant Combined Availability and Utilization Factor

| **Year** | **Actual Electricity Generated from coal EIA Table 8.2b (MW)** | **Electric Net Summer Capacity Electric Power Sector EIA Table 8.11b (MW)** | **Combined Availability and Utilization Factor** |
|---|---|---|---|
| **2001** | 214,932 | **309,800** | **0.69** |
| **2002** | 218,105 | **311,000** | **0.70** |
| **2003** | 222,911 | **308,500** | **0.72** |
| **2004** | 223,425 | **308,800** | **0.72** |
| **2005** | 227,454 | **309,100** | **0.74** |

Since the first FutureGen plant is not yet in operation, availability and utilization data for the plant is not available. Frank Burke of CONSOL Energy Inc. discussed targeted availability of new plant technology (such as FutureGen). He targeted greater than 85% availability in 2010 and greater than 90% in 2020 (Burke, 2004.) A combined factor of 85% will be used in this dissertation for the availability and utilization factor for FutureGen Plants.

**4.1.7. Summary of Plant Efficiencies and Availability/Utilization.** Table 4.5 summarizes the assumptions to be used in this dissertation during the timeframe of 2012-2052 for plant efficiency and combined availability and utilization.

Table 4.5 Assumed Efficiency and Availability/Utilization Summary

| Plant Type | Efficiency Factor | Combined Availability and Utilization Factor |
|---|---|---|
| Traditional Coal-Fired | 0.32 | 0.75 |
| FutureGen | 0.35 | 0.85 |

**4.1.8. Penetration Curve for FutureGen Plants.** The next step will be to estimate the penetration curve of FutureGen Plants. Many penetration theories have been developed with the objective of predicting the market adoption of a new technology. The California Energy Commission's Final Report Compilation for Impact Assessment Framework outlines market penetration approaches provided by the Electric Power Research Institute (EPRI). EPRI states that the rate of market penetration is primarily influenced by the marketing effort, product characteristics, characteristics of potential adopters, and market characteristics. The two market penetration approaches outlined by EPRI include Judgmental Methods and Model-Based Methods (California Energy Commission, 2003).

Judgmental methods are based on qualitative information more than quantitative data. The forecaster relies on his/her own experience and perceptions in order to create "S"-shaped market penetration curves. Since they are not based on well-specified algorithms, they are hard for others to recreate. However, judgmental methods tend to be used more often than model-based methods since judgmental methods take less time to develop, are based on qualitative data, and require less technical skill to implement and interpret (California Energy Commission, 2003).

Model-based methods rely on quantitative data in order to create well-defined algorithms that can be utilized to process and analyze data. Since adequate quantitative data is required, these models usually cost more to create and are much more time consuming than judgmental methods. As a result, model-based methods are not used as widely as judgmental models (California Energy Commission, 2003).

The judgmental method will be used in this dissertation for creating market penetration curves for FutureGen plants. The judgmental method was selected since the first FutureGen plant is not currently fully operational and as a result, quantitative data does not exist to be incorporated into a model-based method. Due to the selection of the judgmental method, extensive literature review and study of related issues to FutureGen penetration was determined to be necessary and performed in order to provide a solid knowledge base from which to draw information to be incorporated into applying the judgmental method. As mentioned above when discussing judgmental methods, an “S”-shaped curve is selected to model the market penetration. Historically, when dealing with technology trend analysis, the three functional sigmoidal forms applied are the Gompertz Curve, the Pearl-Reed Curve, and the Fisher-Pry Curve. The appropriate curve to use depends on the dynamics of the system. The Fisher-Pry Curve, for example, was developed by two researchers (Fisher and Pry) who discovered a relationship between time and replacement of an older technology with a newer one (Yu, 2007.) Since this dissertation is examining the market penetration of FutureGen technologies replacing older coal-fired power-plant technologies, the Fisher-Pry Curve will be used.

The following equation, originated by Fisher and Pry, represents market penetration as a function of time for new products:

$$M(t) = \frac{1}{1 + e^{-c(t-h)}} \tag{4.4}$$

where

M(t) is the fraction of market penetration at time t,

t is the time indexed in years,

h is the time at which half of the market is penetrated, and

c is the parameter determining the rate of penetration.

An adaptation of the Fisher-Pry model specifies the time period s required for the product to go from penetrating 10% to 90% of maximum penetration. Furthermore, a variable, k, expressing the total potential market share is defined, which constitutes the asymptotic limit as t goes to infinity. This specific solution is as follows:

$$M(t) = \frac{k}{1 + e^{-(\ln(81)/s)(t-h)}} \tag{4.5}$$

where

k is the total potential market penetration

t is the time indexed in years

h is the time at which half of the market is penetrated, and

s is the time period required to transition from F=0.1 to F=0.9.

This specific solution is very intuitive and is a useful tool with which to elicit expert judgment about plausible market penetration scenarios (California Energy Commission, 2003). This equation will be used to model the predicted penetration of FutureGen in this dissertation.

The variables k, t, h, and s must be defined for FutureGen plants/technologies. The Annual Energy Outlook 2006 addressed advanced coal power via FutureGen, advanced fuel cells, and hydrogen as potential electricity sources. However, it did not incorporate these technologies into its main reference case or into its models or projections in any significant manner. The main reason given for this was that the technologies in these areas are currently too underdeveloped and/or expensive to be competitive within the market. It was acknowledged that with significant technological progress and successful developments in these areas, that they could then have an impact in the market in later years (EIA, 2006). As a result, the penetration estimates formulated in this dissertation will be independent of the AEO 2006 projections. A high (fast) penetration will be developed as well as four low (slow) penetrations. From the high and each of the low scenarios, a middle or average penetration will be developed. These four FutureGen penetration scenerios will be applied to the previously defined market.

The variable k is the total potential market penetration. For the high-penetration scenario, the potential market penetration of FutureGen plants/technologies will be assumed to be 100% due to the increasingly stringent environmental regulations and the fact that FutureGen plants are far superior environmentally than traditional coal-fired power plants. The k for the first low-penetration scenario will be 50%, since FutureGen plants and technologies are not yet proven and may require more time in order to get fully functional. Also, a competitive technology could enter the market which would make 100% market penetration unlikely. Low-penetration scenarios of 45%, 40%, and 35% will also be examined. The variable t which is the time indexed in years will be 40 years total (2012-2052) for all scenarios. The variable h is the time at which half of the market is penetrated. For the high-penetration scenario, h will be 13 years which approximately corresponds to year 2025 which is predicted to be halfway through the "Expansion of Markets and Infrastructure" in the Transition to the Hydrogen Economy Timeline Figure 3.5. The low-penetration scenarios will designate h as 23, which approximately corresponds to the end of the "Expansion of Markets and Infrastructure" timeframe. Again, the variables were defined based on the judgmental method.

The last variable to be defined is s, which is the time period required to transition from F=0.1 to F=0.9. In the high-penetration scenario, s will be 20 years, and in the low-penetration scenario, s will be 30 years. Analyzing Figure 3.2, it is apparent that the approximated "s" for the automobile was 77 years, 41 years for electricity, and 67 years for the telephone. Figure 3.3 shows the amount of time it will take one-fourth of the U.S. population to adopt a given technology. According to Figure 3.3, the Web took 7 years to accomplish this. FutureGen technologies will take longer to accomplish this. The reason for the increase is due to the fact that information-based technology growth will occur faster than energy-based technologies. However, as technology advances overall, the tools available are more advanced, which means that technology in all facets will increase more quickly as time passes (Kurzweil, 2001). Therefore, the estimated "s" for FutureGen will be greater than for an information-based technology in the same timeframe, but is lower than the "s" for technologies in Figure 3.2 since those were fifteen to one hundred years ago. Table 4.6 displays a summary of the variables selected for the first penetration scenario, Case 1, with the low penetration rate represented by 50% market penetration.

Table 4.6 Summary of Variables Selected for FutureGen Penetration Case 1

| Variable | High Scenario | Low Scenario | Avg. Scenario |
|---|---|---|---|
| k | 100% | 50% | 75% |
| t | 40 years | 40 years | 40 years |
| h | 13 years | 23 years | 18 years |
| s | 20 years | 30 years | 25 years |

The Case 1 penetration curves incorporating these scenarios can be seen below in Figure 4.7.

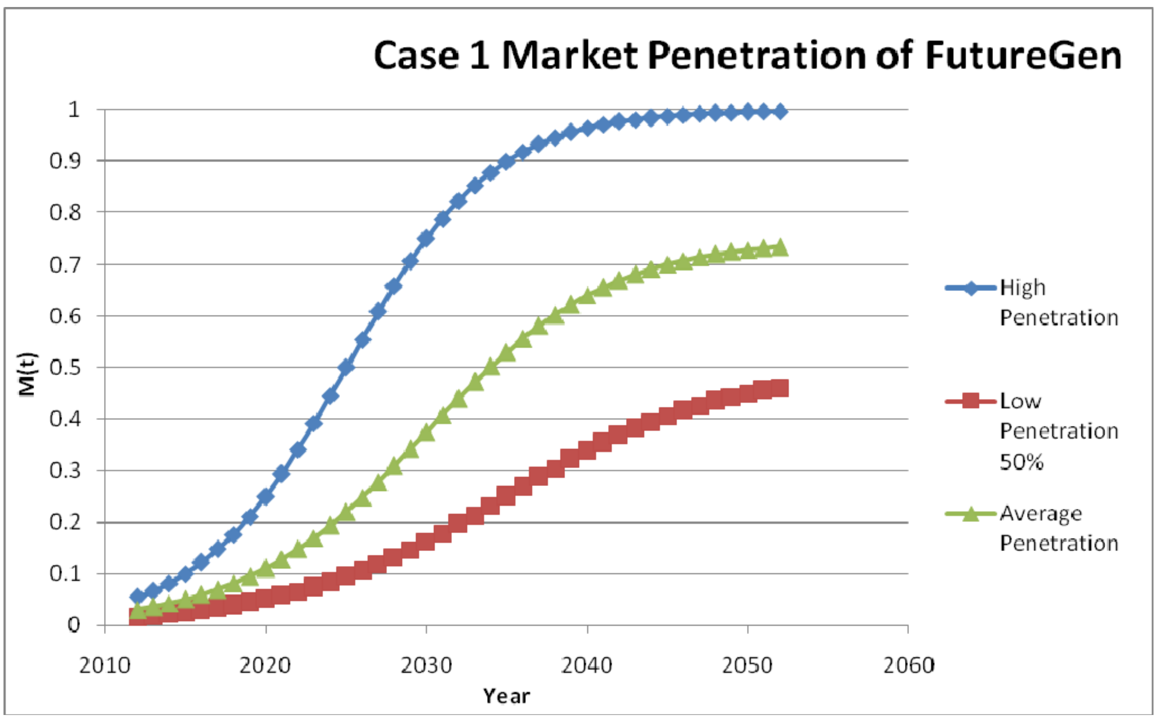



Figure 4.7 Case 1 FutureGen Market Penetration Curves Developed with Fisher-Pry Method

The Case 1 average penetration scenario for FutureGen was then incorporated into the total new plant capacity based on the base case demand scenario. The result can be seen in Figure 4.8.

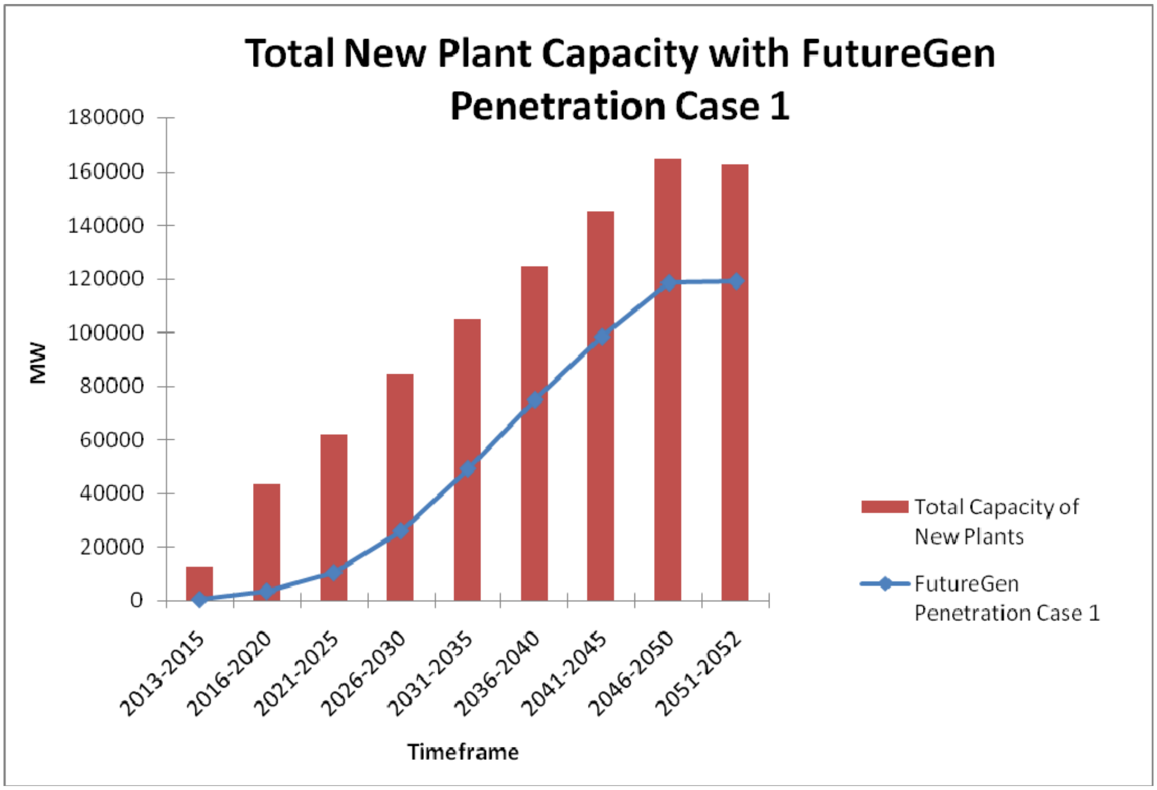



Figure 4.8 Total New Plant Capacity with FutureGen Penetration Case 1

The data utilized to formulate Figure 4.8 is summarized in Table 4.7.

Table 4.7 Coal Based Electricity Capacity Additions and Replacements

| Time Frame | Capacity Additions (MW) | Replacement (MW) | Total Capacity of New Plants (MW) | Capacity by FG (MW) time blocks |
|---|---|---|---|---|
| 2013-2015 | 2500 | 10389 | 12889 | 552 |
| 2016-2020 | 26100 | 17315 | 43415 | 3599 |
| 2021-2025 | 44500 | 17315 | 61815 | 10618 |
| 2026-2030 | 66900 | 17315 | 84215 | 26167 |
| 2031-2035 | 87500 | 17315 | 104815 | 49292 |
| 2036-2040 | 107500 | 17315 | 124815 | 74911 |
| 2041-2045 | 127500 | 17315 | 144815 | 98350 |
| 2046-2050 | 147500 | 17315 | 164815 | 118463 |
| 2051-2052 | 155500 | 6926 | 162426 | 119089 |

To clarify, the capacity by FutureGen was determined by multiplying the percent penetration (M(t)) determined using the Fisher-Pry Method by the total capacity (capacity additions plus replacement capacity) of new plants for each year based on the base case demand scenario. The results were then summed up within the given timeframes. The results are displayed on Table 4.7.

Three more FutureGen penetration scenarios will be examined. The k value will be changed in the low scenario to 45%, 40%, and 35%. Table 4.8 represents Case 2 which includes the 45% low scenario.

Table 4.8 Summary of Variables Selected for FutureGen Penetration Case 2

| Variable | High Scenario | Low Scenario | Avg. Scenario |
|---|---|---|---|
| k | 100% | 45% | 72.5% |
| t | 40 years | 40 years | 40 years |
| h | 13 years | 23 years | 18 years |
| s | 20 years | 30 years | 25 years |

The Case 2 penetration curves incorporating these scenarios can be seen below in Figure 4.9.

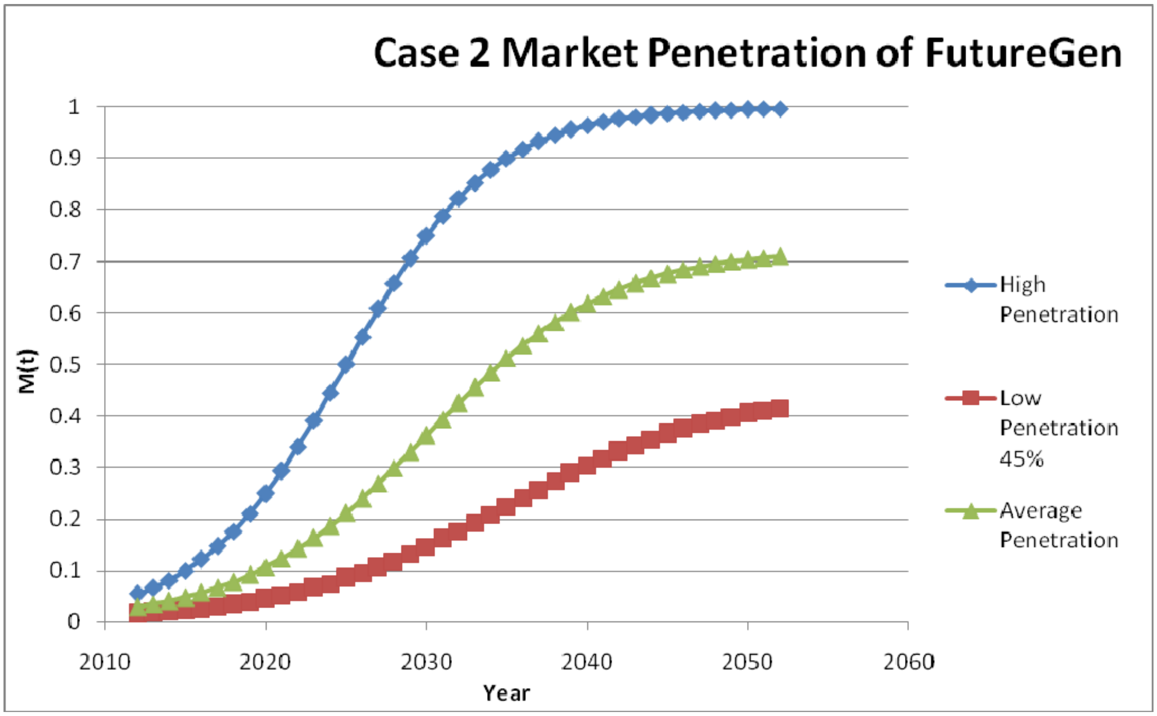



Figure 4.9 Case 2 FutureGen Market Penetration Curves Developed with Fisher-Pry Method

The Case 2 average penetration scenario for FutureGen was then incorporated into the total new plant capacity based on the base case demand scenario. The result can be seen in Figure 4.10.

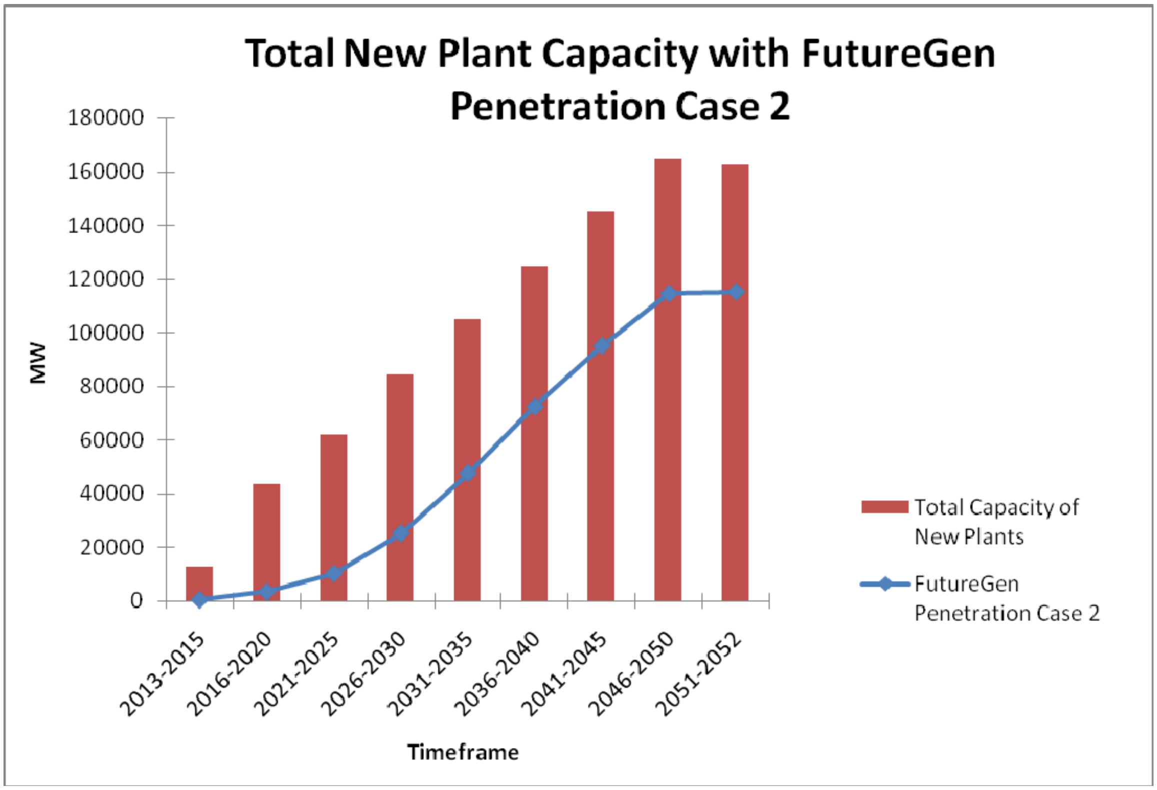



Figure 4.10 Total New Plant Capacity with FutureGen Penetration Case 2

Table 4.9 represents Case 3 which includes the 40% low scenario.

Table 4.9 Summary of Variables Selected for FutureGen Penetration Case 3

| Variable | High Scenario | Low Scenario | Avg. Scenario |
|---|---|---|---|
| k | 100% | 40% | 70% |
| t | 40 years | 40 years | 40 years |
| h | 13 years | 23 years | 18 years |
| s | 20 years | 30 years | 25 years |

The Case 3 penetration curves incorporating these scenarios can be seen below in Figure 4.11.

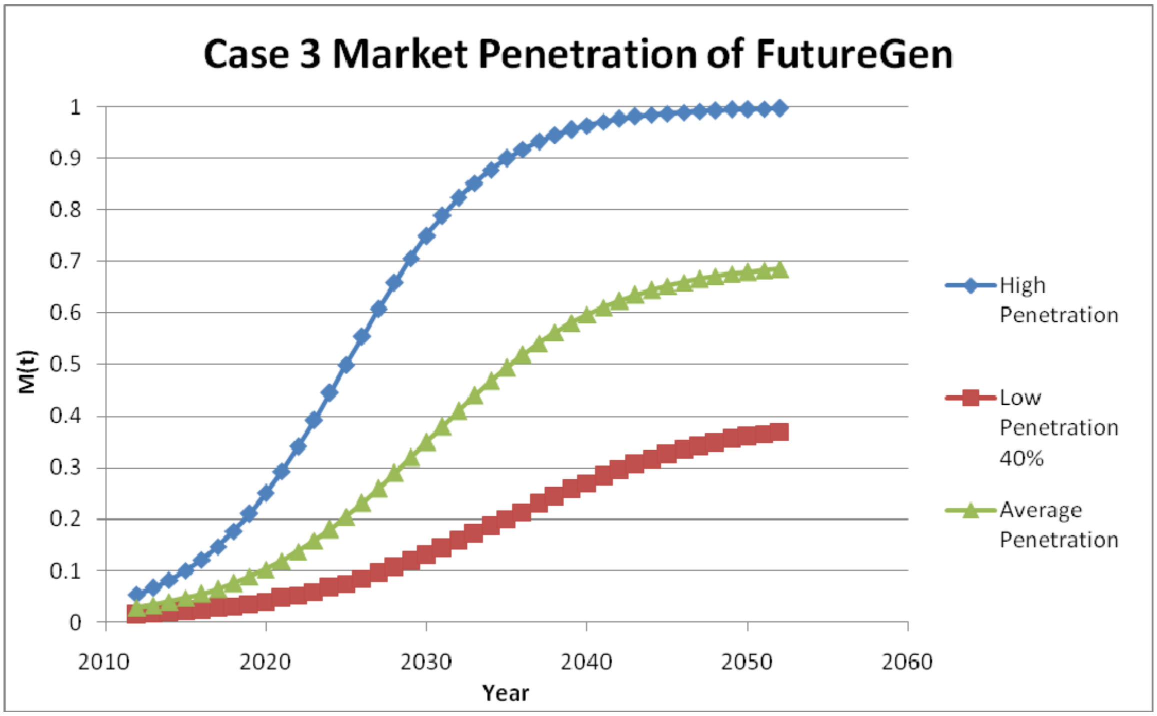



Figure 4.11 Case 3 FutureGen Market Penetration Curves Developed with Fisher-Pry Method

The Case 3 average penetration scenario for FutureGen was then incorporated into the total new plant capacity based on the base case demand scenario. The result can be seen in Figure 4.12.

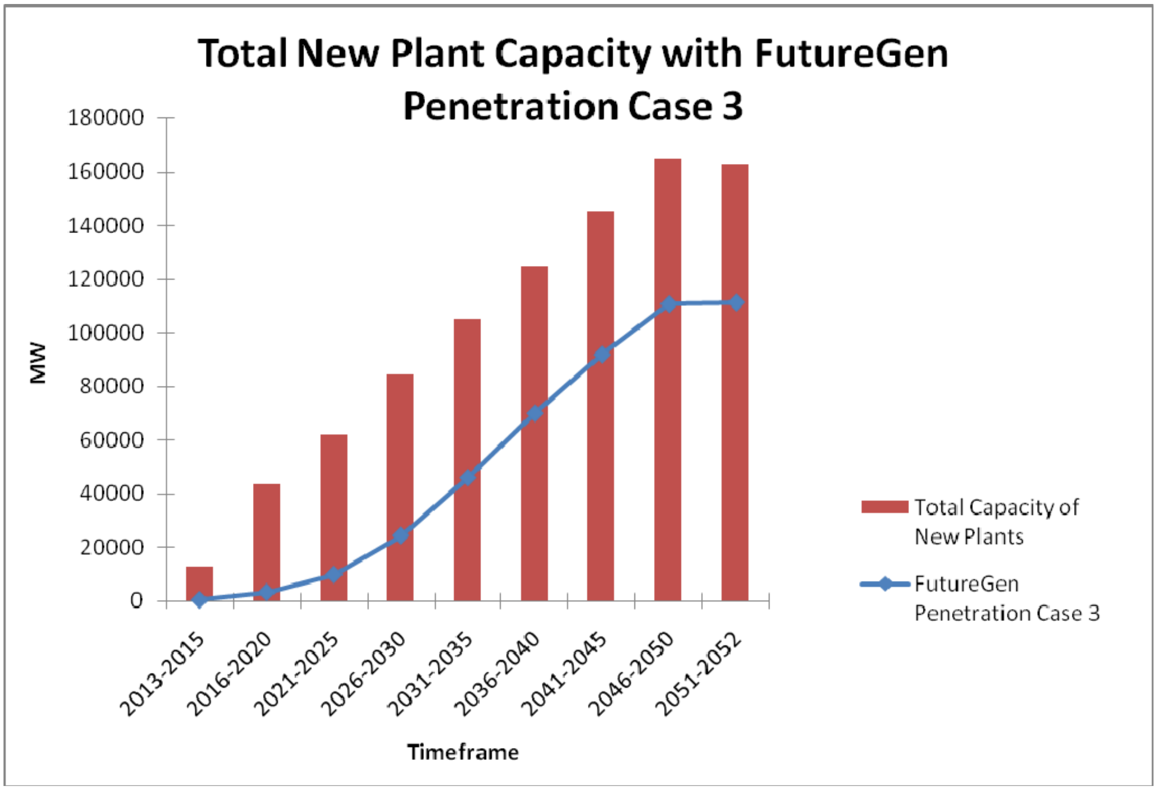



Figure 4.12 Total New Plant Capacity with FutureGen Penetration Case 3

Table 4.10 represents Case 4 which includes the 35% low scenario.

Table 4.10 Summary of Variables Selected for FutureGen Penetration Case 4

| Variable | High Scenario | Low Scenario | Avg. Scenario |
|---|---|---|---|
| k | 100% | 35% | 67.5% |
| t | 40 years | 40 years | 40 years |
| h | 13 years | 23 years | 18 years |
| s | 20 years | 30 years | 25 years |

The Case 4 penetration curves incorporating these scenarios can be seen below in Figure 4.13.

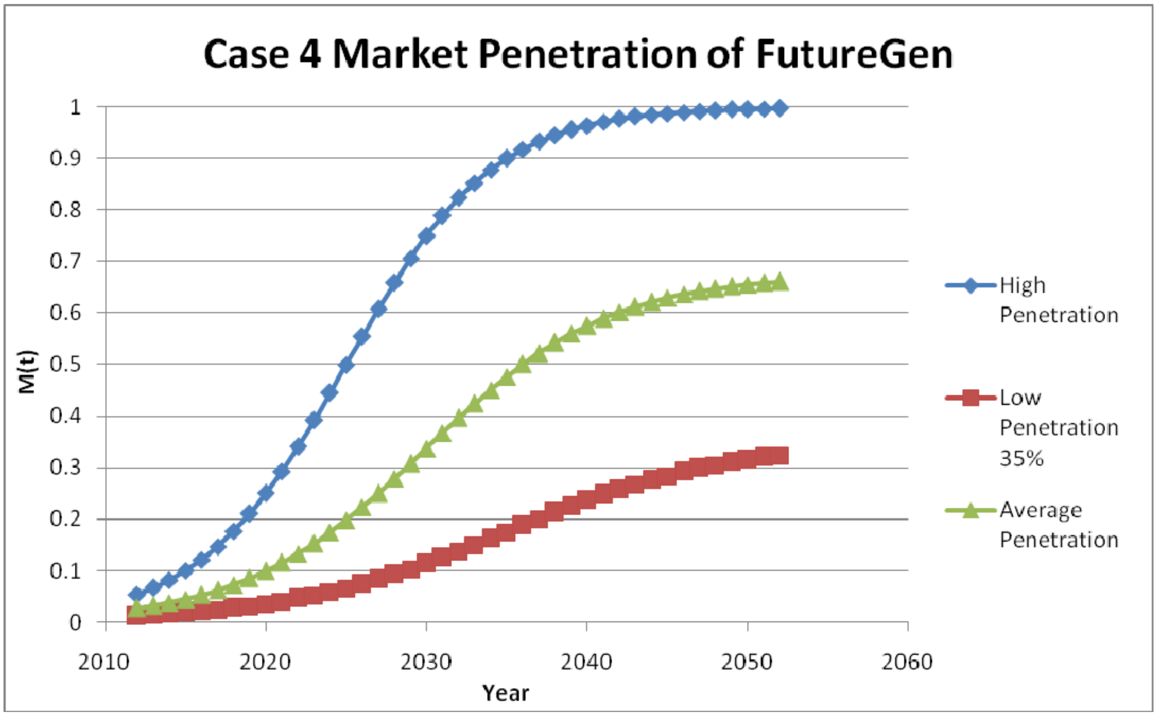



Figure 4.13 Case 4 FutureGen Market Penetration Curves Developed with Fisher-Pry Method

The Case 4 average penetration scenario for FutureGen was then incorporated into the total new plant capacity based on the base case demand scenario. The result can be seen in Figure 4.14.

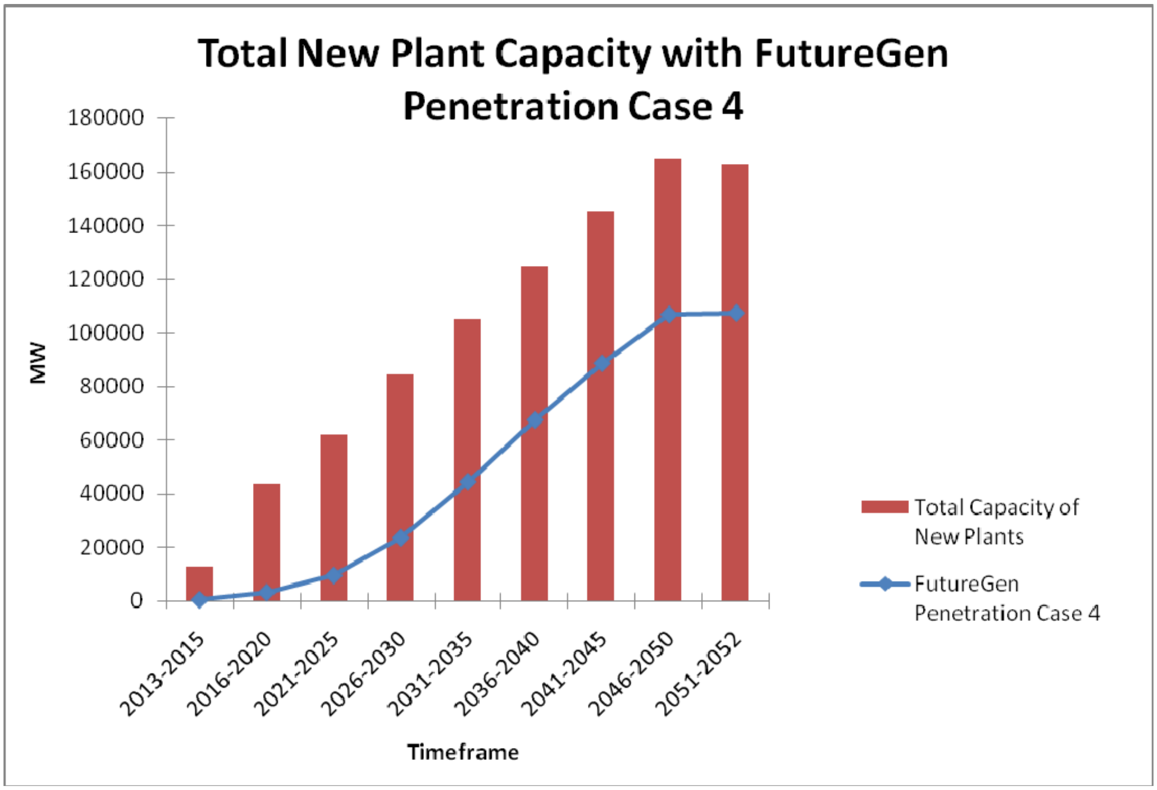



Figure 4.14 Total New Plant Capacity with FutureGen Penetration Case 4

Expansion of Table 4.7 to include the last 3 cases is shown on Table 4.11.

Table 4.11 Predicted FutureGen Penetration into Coal Based Electricity Capacity Additions and Replacements

| Time Frame | Total Capacity of New Plants (MW) | Capacity by FutureGen (MW) Case 2 | Capacity by FutureGen (MW) Case 3 | Capacity by FutureGen (MW) Case 4 |
|---|---|---|---|---|
| 2013-2015 | 12889 | 534 | 516 | 497 |
| 2016-2020 | 43415 | 3479 | 3359 | 3239 |
| 2021-2025 | 61815 | 10264 | 9911 | 9557 |
| 2026-2030 | 84215 | 25295 | 24422 | 23550 |
| 2031-2035 | 104815 | 47649 | 46006 | 44363 |
| 2036-2040 | 124815 | 72414 | 69917 | 67420 |
| 2041-2045 | 144815 | 95072 | 91794 | 88515 |
| 2046-2050 | 164815 | 114514 | 110565 | 106616 |
| 2051-2052 | 162426 | 115120 | 111150 | 107180 |

**4.2. FUTUREGEN PENETRATION RESULTS**

In reviewing the Total New Plant Capacity with FutureGen Penetration charts for the four cases, it is apparent that the amount of traditional coal-fired plants to be added (those additions above the FutureGen penetration curve) remains approximately the same throughout the timeframes. This agrees with the nature of technology penetration in that once the total market is penetrated and/or a new technology enters the market and overcomes the old technology, the S-curve flattens. In this case, the S-curve that has flattened is that of traditional coal-fired power plants. This trend also gives credibility to the FutureGen penetration curves generated in this research.

The calculations and correlations described so far in Chapter 4 can be used to determine the amount of electricity and/or hydrogen predicted to be produced from FutureGen plants based on the previously outlined new plant capacity approximations and estimated penetration of FutureGen plants and technologies into new plants. However, as previously stated, an assumption of this dissertation is that FutureGen plants will be constructed in order to meet electricity demand and not for the sole purpose of producing hydrogen. The possibility of the demand for hydrogen production will be further explored in Chapter 6 through the goal programming model.

Table 4.12 presents the Base Case of total new plant capacity demanded described in this chapter with FutureGen penetration Case 1. Again, in keeping consistent, the utilization/availability for Table 4.12 is assumed to be 85%, and the FutureGen plant efficiency is assumed to be 35%. The information presented in Table 4.12 can be found in detail in Appendix B.

Table 4.12 Estimated Amount of Electricity Capacity to be Provided by FutureGen Plants (FutureGen Penetration Case 1)
(discrepencies in summations on the table are due to rounding)

| Time Frame | Total Capacity of New Plants (MW) | Capacity by FutureGen (MW) | Required Amount of Coal to FutureGen Plants (MMT) |
|---|---|---|---|
| 2013-2015 | 12889 | 552 | 1.75 |
| 2016-2020 | 43415 | 3599 | 11.42 |
| 2021-2025 | 61815 | 10618 | 33.69 |
| 2026-2030 | 84215 | 26167 | 83.03 |
| 2031-2035 | 104815 | 49292 | 156.4 |
| 2036-2040 | 124815 | 74911 | 237.7 |
| 2041-2045 | 144815 | 98350 | 312.1 |
| 2046-2050 | 164815 | 118463 | 375.9 |
| 2051-2052 | 162426 | 119089 | 377.9 |
| Total | 904020 | 501041 | 1,590 |

As the penetration of FutureGen decreases from the Case 1 scenario, the capacity and, therefore, the amount of coal used by FutureGen plants will decrease. The information demonstrated in Table 4.12 is available for the other three FutureGen penetration cases and can be found in Appendix B. The tornado chart in Figure 4.15 demonstrates single-factor sensitivity analysis generated using SensIt 1.31[7]. The base case used was an average of the four penetration cases developed in this chapter.

[7] SensIt 1.31 is a Microsoft Excel sensitivity analysis add-in.

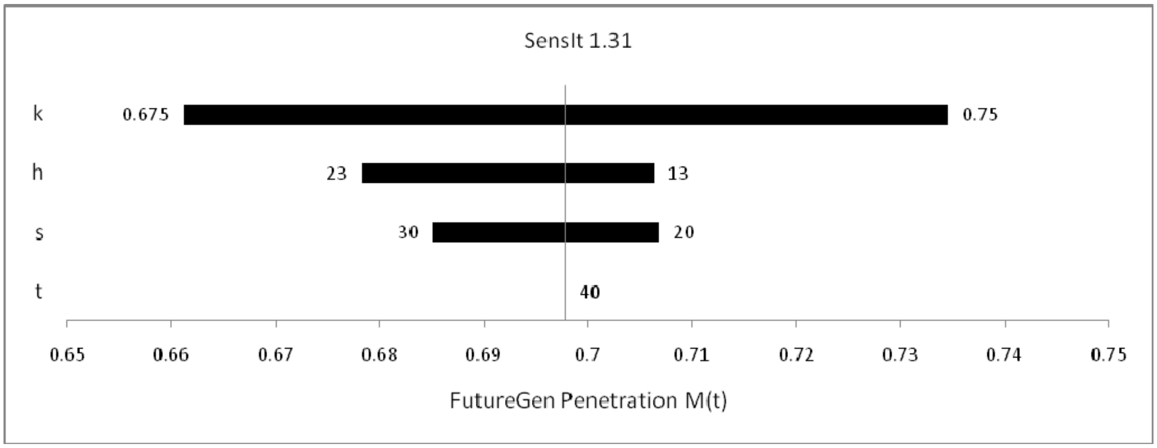



Figure 4.15 FutureGen Penetration Tornado Chart

Figure 4.15 clearly shows that the total expected market penetration contributes to the greatest swing FutureGen penetration rates, as would be expected. The amount of time required to penetrate half of the market (h) contributes to the next greatest amount of swing in penetration rates. However, the amount of swing contributed to h is close to that associated with the time required for the technology to penetrate between 10% and 90% of the market.

Chapter 5 will detail a sensitivity analysis performed on the base case coal-powered electricity demand, which will adjust the estimated total new plant capacity by plus and minus 10% and plus and minus 20%. The four cases of FutureGen penetration described in this chaper will be incorporated into each of the demand scenarios. Based on the results of the base case and those in the sensitivity analysis, the coal material flow analysis (MFA) will be forecast for the years within the selected time period (2012-2052).

# 5. PROJECTED COAL MFA

This chapter is dedicated to the original contribution of forecasting coal MFA's to provide a picture of the coal flows resulting from the predictions made in Chapter 4 that can be used by the coal industry and lawmakers. As discussed in Chapter 3, material flow accounts and analyses can paint a picture of a given material, and in turn, this picture can be utilized by interested industries for a variety of purposes. In 2004, Warneke produced a coal MFA for the United States. This MFA will be updated for each year in the given timeframe (2012-2052) based on the coal capacity additions predictions made in Chapter 4, as well as predictions for outputs identified in the model. It is important to note that since real data is not available to incorporate into the model, the forecasted coal MFA's are based on predictions and estimates. Therefore, as part of the MFA forecasting, research was done and assumptions were made and are explained in this chaper. Furthermore, a sensitivity analysis was incorporated which adjusts the base case capacity additions by plus and minus 10% and 20%. Each year will then have five possible coal MFA predictions for each of the four FutureGen penetration cases.

## 5.1. MFA INPUTS AND OUTPUTS

The information is this section details how the various inputs and outputs of the coal MFA were analyzed and incorporated into the forecasted MFA's.

**5.1.1. Imports and Exports.** The 2006 AEO provides predictions for the amount of coal to be imported and exported through 2030. Figure 5.1 was used to estimate the amount of coal imported and exported throughout the timeframe. Key points (inflections points or points of significant slope change) were approximated and then a straight slope was assumed between those points. Imports were then assumed to increase from years 2030-2052 at a similar rate as between years 2026 and 2030. The same approach was used for Exports. The import and export numbers can be found in Appendix B, and the numbers will be incorporated into the updated MFA's.

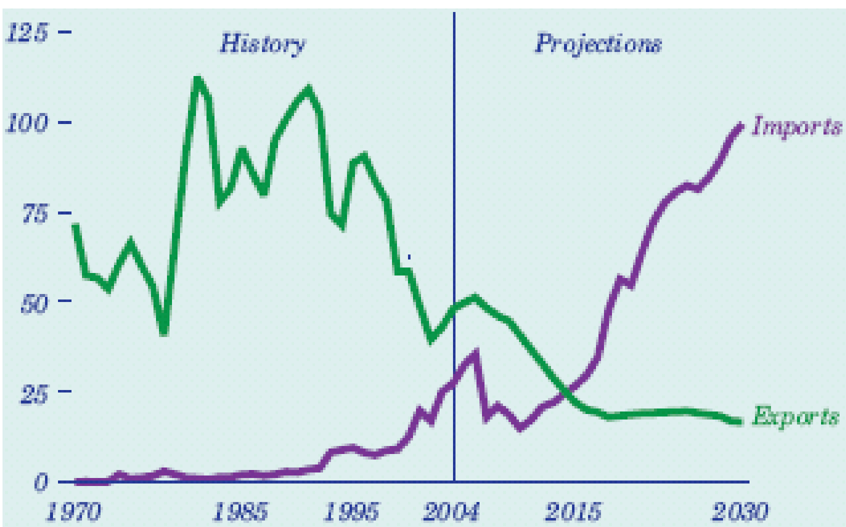



Figure 5.1 U.S. Coal Exports and Imports, 1970-2030 (million short tons) (EIA, 2006).

**5.1.2. Coking, Residential/Commercial, and Industrial/Manufacturing Outputs.** The AEO (2006) also makes predictions about the coal that will be used in coke plants, and for residential/commercial purposes and industrial/manufacturing purposes. Figure 5.2 shows these predictions.

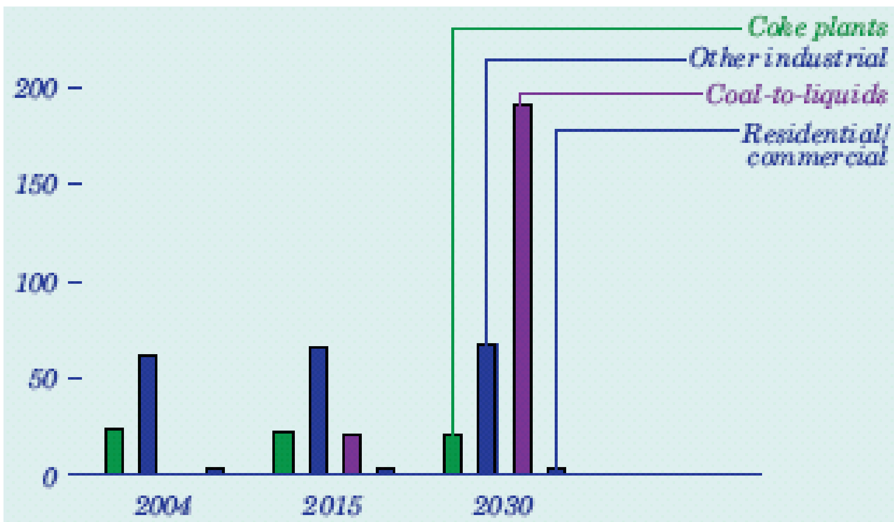



Figure 5.2 Coal Consumption in the Industrial and Buildings Sectors and all Coal-to-Liquids Plants, 2004, 2015, and 2030 (million short tons) (EIA, 2006).

According to Figure 5.2, coal consumption in coke plants, other industrial, and residential/commercial appears to remain stagnant through 2030. Therefore, for the purposes of updating the coal MFA through the designated timeframe, the values given in Warneke's model will be carried through 2052. However, another utilization needs to be added to Warneke's MFA model, and it is coal-to-liquids. Again, a straight-line interpretation was made between the three years shown, and then the year 2030 value was carried through to year 2052. Further increases after 2030 were not assumed due to the seemingly untested coal-to-liquids market.

**5.1.3. $CO_2$, $SO_2$, and $NO_x$ Emissions.** Carbon dioxide emissions are proportional to fuel consumption. Therefore, Warneke's $CO_2$ output from electric power generation will be extrapolated throughout the given timeframe for traditional electric power generation. However, for the FutureGen plants, the $CO_2$ will be sequestered. According to the FutureGen Alliance, it is estimated that the first FutureGen plant will need to sequester a minimum of 1 and up to 2.5 million metric tons of $CO_2$ per year (FutureGen Alliance Website, 2007.) This FutureGen plant has a capacity of 275 MW, and a correlation will be made based on the capacity and estimated amount of $CO_2$ to sequester. In order to be conservative, for each year the correlation will be that 2.5 MMT of CO2 will need to be sequestered per 275 MW created by FutureGen plants. In other words, 0.00909 MMT of $CO_2$ per 1 MW.

EPA's CAIR and CAMR regulations will place stricter requirements on $SO_2$ and $NO_x$ emissions from traditional coal-fired power-plants. The AEO (2006) took these new regulations into account and made predictions for these emissions in 2030. Figure 5.3 shows projections for $SO_2$ emissions, and Figure 5.4 shows projections for $NO_x$ emissions.

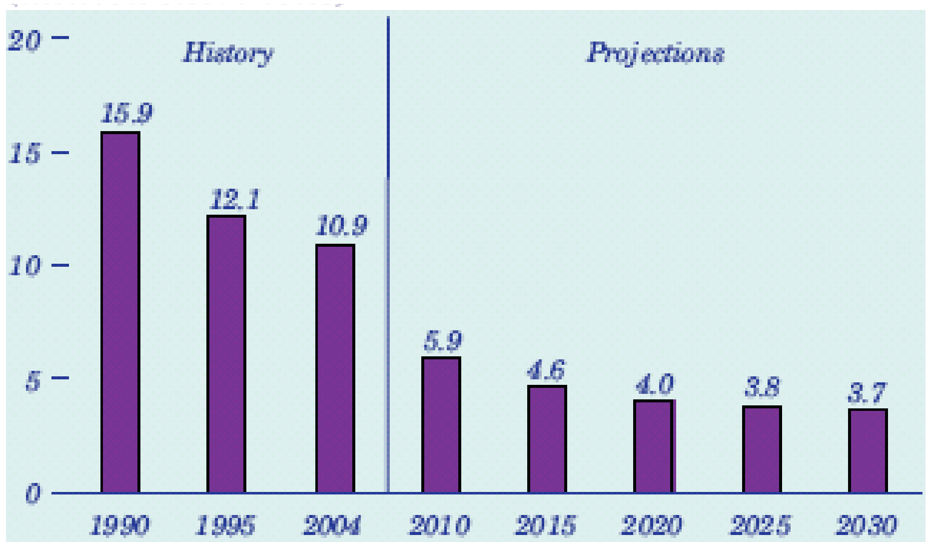



Figure 5.3 Sulfur Dioxide Emissions from Electricity Generation, 1990-2030 (million short tons) (EIA, 2006).

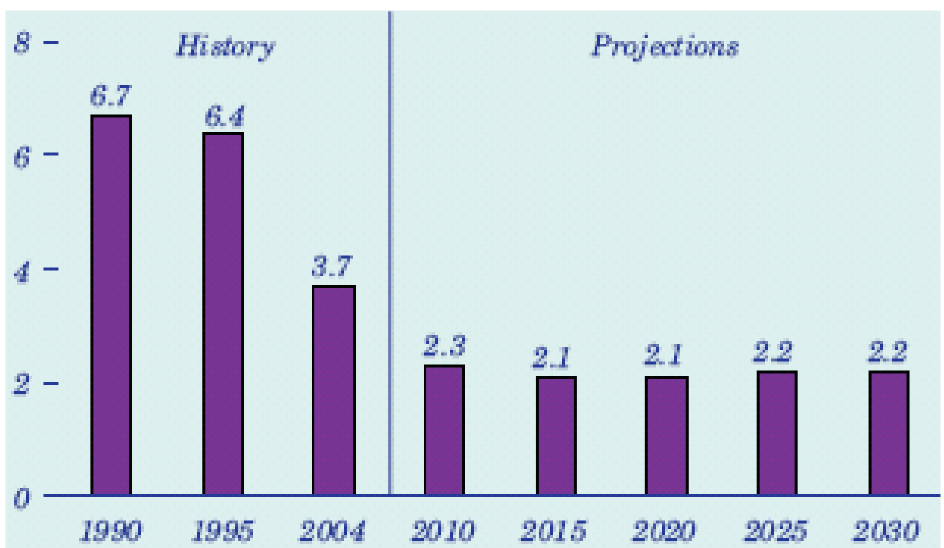



Figure 5.4 Nitrogen Oxide Emissions from Electricity Generation, 1990-2030 (million short tons) (EIA, 2006).

For the portion of the given timeframe (2030-2052) not represented in the above figures, the amount given for year 2030 will be carried through to year 2052 since the emissions appear to have leveled out by 2030. $SO_2$ and $NO_x$ emissions from FutureGen plants will be assumed to be negligible in keeping with the near-zero emissions idea. However, once the FutureGen trial plant is operational, these emissions will be measurable.

These emissions numbers can be found in Appendix B, and the numbers will be incorporated into the updated MFA's.

**5.1.4. Coal Mine Wastes Overburden, Methane, $O_2$, Combustion Products, and $H_2O$.** The amount of coal mine wastes overburden depends upon the amount of coal that is surface mined, and the amount of methane depends upon the depth of the seam. Therefore, the coal mine wastes overburden and methane amounts will not be present in the MFA's created since these values cannot be predicted. These two categories represent a key area for future work.

The amount of oxygen ($O_2$) input into traditional electric power generation will be proportional to the amount of coal input into the system. This amount will be determined using the ratio evident in Warnke's model of 3.233 times the amount of coal. The outputs from traditional electric power generation of $H_2O$ and Combustion Products noted in Warneke's model will be estimated through the 2012-2052 timeframe. The estimation of $H_2O$ and Combustion Products resulting from traditional electric power generation will be a direct correlation to the amount of coal input to traditional electric power generation. These correlations need to be made since applicable data is not available for the future. A prime area of future work will be to update the coal MFA's as accurate reporting of inputs and emissions becomes available.

In regards to FutureGen for the purposes of this dissertation, the predicted MFA's will represent the significant inputs and outputs as they compare to traditional power generation. A more detailed analysis of all the inputs and outputs into the FutureGen system will be possible once the first plant is operational and some quantities are known. Carbon dioxide was previously addressed, as were $SO_2$ and $NO_x$ emissions. Slag or ash generation from FutureGen is assumed to be 87,875 metric tons per year for the initial 275 MW plant (DOE, 2007b.) This amount can be broken down into $3.2 \times 10^{-4}$ MMT/MW and incorporated into the MFA. The amount of oxygen and water utilized by the system can again be analyzed once the plant is operational.

**5.1.5. Amount of Coal to Prep Plants and to Electric Power Generation.** Warneke's method of backcalculating raw coal by assuming 32.5% of coal produced goes through prepartion plants with a 62% average recovery will be adopted in the updated coal MFA's created in this dissertation (Warneke, 2004.) The amount of coal to electric power generation will be separated into traditional and FutureGen. Those amounts will be based on the predicted capacity additions and FutureGen penetration. It will also be assumed that the Net Change of Stock will remain constant at 37.8 MMT, since the purpose of the predicted MFA's is to illustrate the amount of coal that will be demanded and the amount that will be stockpiled is unknown. These numbers can be found in Appendix B, and the numbers will be incorporated into the updated MFA's.

## 5.2. PREDICTED COAL MFA'S

Information described in Section 5.1 was used to update Warneke's Coal MFA and make predictions for the years in the given timeframe, starting with 2013 and ending with year 2052. The data was put into a spreadsheet with headings that easily translate to the model. This spreadsheet can be found on sheet MFA's Base Case in Appendix B. Sheets also exist that create yearly MFA's for each FutureGen penetration case based on the sensitivity analysis employed of plus and minus 10% and 20% for electricity demand.

**5.2.1. Examples of Coal MFA Predictions.** The figures below show the predicted coal MFA's for the year 2035, which was randomly selected. The first will be the base case, and the following will be representative of the cases showing the plus and minus 10% and 20% adjustment in predicted coal-powered electricity demand. FutureGen penetration Case 1 is used for all five scenarios. However, the MFA's for the other three FutureGen penetration cases can be found in Appendix B.

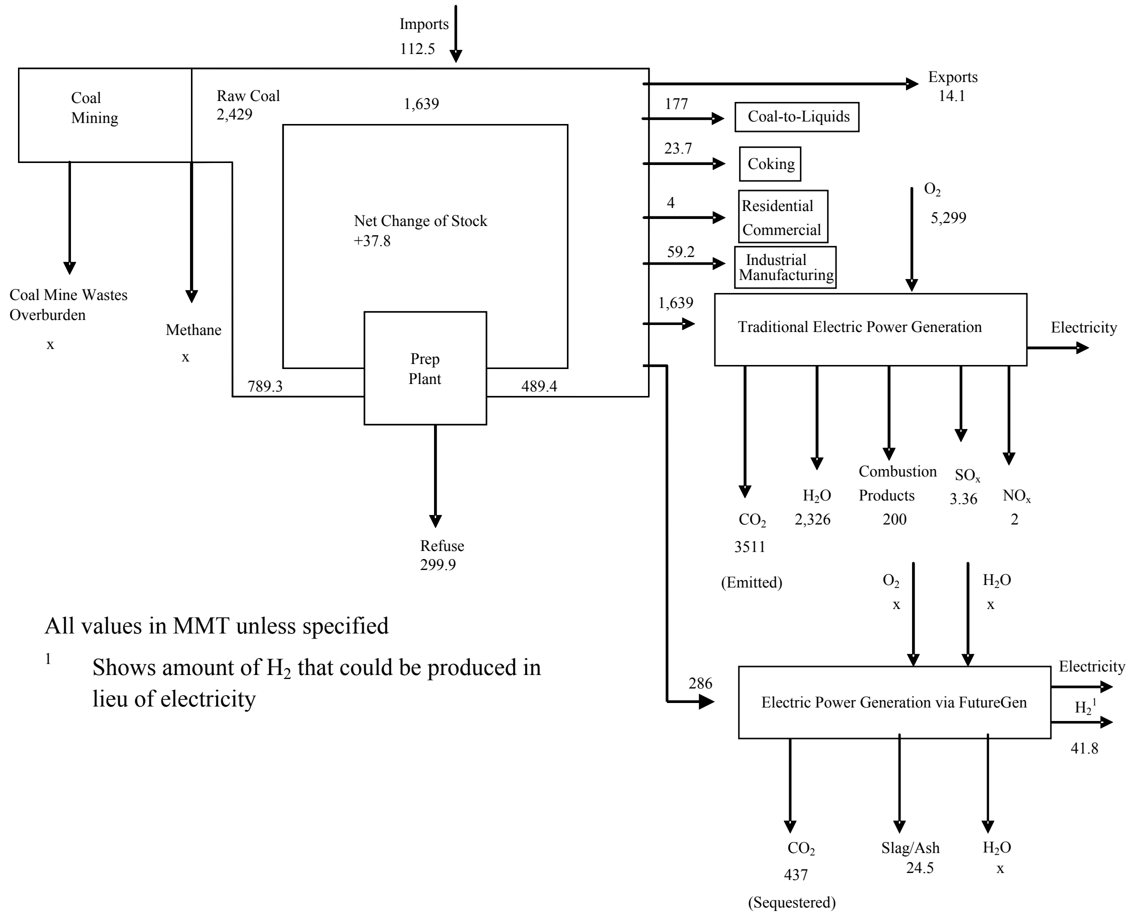



Figure 5.5 Predicted Coal MFA for the United States in year 2035 based on the Base Case.

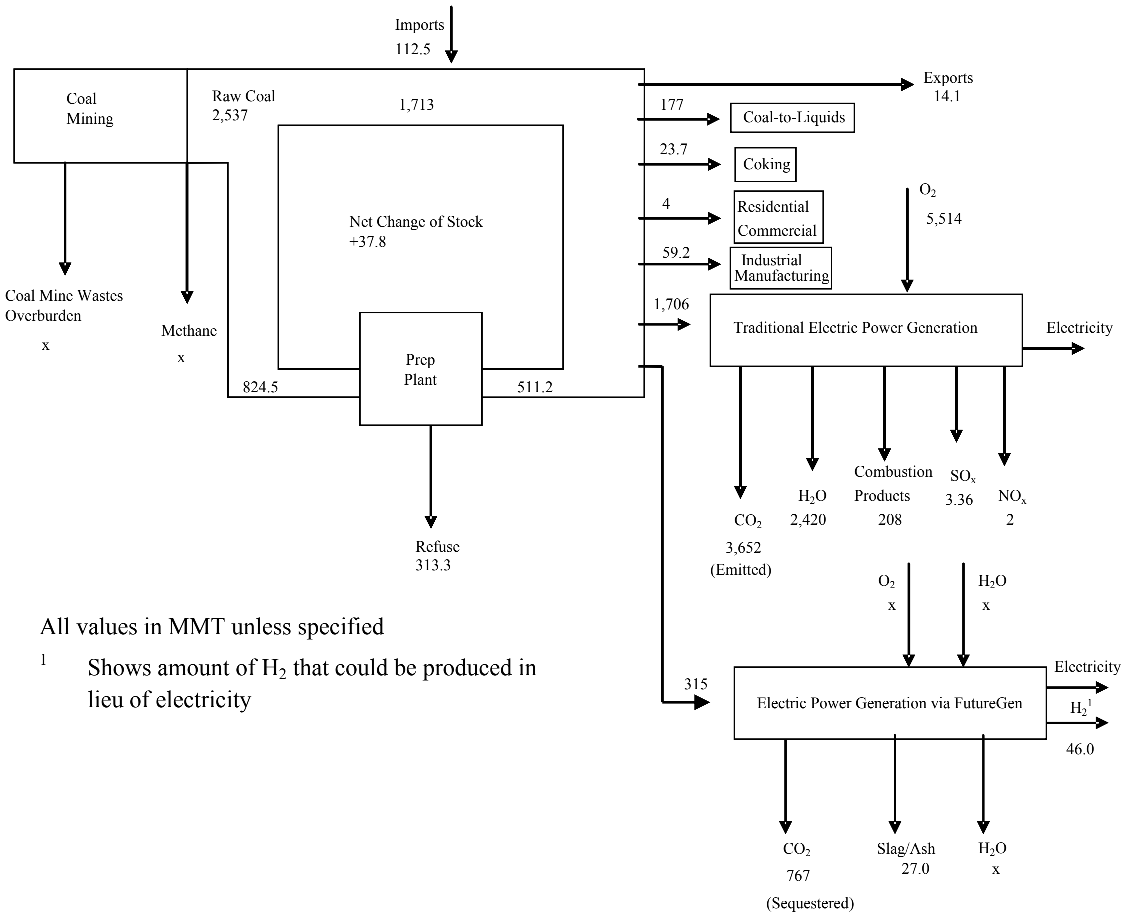



Figure 5.6 Predicted Coal MFA for the United States in year 2035 based on the Plus 10% Predicted Coal Powered Electricity Demand Scenario.

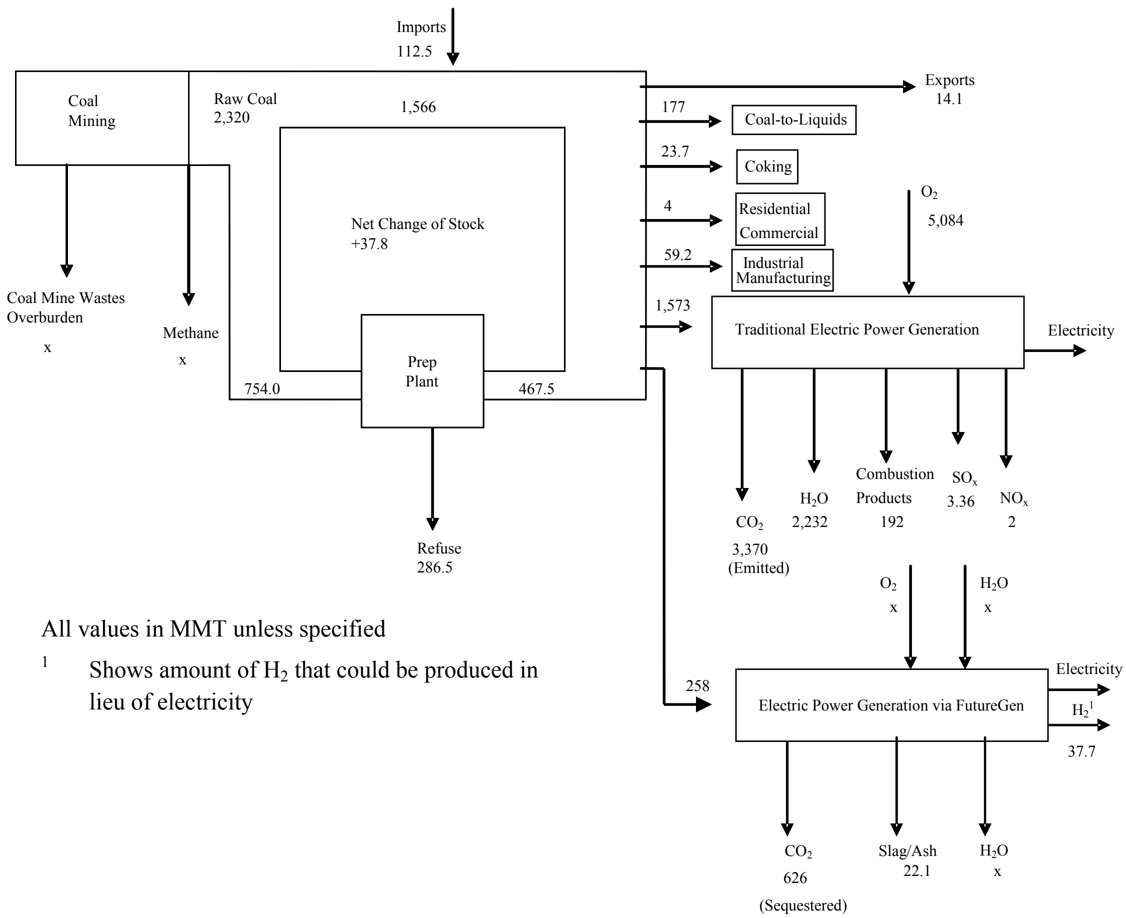



Figure 5.7 Predicted Coal MFA for the United States in year 2035 based on the Minus 10% Predicted Coal Powered Electricity Demand Scenario.

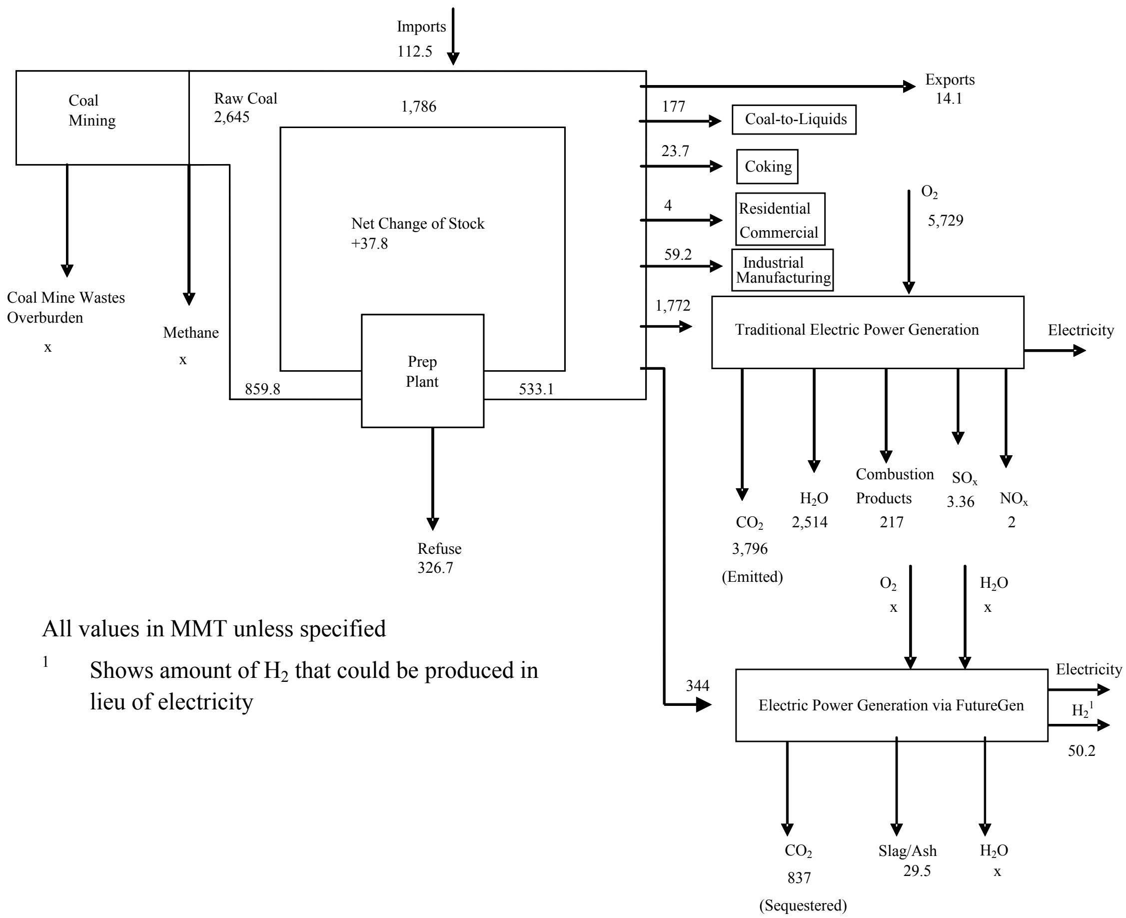



Figure 5.8 Predicted Coal MFA for the United States in year 2035 based on the Plus 20% Predicted Coal Powered Electricity Demand Scenario.

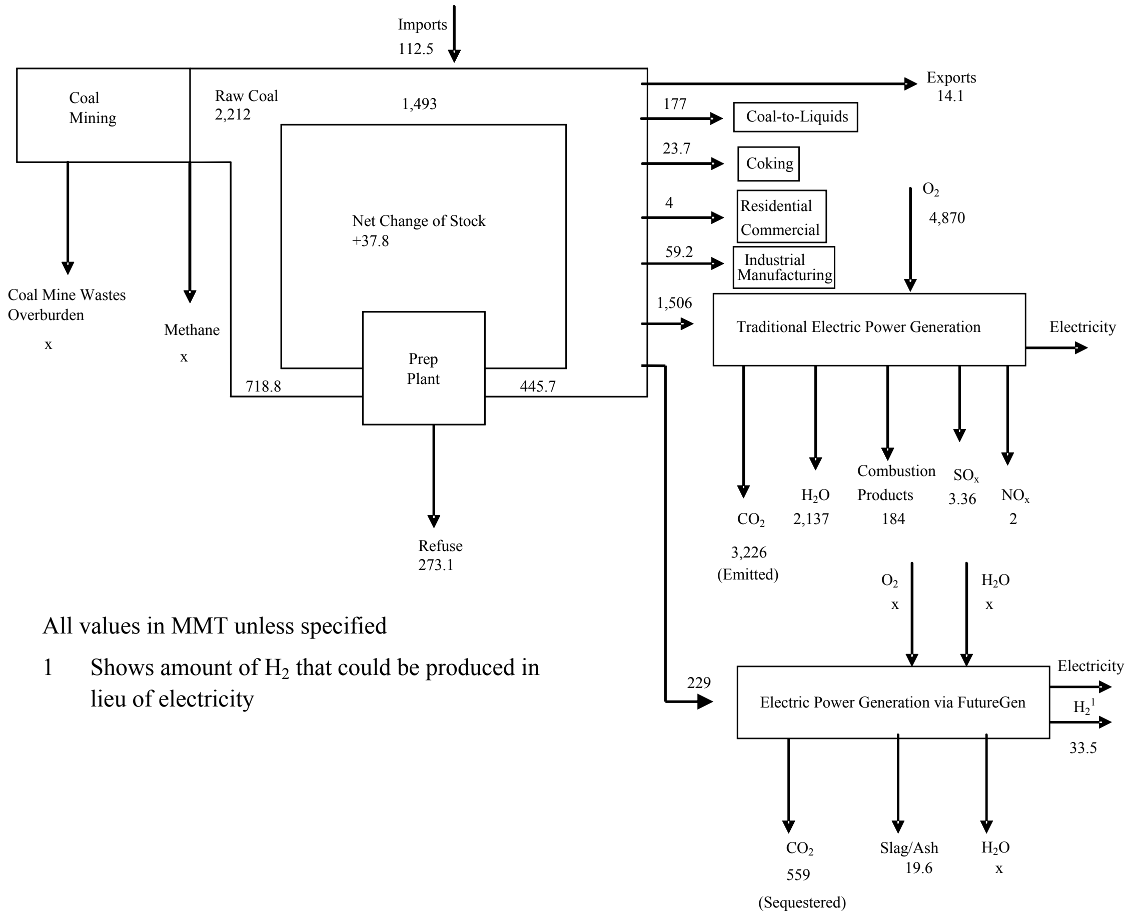



Figure 5.9 Predicted Coal MFA for the United States in year 2035 based on the Minus 20% Predicted Coal Powered Electricity Demand Scenario.

**5.2.2. Summary of Examples.** The figures above are representative of the model formulations of the MFA data presented in Appendix B. Again, year 2035 was selected only to show an example, any year from 2013-2052 could have been selected, as well as any of the FutureGen penetration cases described in Chapter 4. The adjustments in demand for coal-powered electricity were assumed to be fulfilled with increased production in the United States. This assumption is why the amount of coal imported and exported did not change in the different scenarios. For the purposes of this dissertation, much like as in any scientific experiment, it is important to isolate the variables in question. Therefore, it was determined that adjusting the imports and exports predictions in each scenario would not have a significant impact on the model and would only blur the direct relationship between increased coal demand for electricity generation and coal production.

The $SO_x$ and $NO_x$ amounts were also constant in each of the scenarios for a given year. This is due to the fact that the amount of these emissions is capped, which means a power plant will employ the necessary technologies to keep the emissions within the limits. In other words, if more electricity is being generated, then more measures will be taken to keep the emissions within the legal limits.

**5.2.3. Benefit of FutureGen Penetration.** It is also important to note that as the penetration of FutureGen increases, not only does the amount of hydrogen that could be produced increase, the amount of $CO_2$ emissions from coal-powered electricity generation decreases. The estimates made thus far in the dissertation are dependent upon the demand for electricity. It can be easily seen from the example MFA's that the amount of $CO_2$ produced from traditional electric-power generation increases as the amount of coal into these plants increases. Therefore, it can be easily deduced that the greater the portion of electricity produced from FutureGen plants as opposed to traditional electric power generation, the less $CO_2$ will be emitted since FutureGen plants will sequester the $CO_2$. Furthermore, FutureGen plants are nearly emission free which means that even though $SO_2$ and $NO_x$ are capped with environmental regulations, FutureGen plants should be able to lower these emissions.

Tables 5.1-5.5 summarize the benefits of FutureGen penetration on hydrogen production and $CO_2$ emissions from coal-powered electricity generation for the five demand scenarios incorporating FutureGen penetration Case 1.

Table 5.1 Significant Results of FutureGen Penetration in year 2035 (Base Case)

| | Existing Plus Additional Capacity | All Capacity Additions met by Traditional EPG* | With Predicted FutureGen Penetration: Traditional EPG* | With Predicted FutureGen Penetration: FutureGen Plants | CO2 Emission Reduction With FutureGen Penetration |
|---|---|---|---|---|---|
| Electricity Capacity (MW-yr) | 573,800 | | | | |
| Electricity Produced (MW-yr) | | 469,124 | 401,452 | 76,694 | |
| Coal (MMT) | | 1,915 | 1,639 | 286.3 | |
| $CO_2$ (MMT) | | 4,103 | 3,511 | Sequestered | 593 |
| $H_2$ capability in lieu of electricity (MMT) | | 0 | 0 | 41.8 | |

* Electric Power Generation

Table 5.2 Significant Results of FutureGen Penetration in year 2035 (Plus 10% Scenario)

| | Existing Plus Additional Capacity | All Capacity Additions met by Traditional EPG* | With Predicted FutureGen Penetration: Traditional EPG* | With Predicted FutureGen Penetration: FutureGen Plants | $CO_2$ Reduction With FutureGen Penetration |
|---|---|---|---|---|---|
| Electricity Capacity (MW-yr) | 604,515 | | | | |
| Electricity Produced (MW-yr) | | 492,160 | 417,721 | 84,363 | |
| Coal (MMT) | | 2,009 | 1,706 | 315 | |
| $CO_2$ (MMT) | | 4,304 | 3,652 | Sequestered | 652 |
| $H_2$ capability in lieu of electricity (MMT) | | 0 | 0 | 46.0 | |

* Electric Power Generation

Table 5.3 Significant Results of FutureGen Penetration in year 2035 (Minus 10% Scenario)

| | Existing Plus Additional Capacity | All Capacity Additions met by Traditional EPG* | With Predicted FutureGen Penetration: Traditional EPG* | With Predicted FutureGen Penetration: FutureGen Plants | $CO_2$ Reduction With FutureGen Penetration |
|---|---|---|---|---|---|
| Electricity Capacity (MW-yr) | 543,085 | | | | |
| Electricity Produced (MW-yr) | | 446,087 | 385,183 | 69,025 | |
| Coal (MMT) | | 1,821 | 1,573 | 258 | |
| $CO_2$ (MMT) | | 3,900 | 3,370 | Sequestered | 530 |
| $H_2$ capability in lieu of electricity (MMT) | | 0 | 0 | 37.7 | |

* Electric Power Generation

Table 5.4 Significant Results of FutureGen Penetration in year 2035 (Plus 20% Scenario)

| | Existing Plus Additional Capacity | All Capacity Additions met by Traditional EPG* | With Predicted FutureGen Penetration: Traditional EPG* | With Predicted FutureGen Penetration: FutureGen Plants | $CO_2$ Reduction With FutureGen Penetration |
|---|---|---|---|---|---|
| Electricity Capacity (MW-yr) | 635,230 | | | | |
| Electricity Produced (MW-yr) | | 515,196 | 433,990 | 92,033 | |
| Coal (MMT) | | 2,104 | 1,772 | 344 | |
| $CO_2$ (MMT) | | 4,507 | 3,796 | Sequestered | 711 |
| $H_2$ capability in lieu of electricity (MMT) | | 0 | 0 | 50.2 | |

* Electric Power Generation

Table 5.5 Significant Results of FutureGen Penetration in year 2035 (Minus 20% Scenario)

| | Existing Plus Additional Capacity | All Capacity Additions met by Traditional EPG* | With Predicted FutureGen Penetration: Traditional EPG* | With Predicted FutureGen Penetration: FutureGen Plants | $CO_2$ Reduction With FutureGen Penetration |
|---|---|---|---|---|---|
| Electricity Capacity (MW-yr) | 512,370 | | | | |
| Electricity Produced (MW-yr) | | 423,051 | 368,914 | 61,355 | |
| Coal (MMT*) | | 1,727 | 1,506 | 229 | |
| $CO_2$ (MMT) | | 3,700 | 3,226 | Sequestered | 474 |
| $H_2$ capability in lieu of electricity (MMT) | | 0 | 0 | 33.5 | |

The benefits of FutureGen penetration as demonstrated in Tables 5.1-5.5 are embodied by the reduction in $CO_2$ emissions as well as the hydrogen production capability available. Also, there is more total electricity produced with the penetration of FutureGen plants, as opposed to all capacity additions being met by traditional electric power generation, due to expected greater availability of FutureGen plants versus traditional coal-fired power plants. The amount of coal required is comparable for both scenarios, but as FutureGen plant efficiencies improve, the amount of coal demanded should decrease. Figure 5.10 displays a sensitivity analysis performed on the critical variables associated with the amount of coal to be required to fuel the electricity capacity additions.

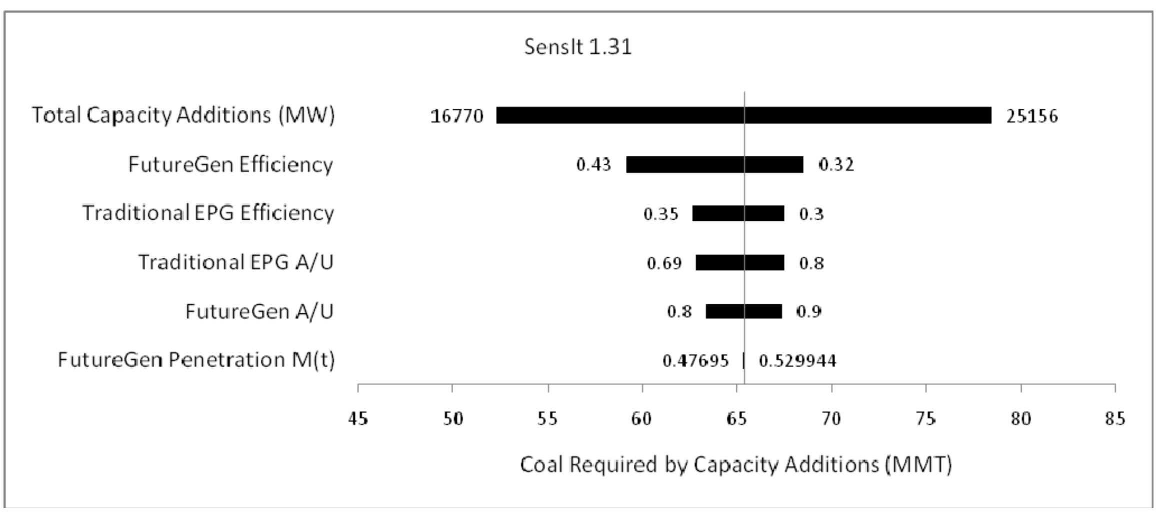



Figure 5.10 Coal Required by Capacity Additions Tornado Chart for Year 2035

Figure 5.10 clearly illustrates that the greatest swing in coal demand is due to the amount of capacity additions, i.e. the extent to which coal-fired electricity demand increases. For this reason, the sensitivity analysis performed in this research of adding plus and minus 10% and 20% to the base case demand for electricity capacity additions is appropriate. It is also appears in Figure 5.10 that FutureGen efficiency is the most significant factor after capacity additions. This suggests that improvements in FutureGen efficiency could have a considerable impact on the amount of coal required. Of course, this is dependent upon the improved availability/utilization of FutureGen plants compared to traditional coal-fired power plants.

# 6. GOAL PROGRAMMING MODEL

The final contribution of this research is to provide a tool that can be utilized by policy-makers in order to examine the downstream effects of priorities and weights given to environmental, social, and economic issues associated with coal-based electricity generation and the Hydrogen Economy. The tool developed is a goal programming model that seeks the maximum benefit to society based on trade-offs of the various impacts, such as coal production, carbon dioxide emissions, and hydrogen production, of a transition to a coal-based Hydrogen Economy via FutureGen penetration.

It is not an expressed goal of this research to exhaust all weighting possibilities or to determine an optimal set of weights and priorities. The goal is to provide a tool that can be tailored to the user's specific situation.

## 6.1. GOAL PROGRAMMING MODEL FORMULATION

The following shows the mathematical formulation of the goal programming model:

Objective: Maximize the net benefit to Society

$$\text{Maximize } z = \sum_{i=1}^{I} P_i(w_{pi}d_{pi} - w_{ni}d_{ni}) \qquad (6.1)$$

Subject to:

$$\text{System constraints } \sum_{j=1}^{J} C_jX_j \geq, \leq, \text{ or } = k_j \qquad (6.2)$$

$$\text{Goal constraints } \sum_{m=1}^{M} A_{mi}X_m \geq, \leq, \text{ or } = d_{pi} - d_{ni} \qquad (6.3)$$

Where: $P_i$ = Value representing relative importance among goals

$w_{pi}$ = weighting coefficient for a positive deviation

$w_{ni}$ = weighting coefficient for a negative deviation

$d_{pi}$ = positive deviation away from goal i

$d_{ni}$ = negative deviation away from goal i

$C_j$ = value of coal use as evaluated by system constraint j

$X_j$ = the amount of coal required for use j

$k_j$ = system constraint constant

$A_{mi}$ = value of coal use as evaluated by goal i

$X_m$ = the amount of coal required for use m

**6.1.1. Goals.** The goals incorporated into the model were selected to reflect important issues representative of key coal indicators and the Hydrogen Economy. The list of the goals that were incorporated into the model is as follows:

1. Minimize $CO_2$ cost
2. Maximize economic benefit to owners
3. Minimize land disturbance cost
4. Minimize water pollution cost
5. Maximize hydrogen utilization benefit
6. Maximize economic benefit to communities

**6.1.2. Variable Definitions.** The $P_i$'s and weighting factors are variables that will be defined by the user of the model. As a result, in order to provide sample model runs in this research, a range of weighting factors will be developed that will be incorporated into the model as weighting coefficients that will explore the impact that different priorities have on the results of the model. Weighting factors will be particularly chosen in order to explore the tradeoffs among conflicting goals/priorities. These different scenarios of weighting factors will be defined in section 6.4 with the sample runs of the model.

The coal uses that were incorporated into the model were coal used to generate electricity at traditional electric power plants, coal used to generate electricity at FutureGen plants, and coal used to create hydrogen at FutureGen plants. The unit used is million metric tons.

$X_1$ Coal for traditional power plants

$X_2$ Coal for FutureGen plants (electricity)

$X_3$ Coal for FutureGen plants (hydrogen)

The value of coal use as evaluated by use i, or $A_{mi}$, will be defined within the constraints. The constraints chosen for this model are general in nature and are intended to quantify the goals in a realistic way. A prime example of future research is to investigate and more exactly quantify the costs, reflected in the constraints, of each goal. Furthermore, in order to specifically quantify the costs, the region and users of the model will need to be known, so the model will be reflective of their situation.

## 6.2. SYSTEM CONSTRAINTS

The first three constraints are system constraints and are used to insure that enough electricity is generated to meet demand, maximum capacity is not exceeded, and FutureGen utilization does not exceed FutureGen penetration. Year 2030, with the base case capacity addition scenario and FutureGen penetration Case 1, was selected for the sample runs of the model. The impact of this selection on the constraints will be apparent in the constraint descriptions. As a result, in future utilizations, the constraints can be easily manipulated to reflect different scenario selections as imposed by the user. Again, the year 2030 case described above is used merely as an example.

Constraint 1 is as follows:

$$244.9X_1 + 267.9X_2 \geq 364{,}725 \text{ MW} \tag{6.4}$$

(244.9 and 267.9 reflect the amount of electricity in MW that are created from one million metric ton of coal in traditional electric power plants and FutureGen plants, respectively, using the equations previously described in this dissertation. In these sample runs, the electricity demand is assumed to be 75% of the predicted available capacity; this value can be adjusted by the user to adequately represent his/her specifications.)

Constraint 2 is as follows:

$$244.9X_1 + 267.9X_2 + 267.9X_3 \leq 486{,}300 \text{ MW} \tag{6.5}$$

(486,300 MW is the predicted available capacity in 2030.)

Constraint 3:

$$267.9X_2 + 267.9X_3 \leq 34{,}796 \text{ MW} \tag{6.6}$$

(34,796 MW is the maximum FutureGen capacity based in the estimated penetration in year 2030.)

## 6.3. GOAL CONSTRAINTS

Constraints 4 through 9 were developed for the six goals—one constraint for each goal. The objective of the model is to maximize the net benefit to communities which is represented by a monetary value. The goal constraints are, therefore, formulated by putting a monetary value on the given constraint. As with the system constraints, the goal constraints are designed to be manipulated by the user in order to tailor each constraint to the user's given situation.

Constraint 4 is intended to reflect the cost of carbon dioxide emissions. In the pretext of this model, carbon dioxide emissions would be considered externalities. Externalities are an important class of market failures in the field of environmental and resource economics. A brief definition of an externality is an unintended consequence or side effect associated with market transactions (Kahn, 2005.) In other words, when electricity is produced, carbon dioxide is emitted and is attributed to global warming, which is viewed as a negative effect on society. The goal of the electric power plant is not to emit carbon dioxide/ "harm society" but to produce electricity. As a result, there is a disparity between the marginal social cost function and the marginal private cost function, which causes a market failure. In order to correct the failure, a tax could be imposed. In order to quantify the impact of carbon dioxide emissions, a suggested tax on carbon dioxide emissions was utilized. Duke Energy proposed a tax of $12 per metric ton of carbon for the year 2005 (Osborne, 2005.) The costs incorporated into the model will be inflated to 2006 dollars in order to maintain consistency. Therefore, the assumption is that inflation will impact all of the costs similarly. However, future legislation and/or unforeseen events are likely to impact the costs associated with the goals in this model and will need to be incorporated as they become apparent. The $12 becomes $12.41 in 2006 dollars.

Constraint 4 is formulated as follows:

$0.5784X_1 + (267.9 \times 0.00909 \times 0.27)X_2$ = Amount of $CO_2$ produced.

(0.5784 represents the amount of carbon dioxide created during traditional electric power generation per MMT of coal as deduced from Warneke's model. $267.9X_2$ represents the amount of MW created per MMT tons of coal at a FutureGen plant. The coefficient 0.00909 was taken from the estimate by the FutureGen Alliance that a 275 MW FutureGen plant will produce between 1 and 2.5 MMT of carbon dioxide per year. The coefficient is conservative based on the estimate.)

An assumption of this dissertation is that 100% of the $CO_2$ created at a FutureGen plant will be sequestered. Therefore, the emission, or environmental, cost associated with this $CO_2$ creation will be zero. However, once more research is performed on sequestration, there will most likely be a cost associated with sequestration as well. Once this value is more apparent, it can be incorporated into the model. The cost is considered to be a negative cost and is designated as such.

Constraint 4:

$-0.5784(12.41)X_1 = d_{p1} - d_{n1}$, or

$$-7.178X_1 = d_{p1} - d_{n1} \quad (6.7)$$

(The dollar amounts in all of the constraints are in millions of dollars.)

Constraint 5 addresses the economic benefit to owners. The economic benefit to owners was quantified by approximating the profit generated by selling the electricity. The cost of electricity used was \$0.0454/kWh for traditional electric power generation and \$0.0592 for FutureGen plant generation (David, 2000.) The FutureGen plant cost was estimated by taking the cost of electricity from an ICGG plant and adding 30% to account for the cost of carbon dioxide sequestration (Courtright, 2003.) The selling price of electricity was \$0.0852/kWh in April 2006 (EIA Electric Power Monthly, 2007.) The profits can therefore be estimated to be \$0.0398/kWh and \$0.026/kWh for traditional electric power generation and FutureGen, respectively. The profit for selling hydrogen was estimated to be equivalent to the profit on electricity from a FutureGen plant. The reason is that the FutureGen plant is not yet in operation, and it is impossible to know the cost of producing the hydrogen. Therefore, it is assumed that in order to produce hydrogen, the profit would need to be equal to or greater than the profit for selling electricity. The profit per kWh can be used to find the profit per MMT coal as follows:

\$0.026/kWhr x (kWh/3.6MJ) x (MJ/0.00004143 metric tons coal) x (0.35 efficiency) x (1,000,000 metric tons/MMT) = \$61,000,000/MMT coal FutureGen

\$0.0398/kWhr x (kWh/3.6MJ) x (MJ/0.00004143 metric tons coal) x (0.32 efficiency) x (1,000,000 metric tons/MMT) = \$85,400,000/MMT coal traditional

Constraint 5 is as follows:

$$85.4X_1 + 61.0\,(X_2 + X_3) = d_{p2} - d_{n2} \tag{6.8}$$

Constraint 6 covers land disturbance costs. The land disturbance cost was calculated similarly to the carbon dioxide cost calculation—in terms of taxes/permit fees and reclamation costs. The first step was to estimate how many acres of land were disturbed per MMT of coal mined. It was assumed that all the coal mined was from surface mines as this is a conservative estimate for the model; again, this value can be adjusted by the users of the model to more closely approximate the particular situation for the time. According to the Southern Journal of Economics, approximately 173,560 acres of land were disturbed to accommodate a production of 366.1 million tons of coal surface mined (Catlett, 1979.) This equates to 522.6 acres/MMT of coal mined. Missouri Statutes were used to get an example of permit fees which resulted in a yearly permit fee of \$100 plus \$35 per acre of land disturbed that year (Missouri Revised Statutes, 2006.) The reclamation cost used was taken from an assessment of Pennsylvania's bonding program for surface coal mine. The average reclamation cost per acre of land disturbed was determined to be \$5,426/acre in 1998 dollars which equates to \$6,629/acre in 2006 dollars.

The resulting total land disturbance cost is as follows:

$$100 + 35(522.6\text{acres/MMT})(X_1 + X_2 + X_3) + 6{,}629(522.6\text{Ac/MMT})(X_1 + X_2 + X_3)$$

This is used to create constraint 6 which is as follows:

$$-\,3.483(X_1 + X_2 + X_3) = 0.0001 + d_{p3} - d_{n3} \tag{6.9}$$

Constraint 7 addresses water pollution cost. The Abandoned Mine Land (AML) program receives a tax paid by mines in the amount of 25 cents per ton of coal mined on the surface and 15 cents per ton underground. It uses the money to clean up water impacted by mines (Buck, 2001). Therefore, 25 cents per ton of coal mined will be used to represent the water pollution cost. Constraint 7 is as follows:

$$-0.2756(X_1 + X_2 + X_3) = d_{p4} - d_{n4} \tag{6.10}$$

Constraint 8 signifies utilization of the hydrogen economy. In order to quantify this, hydrogen cars were used as the measure. According to EPRI, 1% of the produced syngas from a 500 MW IGCC plant is enough to fuel 10,000 hydrogen cars for one year (Holt, 2004.) Based on IGCC plants with $CO_2$ sequestration, essentially FutureGen plants, one MMT of coal would fuel approximately 537,000 hydrogen cars for one year. This evolved based on 80 MW syngas are needed to make 43 MW of electricity (Phillips, 2005), which decreases to 35 MW with $CO_2$ sequestration (NETL, May 2007.) Therefore, 1143 MW of syngas are needed to produce 500 MW of electricity with $CO_2$ sequestration. One percent of this amount is 11.4 MW of syngas, and according to Phillips' relationships, 14.25 MW worth of coal is needed to create 11.4 MW of syngas. 14.25 MW of coal equates to 18,618 metric tons of coal, which is enough to fuel 10,000 hydrogen cars for one year, and in turn, one MMT of coal can, therefore, fuel approximately 537,000 hydrogen cars for one year. In order to quantify this benefit to society, a tax credit was utilized. According to the Internal Revenue Service, tax credits for hybrid vehicles purchased in 2006 were worth as much as $3,150 for the most fuel efficient models (IRS, 2007.) Assuming the tax credit would be approximately $3,000 for a hydrogen powered car and that owner would keep the car for five years, it can be assumed that the benefit to society would be approximately $600 per year per car. Therefore, if the amount of cars (537,000) fueled by one million metric ton of coal is multiplied by this $600, this results in $322,000,000. This results in constraint 8:

$$322.2X_3 = d_{p5} - d_{n5} \tag{6.11}$$

The final constraint encompasses economic benefit to communities. The measures of gross economic output and annual household incomes were used to quantify this goal. In a report prepared for The Center for Energy and Economic Development, Inc. titled “The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015” (Rose, 2006), these two measures were used. It estimated that U.S. coal-fueled electric generation in 2015 will contribute $1.05 trillion (2005 dollars) in gross economic output and $362 billion in annual household incomes. In order to obtain a value per MMT of coal, the example given in the paper for Pennsylvania was used. The numbers of $41,959 million in economic output and $14,327 million in annual household incomes were converted to 2006 dollars (43,386 and 14,814, respectively) for the model and divided by the amount of coal corresponding to the amount of BTU’s consumed by the electric power sector in Pennsylvania, which is 45.75 MMT. This resulted in $948.3 million per MMT of coal in gross economic output and $323.8 million per MMT of coal in annual household incomes (Rose, 2006.) As a result, constraint number nine is as follows:

$$1272.1\ (X_1 + X_2 + X_3) = d_{p6} - d_{n6} \quad (6.12)$$

In summary, the nine constraints are as follows:

- $244.9X_1 + 267.9X_2 \geq 364{,}725$ MW
- $244.9X1 + 267.9X2 + 267.9X3 \leq 486{,}300$ MW
- $267.9X2 + 267.9X3 \leq 34{,}796$ MW
- $-7.178X_1 = d_{p1} - d_{n1}$
- $85.4X_1 + 61.0\ (X_2 + X_3) = d_{p2} - d_{n2}$
- $- 3.483(X_1 + X_2 + X_3) = -0.0001 + d_{p3} - d_{n3}$
- $-0.2756(X_1 + X_2 + X_3) = d_{p4} - d_{n4}$
- $322.2X3 = d_{p5} - d_{n5}$
- $1272.1\ (X_1 + X_2 + X_3) = d_{p6} - d_{n6}$

The following section will incorporate these constraints into the goal programming model sample runs.

## 6.4. SAMPLE RUNS AND RESULTS

The software package Storm 4.0 Quantitative Modeling for Decision Support was used to run the models. Storm 4.0 employs a linear programming model based on the simplex algorithm, and is a standard linear programming tool with well established efficiency criteria. As discussed in Chapter 3, the simplex algorithm has been widely applied to economic and engineering problems. It is widely accepted and has been incorporated into many mathematical programming systems, such as Storm, as an efficient method for solving linear programs, such as the goal programming model formulated in this research.

In order to run the model, $P_i$'s and weighting coefficients must be provided. The model is designed to allow the user to input these values based on his/her priorities and preferences. The following table shows three different weighting coefficient scenarios created by the author.

Table 6.1 Example Weighting Coefficients

| Group | Min $CO_2$ Costs | Max Economic Benefit to Owners | Min Land Disturb-ance Cost | Min Water Pollution Cost | Max $H_2$ Utili-zation Benefit | Max Economic Benefit to Com-munities |
|---|---|---|---|---|---|---|
| Extreme Environ-mentalists | 0 ($w_{p1}$)<br>25 ($w_{n1}$) | 0<br>0 | 0<br>25 | 0<br>25 | 25<br>0 | 0<br>0 |
| Mining Industry | 0<br>0 | 65<br>0 | 0<br>10 | 0<br>5 | 0<br>0 | 20<br>0 |
| Average | 0<br>12.5 | 32.5<br>0 | 0<br>17.5 | 0<br>15 | 12.5<br>0 | 10<br>0 |

The weights shown in the above table were created by allotting each group 100 percent worth of weights. All $P_i$'s will be equal for the first set of runs and will equal 1.

The first run, extreme environmentalists, is shown as an example as follows:

Maximize $z = -25d_{n1} - 25d_{n3} - 25d_{n4} + 25d_{p5}$

Subject to:

- $244.9X_1 + 267.9X_2 \geq 364{,}725$ MW
- $244.9X1 + 267.9X2 + 267.9X3 \leq 486{,}300$ MW
- $267.9X2 + 267.9X3 \leq 34{,}796$ MW
- $-7.178X_1 = d_{p1} - d_{n1}$

- $85.4X_1 + 61.0\ (X_2 + X_3) = d_{p2} - d_{n2}$
- $-0.0001 - 3.483(X_1 + X_2 + X_3) = d_{p3} - d_{n3}$
- $-0.2756(X_1 + X_2 + X_3) = d_{p4} - d_{n4}$
- $322.2X3 = d_{p5} - d_{n5}$
- $1272.1\ (X_1 + X_2 + X_3) = d_{p6} - d_{n6}$

The other two runs for the mining industry weights and the average weights are formulated in a similar fashion with the same constraints. The results from the three runs are shown in Table 6.2, as well as the number of iterations performed to reach the optimized solution. Again, $X_1$, $X_2$, and $X_3$ are in MMT of coal, and the dollar amounts are in millions of 2006 dollars.

Table 6.2 Results

| Variable | Extreme Environmentalists | Mining Industry | Average |
|---|---|---|---|
| $X_1$ | 1,489 | 1,986 | 1,844 |
| $X_2$ | | | |
| $X_3$ | 130 | | 130 |
| $d_{p1}$ | | | |
| $d_{n1}$ | 10,690 | 14,253 | 13,234 |
| $d_{p2}$ | 135,108 | 169,580 | 165,369 |
| $d_{n2}$ | | | |
| $d_{p3}$ | | | |
| $d_{n3}$ | 5,638 | 6,914 | 6,872 |
| $d_{p4}$ | | | |
| $d_{n4}$ | 446 | 547 | 544 |
| $d_{p5}$ | 41,849 | | 41,849 |
| $d_{n5}$ | | | |
| $d_{p6}$ | 2,059,741 | 2,526,020 | 2,510,502 |
| $d_{n6}$ | | | |
| Objective Function Value | 626,862 (9 iterations) | 61,471,180 (10 iterations) | 30,708,780 (11 iterations) |

Based on the weights selected and the valuation of the constraints, the best case for the maximum benefit to society is the mining industry case. In this case, $X_1 = 1986$ which makes Equation 6.4 and 6.5 approximately equal to 486,300 MW. This means that the electricity produced exceeds demands, and also that the maximum capacity available is utilized. Furthermore, the electricity is generated at traditional coal-fired power plants. Another key result is that no coal was designated to go to FutureGen for electric power generation in any of the cases, and in the extreme environmentalist case and the average case, the maximum capacity of FutureGen was utilized to make hydrogen. Also, in the average case, like in the mining industry case, the maximum capacity available at traditional coal-fired power plants was utilized to make electricity. The maximum capacity of traditional coal-fired power plants is less in the average case than in the mining industry case, since the average case specifies hydrogen production which means FutureGen penetration into the total capacity available. In the extreme environmentalists case, however, just enough electricity was produced to meet demand (364,725 MW).

Now, the next run will take the average case shown above, but change the value of $P_5$ to signify a lesser importance being placed on utilization of the hydrogen economy. $P_5$ will be equal to 0.5, which means that the goal of hydrogen utilization is half as important as the other goals. The results are shown in Table 6.3:

Table 6.3 Results

| Variable | $P_5 = 0.5$ |
|---|---|
| $X_1$ | 1,986 |
| $X_2$ | |
| $X_3$ | |
| $d_{p1}$ | |
| $d_{n1}$ | 14,253 |
| $d_{p2}$ | 169,580 |
| $d_{n2}$ | |
| $d_{p3}$ | |
| $d_{n3}$ | 6,914 |
| $d_{p4}$ | |
| $d_{n4}$ | 547 |
| $d_{p5}$ | |
| $d_{n5}$ | |
| $d_{p6}$ | 2,526,020 |
| $d_{n6}$ | |
| Objective Function Value | 30,464,160 (10 iterations) |

The results show that no coal is designated to make hydrogen, and the objective function value is less than the average case shown in Table 6.2 with all goals having the same priority. Again, the maximum capacity available to make electricity at traditional power plants is utilized.

The next run will examine the effect of the carbon tax on the decision to make electricity at traditional plants or at FutureGen plants. Again, keeping the priority, or $P_i$'s, equal for all goals, the amount of the carbon tax will be manipulated to see where the break point is to switch from making electricity at traditional power plants to utilizing FutureGen to make electricity. In the previous examples, the goal to minimize carbon dioxide costs was represented by equation (6.7) which incorporated a carbon tax of $12.41 per metric ton of carbon. Using the weights from the average case scenario, it was found that the carbon tax needed to increase over 200 times before making electricity at FutureGen plants was considered the best option in order to maximize the net benefit to society. The results are shown in table 6.4.

Table 6.4 Results

| Variable | Carbon Tax $2,643/metric ton | Carbon Tax $2,644/metric ton |
|---|---|---|
| $X_1$ | 1489.2810 | 1,347.1990 |
| $X_2$ | | 129.8843 |
| $X_3$ | 129.8843 | |
| $d_{p1}$ | | |
| $d_{n1}$ | 2,276,681.0000 | 2,060,258.0000 |
| $d_{p2}$ | 135,107.6000 | 122,973.7000 |
| $d_{n2}$ | | |
| $d_{p3}$ | | |
| $d_{n3}$ | 5,637.9350 | 5,143.2040 |
| $d_{p4}$ | | |
| $d_{n4}$ | 446.2420 | 407.0841 |
| $d_{p5}$ | 41,848.7200 | |
| $d_{n5}$ | | |
| $d_{p6}$ | 2,059,741.0000 | 1,878,997.0000 |
| $d_{n6}$ | | |
| Objective Function Value | -3,052,360 (10 iterations) | -3,062,714 (8 iterations) |

The results in Table 6.4 show that the carbon tax needs to reach approximately $2,644/metric ton of carbon before utilizing FutureGen plant capacity for generating electricity. The results also show that raising the carbon tax to this level creates a negative result for the objective function value. In other words, there is not an overall net benefit to society; in fact, the overall benefit is negative. This is due to the fact that a tax, such as the carbon tax, is representative of the amount of harm the carbon emitted does to the environment/society. Therefore, if the harm is actually to the magnitude shown by the carbon tax in Table 6.4, then generating electricity using coal may not be the proper course and alternative sources, such as nuclear should be examined. Another conclusion that can be taken from the results in Table 6.4 is that perhaps the ability of FutureGen plants to reduce $CO_2$ emissions is not a great enough benefit to warrant a switch from traditional coal-fired power plants to FutureGen plants. Perhaps the emphasis in support of FutureGen plants should be placed in the ability to produce hydrogen.

In order to look at the possible implications of varied FutureGen penetration rates, the extreme environmentalist case, the mining industry case, and the average case detailed in Table 6.1 will be rerun with the FutureGen penetration Case 4 incorporated. This results in system constraint 3 changing to the following:

$$267.9X2 + 267.9X3 \leq 34{,}796 \text{ MW} \qquad (6.13)$$

The results of this run are displayed in Table 6.5.

Table 6.5 Results with FutureGen Penetration Case 4

| Variable | Extreme Environmentalists | Mining Industry | Average |
|---|---|---|---|
| $X_1$ | 1,489 | 1,986 | 1,858 |
| $X_2$ | | | |
| $X_3$ | 117 | | 117 |
| $d_{p1}$ | | | |
| $d_{n1}$ | 10,690 | 14,253 | 13,336 |
| $d_{p2}$ | 134,315 | 169,580 | 165,790 |
| $d_{n2}$ | | | |
| $d_{p3}$ | | | |
| $d_{n3}$ | 5,593 | 6,914 | 6,876 |
| $d_{p4}$ | | | |
| $d_{n4}$ | 443 | 547 | 544 |
| $d_{p5}$ | 37,663 | | 37,665 |
| $d_{n5}$ | | | |
| $d_{p6}$ | 2,043,216 | 2,526,020 | 2,512,054 |
| $d_{n6}$ | | | |
| Objective Function Value | 523,449 (9 iterations) | 61,471,180 (10 iterations) | 30,684,310 (11 iterations) |

The only difference between the runs whose results are shown in Table 6.2 and Table 6.5 is the FutureGen penetration case incorporated. Case 1 was used in the first run (Table 6.2) and Case 4 (decreased FutureGen penetration) was used for Table 6.5. In both of the runs, the maximum available FutureGen capacity is utilized to make hydrogen in the extreme environmentalist case and the average case. However, the objective function value, i.e. the overall maximum benefit to society, has gone down in both cases with FutureGen penetration Case 4. This signifies that based on the weights, priorities, and constraints formulated in these sample runs that the overall benefit to society increases as FutureGen penetration increases. However, the mining industry case remained constant in both scenarios since no coal was designated to go to FutureGen plants, and the mining industry case has the greatest objective function value, or benefit to society.

Another variation of the run shown in Tables 6.1 and 6.2, is to incorporate the plus twenty percent scenario for capacity additions. Table 6.6 shows the results of the run incorporating the plus twenty percent capacity additions scenario and FutureGen penetration scenario Case 1.

Table 6.6 Results with Plus Twenty Percent Capacity Additions and FutureGen Penetration Case 1

| Variable | Extreme Environmentalists | Mining Industry | Average |
|---|---|---|---|
| $X_1$ | 1,613 | 2,151 | 1,980 |
| $X_2$ | | | |
| $X_3$ | 156 | | 156 |
| $d_{p1}$ | | | |
| $d_{n1}$ | 11,580 | 15,440 | 14,216 |
| $d_{p2}$ | 147,276 | 183,691 | 178,638 |
| $d_{n2}$ | | | |
| $d_{p3}$ | | | |
| $d_{n3}$ | 6,160 | 7,490 | 7,439 |
| $d_{p4}$ | | | |
| $d_{n4}$ | 488 | 593 | 589 |
| $d_{p5}$ | 50,218 | | 50,218 |
| $d_{n5}$ | | | |
| $d_{p6}$ | 2,250,434 | 2,736,220 | 2,717,599 |
| $d_{n6}$ | | | |
| Objective Function Value | 799,779 (9 iterations) | 66,586,450 (10 iterations) | 33,292,750 (11 iterations) |

The results shown on Table 6.6 show that as the capacity addition demand increases (in this case to 20%), the overall net benefit to society increases. It is interesting to note that the largest percent increase occurs in the extreme environmentalist case (28%) as compared to approximately 8% for the other two cases. Similar distribution of the coal occurs in this run and also the run results shown on Table 6.2 in that the maximum capacity of FutureGen is utilized to make hydrogen in both the extreme environmentalist case as well as the average case.

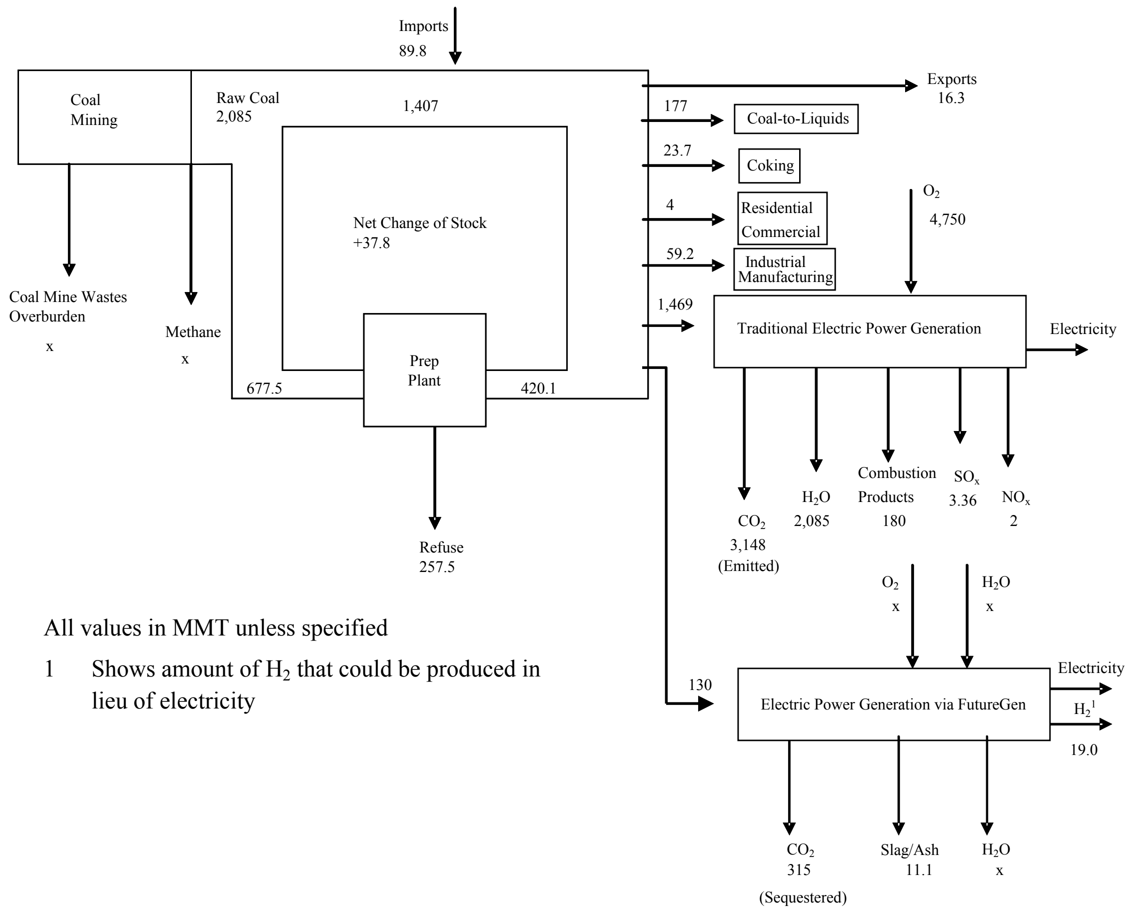
## 6.5. SUMMARY OF EXAMPLE RUNS

The example runs and results described in the previous section are arbitrary, in that they were based on the author's weighting and priority preferences. Furthermore, the values of the goal constraints were general determinants and intended merely to be a guide for the user to specify goal constraint values specific to his/her situation and or application. However, the sample runs do provide examples on ways in which the goal programming model can be utilized and do provide some insight on the way in which the decisions will change based on varying priorities, system constraints, and goal constraints.

A prime are of future work will be to apply the goal programming model to a specific case study in order to examine to full capabilities and sensitivities of the model.

## 6.6. INCORPORATION INTO COAL MFA'S

Chapter 5 described coal MFA predictions throughout the timeframe of 2012-2052. These coal MFA's can be adjusted to incorporate the model results of a chosen scenario in order to see the overall impact on the coal industry, as well as downstream effects on the environment. For example, the base case MFA for year 2030 can be used as a template to incorporate the results of the extreme environmentalist's case and the mining industry case shown in Table 6.2. The year 2030 coal MFA as described in Chapter 5, with no adjustments based on the goal programming model, can be seen in Figure 6.1.




All values in MMT unless specified

1 Shows amount of $H_2$ that could be produced in lieu of electricity

Figure 6.1 Predicted Coal MFA for the United States in year 2030 based on the Base Case Predicted Coal Powered Electricity Demand Scenario.

Figures 6.2 and 6.3 will show the manipulated coal MFA's for year 2030 incorporating the results of the model shown in Table 6.2 for the extreme environmentalists case and the mining industry case, respectively, for the amount of coal designated to go to traditional electric power generation and to electric power generation via FutureGen.

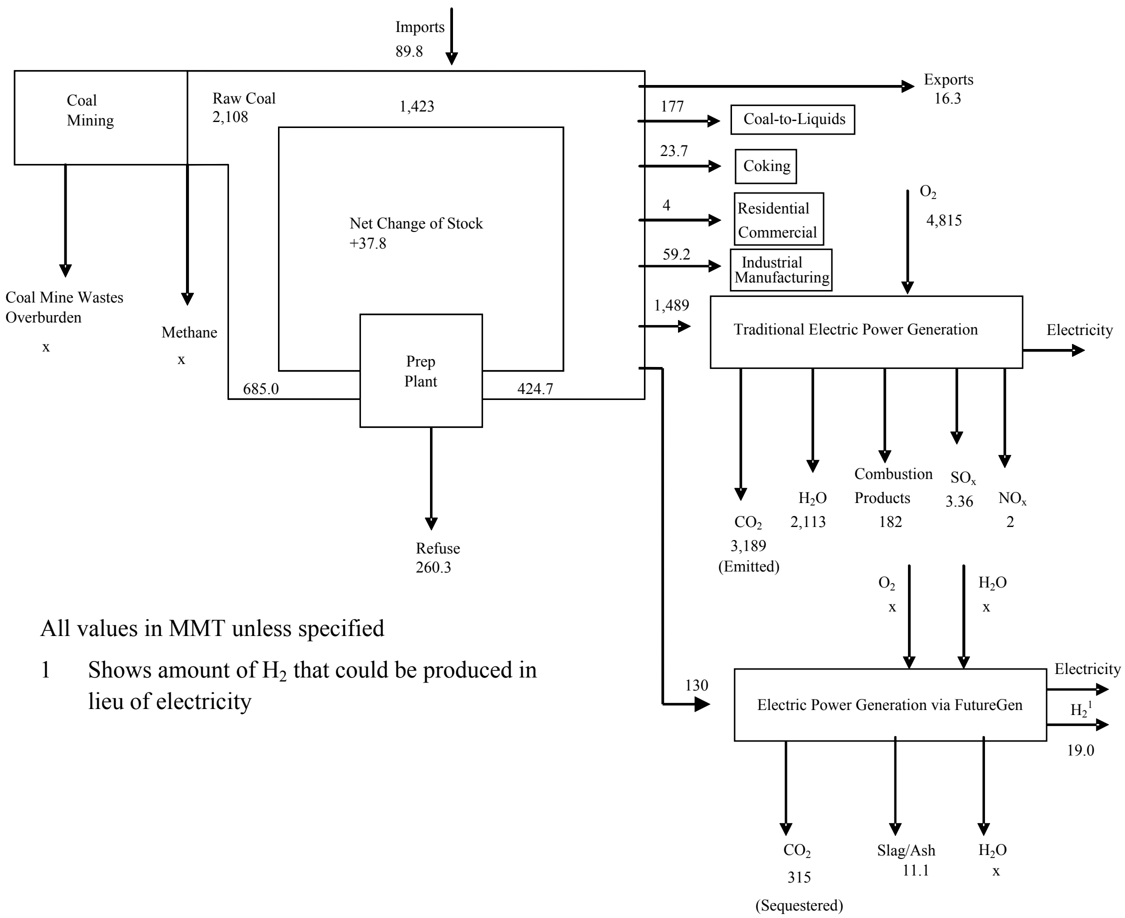



Figure 6.2 Predicted Coal MFA for the United States in year 2030 based on the Base Case Predicted Coal Powered Electricity Demand Scenario with the Model Results for the Extreme Environmentalist Case Incorporated.

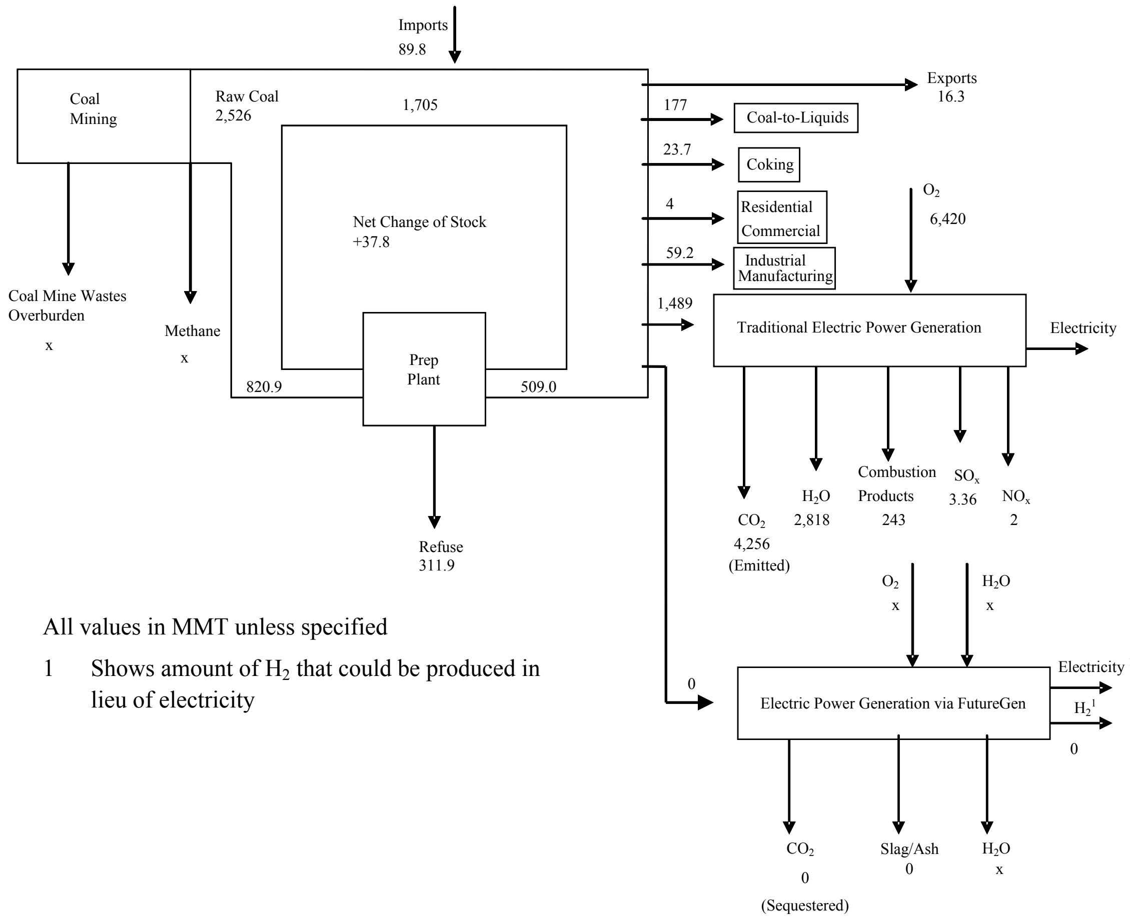



Figure 6.3 Predicted Coal MFA for the United States in year 2030 based on the Base Case Predicted Coal Powered Electricity Demand Scenario with the Model Results for the Mining Industry Case Incorporated.

## 6.7. APPLICATIONS OF THE GOAL PROGRAMMING MODEL (SOUND PUBLIC POLICY MAKING)

The ultimate application will be for policy-makers and other interested parties to use the model to predict the possible impacts, regarding FutureGen's penetration/the Hydrogen Economy's impact on the coal industry, that could result by placing emphasis on certain areas.  It is intended to be a tool that will assist law-makers to make educated policy decisions concerning coal-based electricity generation, the hydrogen economy, and related issues.  In other words, they should be able to tailor the model to a particular situation and use it to determine the impact of proposed policy and priorities, such as a carbon tax.  This will enable downstream effects to be more visible and easier to consider.

# 7. RESULTS AND DISCUSSION

It can be argued whether making energy supply and demand predictions is more of an art or a science. The difficulties lie in the unpredictable nature of the influencing factors on the energy market. Significant influencing factors include undulating prices for various energy producing technologies and sources, U.S. economic growth, technological advances, changes in weather patterns, and future public policy decisions.

The objective of this research was to analyze the holistic impact of the Hydrogen Economy on the coal industry. The first connection lies in the likelihood that coal will be the most practical feedstock for hydrogen. The research was then led to analyzing the process by which hydrogen can be produced from coal, which lies in FutureGen. In order to get an idea about the productive capabilities of FutureGen, the penetration of this type of plant and relative technologies was analyzed. As a result, possible penetration scenarios of FutureGen were predicted with electricity demand being the driving force behind new coal-based electricity plant construction, since producing electricity with domestically available coal is presently a more pressing concern than hydrogen production. However, once FutureGen plants are in place, the ability to produce hydrogen exists. The attractiveness to build FutureGen plants is encompassed by the promise of basically emission-free electricity generation and the ability to produce a value added product in the form of hydrogen.

New plant capacity was estimated through year 2052, and the FutureGen predicted penetration was incorporated. Scenarios of plus and minus 10 and 20 percent in capacity additions were reviewed in order to allow for fluctuations in coal-based electricity demand. These scenarios were then used to update and predict what coal MFA's could look like throughout the time period of 2012 to 2052. In other words, coal MFA's were used to map the results of different electricity demand and FutureGen penetration scenarios. As discussed in Chapter 3, MFA's can paint an overall picture about a specific material's movement within a system. In this case, the forecasted coal MFA's give an idea about the amount of coal that will be demanded in the U.S. and its uses, as well as identify downstream impacts on the economy, environment, and society. For example, the forecasted MFA's provide specific quantities of carbon dioxide to be both emitted and sequestered based on coal-based electricity generation via traditional coal-fired power plants and FutureGen plants. The forecasted MFA's are dependent upon the assumptions stated in this dissertation, but, again, the scenarios of plus and minus 10 and 20 percent are designed to give some flexibility and robustness to the potential utilizations of the predicted coal MFA's. Importantly, MFA's are, unto themselves, a tool for use by policy makers.

The forecasted coal MFA's could also be useful tools for the coal industry. Based on the predicted amount of coal to be produced in the U.S., mining companies will be able to strategically plan the resources, such as miners, engineers, equipment, land, etc., required in order to meet the increased coal demand. Furthermore, the feasibility of meeting the demand will have to be examined. In an era of more mining engineering job openings open than mining engineers available and ever-increasing safety regulations, the ability of the coal industry to meet the demand lies more simply upon capability or capacity, i.e. resource limitations and economics, than in the decision to try to meet demand. However, the mining industry would be better prepared for expansion by utilizing the predictions and penetrations outlined here in a strategic planning way. Recent shortfalls in graduation rates for mining engineers have already placed a burden on an aging workforce, and tools showing the demand in future years will be invaluable in creating industry standards for supporting the institutions which turnout these needed graduates. This is just one example of how the coal industry could use the penetration tools for strategic planning.

In order to look at the economic, environmental, and societal impacts of the hydrogen economy on the coal industry, a goal programming model was created that incorporated both the electricity generating capacity predictions along with the FutureGen penetration and the forecasted coal MFA's resulting from this research. Goals were formulated that represented economic, environmental, and social issues indicative of previously established coal indicators as well as the hydrogen economy. The goal programming model was designed to allow its users to place emphasis on different areas based on their preferences. Therefore, the model will be able to provide different conclusions to the user, based on the user's priorities, objectives, and biases. As such, it is intended to be a potential tool for policy-makers when making decisions and legislation relating to coal and the hydrogen economy. Many factors within the model constraints and weighting priorities could be investigated in an entirely different body of work that is outside the scope of this research.

Regarding FutureGen penetration, the success of the first plant will play a pivotal role. Based on this research, the efficiency of FutureGen plants is comparable to traditional coal-fired plants. The main contributor to decreasing the more efficient IGCC processes housed in FutureGen is the addition of $CO_2$ sequestration, which is one of the main highlights and reasons for enthusiasts backing FutureGen in the current political and social environment that has awarded Al Gore a Nobel Peace Prize for his work, which warns the world that global warming is “the greatest challenge we’ve ever faced (MSNBC.com, 2007).” Applying the goal programming model to examine this situation is a perfect example of its intended use. When the goal programming model examined the carbon tax amount it would take to switch electricity production over to FutureGen from traditional coal power plants, the result was over 200 times the proposed carbon tax. The conclusion drawn from this case is that companies involved with power generation are likely to continue generating electricity and adding capacity through traditional power plants and pay the proposed carbon tax rather than adding capacity of FutureGen with costly $CO_2$ sequestration and unproven technology. However, this result was based on the weights, priorities, and constraint values supplied by the author. Assuming these values were truly representative of a policy maker’s situation, a finding like this could promote the response of looking elsewhere for reducing carbon dioxide emissions and implementing the policy to accomplish this objective. For example in one respect, placing more emphasis on reducing carbon dioxide emissions from transportation sources as opposed to electricity generation might be a more feasible and less costly solution.

It is also important to note that unless a large priority was placed on the hydrogen economy, the model selected electricity generation from traditional power plants over FutureGen plants. Again, assuming that the values in the model were truly representative of a policy maker’s situation, it could be concluded that in order for FutureGen penetration to be solely market driven, as opposed to government-intervention driven, the Hydrogen Economy, i.e. hydrogen production would need to be a driving force and not just electricity demand. This conclusion is derived from model results showing that the overall maximum benefit to society is not significantly tied to carbon dioxide emissions, especially since regulations will cap emissions from traditional coal-fired power plants making that electricity production cleaner, through the use of improved technology in scrubbers and other emission control measures.

# 8. CONCLUSIONS AND FUTURE WORK

## 8.1. CONCLUSIONS

It is an important study to provide tools and methods for analyzing the impact of alternative energy plans on our existing energy sources and processes. The general objective of this research was to analyze the impact of the Hydrogen Economy on the coal industry, and to provide related tools that can be used by both policy makers and the coal industry. This research combined the unique contributions of developing technology penetration models for FutureGen plants, forecasting coal MFA's based on electricity demand and FutureGen penetration, and formulating a goal programming model that seeks maximum benefit to society while analyzing the trade-offs of the various impacts associated with a transition to a coal-based Hydrogen Economy.

In summary, the two main contributions of this dissertation are as follows:

- It provides a scientific tool (the goal programming model) for lawmakers to utilize in order to create sound public policy in regards to the impact of the Hydrogen Economy on the coal industry and its downstream effects on the economy, the environment and society.
- It provides the coal industry with a general overview of how it may be impacted by the implementation of the Hydrogen Economy. This overview is demonstrated with the unique contributions of
    - providing predicted penetration models for FutureGen plants into coal-powered electricity capacity, and

- providing coal MFA's for the years 2013 to 2052 based on predicted demand for coal-powered electricity capacity additions that includes a sensitivity analysis of plus and minus ten and twenty percent.

The intent of this research is to provide scientific insight into the realistic effects and results of a push to a coal-based hydrogen economy. The use of tools such as these is necessary in order to ensure that the nation's energy needs are met as coal transitions from a source primarily used for electricity production to a source potentially capable of achieving U.S. energy independence.

**8.2. FUTURE WORK**

Due to the predictive nature of this research, future research will need to be done in order to update the predictions with what realistically occurs. The calculations in the research were formatted so that adjustments will be fairly simple to make and the results easily seen.

FutureGen abilities will be readily seen once full scale plant operations occur. Information, such as plant efficiency, electricity and hydrogen producing capabilities, and CCS abilities, will be useful to incorporate into FutureGen penetration models. Also, as this information becomes available, it will be interesting to study the trade-offs associated with producing both electricity and hydrogen, and the ease of switching between the two.

Regarding the forecasted coal MFA's, an area of future work lies in predicting the amount of methane and coal mine wastes overburden created due to the amount of raw coal required. Also, the emissions from FutureGen plants can be updated to reflect the emissions from the experimental plant once it is in operation. The forecasted coal MFA's could also be incorporated into future work examining the logistics associated with meeting increased electricity demand as well as the Hydrogen Economy.

A key area of future work following this research will be to apply the goal programming model to a case study. This case study will enable the weights and priorities to be reflective of a real situation with the system and goal constraints tailored specifically to the same situation. A case study will enable realistic results to be generated and provide a study where the full extent of sensitivities and correlations can be examined. Future research will also involve expanding the goal programming model to include other factors, such as new fuel-cell technologies, new electricity-generating technologies, changing economics of hydrogen-production technologies, environmental legislation, changing social concerns, etc. Furthermore, quantifying each of the goals and objectives in the model could be significant research in itself when trying to be all-encompassing or to tailor the quantification to a specific region.

This dissertation research could also provide a tool for larger projects. For example, in May 2006, DOE was seeking proposals to research and determine the employment effects of a transition to the Hydrogen Economy. The model in this research could be used to show the impact from a coal perspective and could be combined into a larger model showing all facets of the Hydrogen Economy.

Another important issue to address will be communicating the results of this research to policy-makers in a usable and easily-understood manner. Research would need to be performed to determine the best method to accomplish this communication.

# APPENDIX A

# COAL INDICATOR INFORMATION

COAL INDICATORS

In 2004, Warneke developed a comprehensive set of indicators for the coal industry. He divided the indicators into seven main categories: economic, environmental, social, economic-environmental, economic-social, environmental-social, and economic-environmental-social. Figure A1 illustrates these relationships (Warneke, 2004).

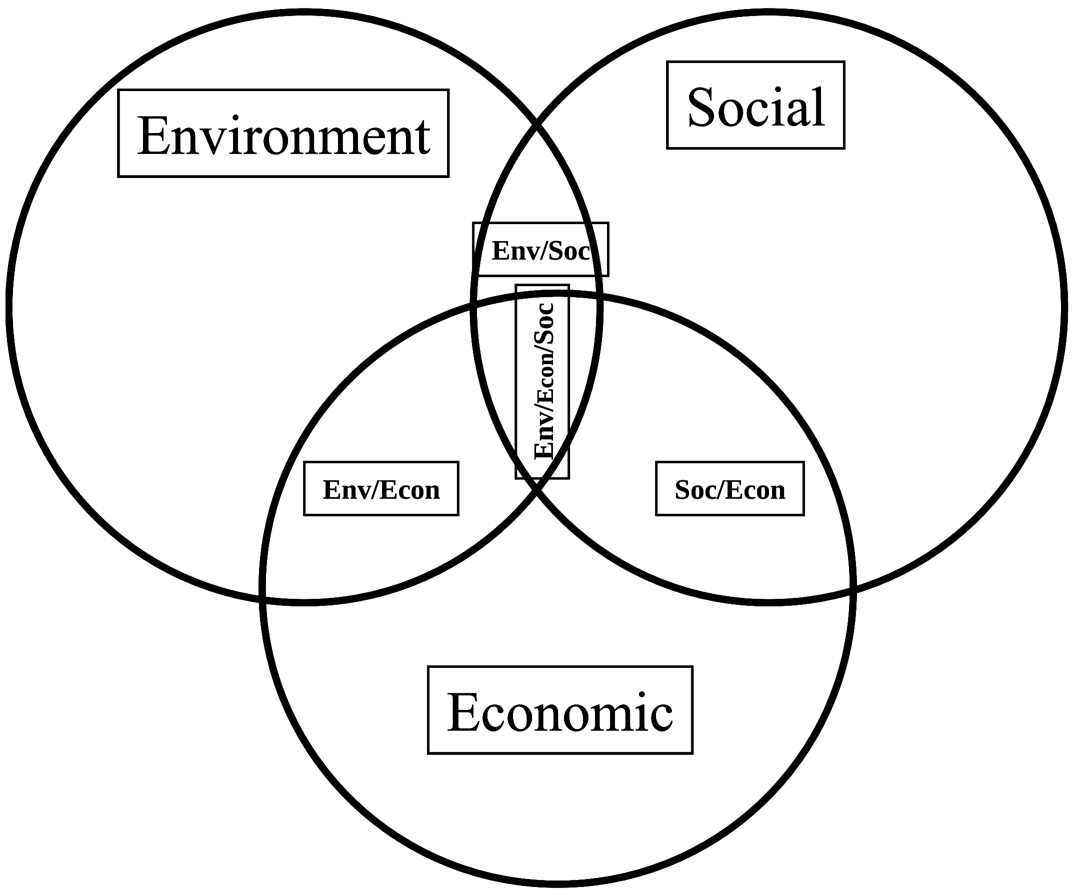



Figure A1 Interactions (Warneke, 2004).

Warneke created tables showing the indicators for the coal industry for each category along with the units and definition for each indicator and the availability and compilation status of the data about the indicator. The tables are shown below.

Table A1 - Economic core indicators for the U.S. coal industry (Warneke, 2004).

| **INDICATOR TITLE** | **UNITS** | **DEFINITION** | **DATA AVAILABILITY / COMPILATION** |
|---|---|---|---|
| Capital Expenditures - Coal Industry | $/yr | An outlay of funds by the firm that is expected to produce benefits over a period of time greater than one year | all data available / not compiled |
| Coal Consumption per GDP | tons/$GDP | Metric tons of coal consumed per million dollars of GDP | all data available / compiled |
| Consumption per Sector | tons/yr | Metric tons of coal consumed per year | all data available / compiled |
| Cost of Coal at Electric Utilities | $/yr | Cost of delivered coal at electric utilities per year | all data available / compiled |
| Cost of Coal for Industrial Uses | $/yr | Cost of delivered coal at industrial plants per year | all data available / compiled |
| Cost of Coking Coal at Coke Plants | $/yr | Cost of delivered coking coal at coke plants per year | all data available / compiled |
| Cost of Energy vs. Total Cost | $/$ | Ratio of energy costs to total costs to produce one ton of coal | no data available / not compiled |
| Energy Consumption per GDP by Energy Source | energy unit/$ | Energy consumed per dollars of GDP by type of energy source | all data available / compiled |
| Expenditures to Enforce Coal Mining Regulations | $/yr | Expenditures per year by enforcement agencies to enforce coal mining regulations | limited data available / not compiled |
| Expenditures for Exploration | $/yr | Expenditures per year for coal exploration | limited data available / not compiled |

Table A1 Continued - Economic core indicators for the U.S. coal industry (Warneke, 2004).

| **INDICATOR TITLE** | **UNITS** | **DEFINITION** | **DATA AVAILABILITY / COMPILATION** |
|---|---|---|---|
| GDP per Capita | $/capita | Dollars of GDP per person | all data available / compiled |
| GDP | $/yr | The total dollars of goods and services produced by a nation over a given period, usually 1 year | all data available / compiled |
| Idle Capacity - Coal Mines | tons/tons | The extent of idle capacity that can be utilized within coal mines | no data available / not compiled |
| Idle Capacity - Coal-fired Power Plants | tons/tons | The extent of idle capacity that can be utilized within coal-fired power plants | no data available / not compiled |
| Labor Expenditure/GDP | $/$ | Worker compensation within coal industry per dollars of GDP | limited data available / not compiled |
| Labor Expenditure/GDP - Coal Mines | $/$ | Worker compensation within coal industry per coal dollars of GDP | limited data available / not compiled |
| Percentage of GDP Attributable to Coal | $/$ | Gross income from coal per dollar of GDP | all data available / compiled |
| Permit Ratio | #/# | Ratio of granted permits to requested permits | all data available / compiled |
| Production Efficiency | tons/miner/hr | Ratio of total tons of coal mined per miner per hour | all data available / compiled |
| Production per Number of Mines | tons/no. of mines | Average production per mine in U.S. | all data available / compiled |

Table A1 Continued - Economic core indicators for the U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Production | tons/yr | The quantity of something (as a commodity) that is created, mined, or grown (usually within a given period of time); "production was up in the second quarter" | All data available / compiled |
| Production by Mining Method | tons/method | Total production for each method | All data available / compiled |
| Resource Sterilization | tons/yr | Resource sterilization occurs when the development of resources is precluded by either an existing land use or the development of another resource. | Limited data available / not compiled |
| Royalties from Coal Mines (public and private) | $/yr | Royalties means payment. A claim owner usually receives a percentage of what an operation finds on his claim. A grubstaker may also receive a percentage. These payments are often referred to as "royalties." | Limited data available / not compiled |
| Surface Production | tons/yr | Number of tons produced each year by surface mines | All data available / compiled |
| Tax Income from Coal Mines | $/yr | A sum of money imposed on coal by a government for its support | All data available / compiled |
| Tax Income from Coal-Fired Power Plants | $/yr | A sum of money imposed on coal-fired power plants by a government for its support | All data available / compiled |

Table A1 Continued - Economic core indicators for the U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY/COMPILATION |
|---|---|---|---|
| Underground Production | tons/yr | Number of tons produced each year by underground mines | All data available / compiled |
| Value fob Mines | $/yr | Value of coal free on board at mines | All data available / compiled |

Table A2 - Environmental core indicators for U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Hazardous Waste Generation | tons/yr | A hazardous waste is a solid waste which because of its quantity, concentration, or characteristics may cause an increase in mortality or serious irreversible illness or pose a substantial hazard to human health or the environment when improperly treated, stored, transported, disposed of, or otherwise managed. Under RCRA, hazardous wastes are identified and managed as a result of their being specifically placed on lists, or because they exhibit at least one of four particular characteristics (ignitability, corrosively, reactivity, or toxicity). | Limited data / not compiled |

Table A2 Continued - Environmental core indicators for U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Nutrients and Toxics | tons/yr | Amount of nutrients and toxics released to the environment each year | Limited data available / compiled |
| Coastal Water Heavy Metals | tons/yr | Amount of heavy metals in coastal water ways from coal | Limited data available / compiled |
| Landfill Waste | tons/yr | Amount of waste sent to the landfill by coal-fired power plants | All data available / not compiled |
| Use of Environmental Audit System | % | Percentage of companies using an environmental audit system | All data available / not complied |
| $CO_2$ Emissions per Household | tons/household | Average $CO_2$ emissions per household in U.S. | All data available / compiled |

Table A3 - Social core indicators for the U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Avg No. of Mine Workers Daily | no. of personnel | Average total number of miners reporting for work each day | All data available / compiled |
| Avg No. of Mine Workers Daily – UG | no. of personnel | Average total underground miners reporting for work each day | All data available / compiled |
| Avg No. of Mine Workers Daily – S | no. of personnel | Average total surface miners reporting for work each day | All data available / compiled |
| No. of Mine Injuries | no. injuries | Total number of coal mine injuries reported each year | All data available / compiled |

Table A3 Continued - Social core indicators for U.S. coal industry (Warneke, 2004).

| **INDICATOR TITLE** | **UNITS** | **DEFINITION** | **DATA AVAILABILITY / COMPILATION** |
|---|---|---|---|
| No. of Fatal Injuries | no. injuries | Total number of coal mine related fatalities each year | All data available / compiled |
| Education Funding | $/yr | Education funding in coal mining states vs. non-coal mining states | All data available/not compiled |
| Health Care Spending | $/yr | Health care spending in coal mining states vs. non-coal mining states | All data available / not compiled |
| Respiratory Illness | | Number of coal workers with respiratory illness | All data available / compiled |
| Poor Households - Below Poverty Line | % | Number of households below the poverty line in coal mining areas | All data available / not compiled |
| Noise | dB | How the surrounding communities are affected by coal mining related noise | No data available / not compiled |
| Deaths from Work-Related Diseases | #/yr | Number of coal worker deaths from work related disease | All data available / compiled |
| Public Awareness - Coal Uses | % | % of the public that is aware of coals different uses | No data available / not compiled |
| Community Investment | $/yr | Amount of money that coal companies invest in communities that have coal mining | Limited data available / not compiled |

Table A4 - Econoenviron core indicators for U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Consumption by Coking | tons/yr | Tons of coal used to produce coking coal | All data available/compiled |
| Percent of By-Products Recycled | tons/tons | A percentage of by-products from various coal processes recycled compared to landfilled | All data available / not compiled |
| Waste Collection Spending | $/yr | Amount of money spent each year on waste collection and storage | Limited data available / not compiled |
| Water Consumption | gal/yr | Amount of water used in the production and consumption of coal | Limited data available / not compiled |

Table A5 - Econosocial core indicators for the U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Recoverable Reserves | tons/yr | Amount of coal that is considered recoverable | All data available / compiled |
| Coal Extraction Rate | tons/yr | The total amount of coal that is extracted each year | All data available / compiled |
| Extraction/Reserves Replaced | tons/tons | A ratio of the extraction rate to the replacement rate of coal reserves | Limited data available/not compiled |
| Income Trend | $/yr | The trend in the income of coal workers | Limited data available / not compiled |
| Expenditures for Sustainable Communities | $/yr | The amount of money coal companies spend on making communities sustainable after the mine shuts down | Limited data available / not compiled |
| Unemployment Rate | % | The unemployment rate of coal miners | Limited data available / not compiled |

Table A5 Continued - Econosocial core indicators for the U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Incident Rates - Subsurface | incident/hr | The rate that underground coal miners get injured | All data available / compiled |
| Income Level | $/$ | Comparing the average coal mining worker to the average salary in the U.S. | Limited data available / compiled |

Table A6 - Envirosocial core indicators for U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Consumption Per Capita | Tons/capita/yr | Tons of coal consumed per capita | All data available / compiled |
| Total Water Discharges | gal/yr | Total water discharged in coal mining | Limited data available / not compiled |
| Greenhouse Gas Emissions | gas units/yr | Amount of green house gas emissions released by coal mines and power plants each year | All data available / compiled |
| Greenhouse Gas Reduction | gas units/gas units | Amount of greenhouse gas emissions reduced by coal mines and power plants each year | All data available / compiled |
| Sulfur Oxides Emissions | gas units/yr | Amount of $SO_X$ released from the burning of coal | All data available / compiled |
| Nitrous Oxides emissions | gas units/yr | Amount of $NO_X$ released from the burning of coal | All data available / compiled |
| Sulfur Oxides Reduction | gas units/gas units | Amount of $SO_X$ emissions reduced from a given standard | All data available/compiled |
| Nitrous Oxides Reduction | gas units/gas units | Amount of $NO_X$ emissions reduced from a given standard | All data available / compiled |
| Environment Protection Expenditures | $spent/$profit | Amount of money spent on environmental protection by coal companies | Limited data available/not compiled |

Table A6 Continued - Envirosocial core indicators for U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Contaminated Water Discharge | gal/yr | Amount of contaminated water discharged to the environment each year | Limited data available / not compiled |
| Surface Water Quality | water quality/yr | Quality of surface water at and around surface mines | All data available / not compiled |
| # Days Exceeding Air Quality Standards | #/yr | Total number of days exceeding the air quality standards by both the mines and power plants | Limited data available / not compiled |
| Acidifying Emissions | gas units/yr | Amount of acidifying emissions released to the air each year | All data available / compiled |
| Reclamation | acre/acre | Amount of land reclaimed as a ratio to the amount of land disturbed | Limited data available / not compiled |
| Expenditures for Reclamation | $/yr | Amount that mining companies spend each year on reclamation | Limited data available / not compiled |

Table A7 - Econoenvirosocial core indicators for U.S. coal industry (Warneke, 2004).

| INDICATOR TITLE | UNITS | DEFINITION | DATA AVAILABILITY / COMPILATION |
|---|---|---|---|
| Consumption by Elec. Utilities | tons/yr | Total consumption of coal by electric utilities | All data available / compiled |
| Consumption by other Power Prod. | tons/yr | Total consumption of coal by other power producers | All data available / compiled |
| Consumption by other Industrial | tons/yr | Total consumption of coal by other industries | All data available / compiled |
| Consumption by Res. and Comm. | tons/yr | Total consumption of coal by residential and commercial | All data available / compiled |

Table A7 Continued - Econoenvirosocial core indicators for U.S. coal industry (Warneke, 2004).

| **INDICATOR TITLE** | **UNITS** | **DEFINITION** | **DATA AVAILABILITY / COMPILATION** |
|---|---|---|---|
| Energy Consumption by Type | energy unit/capita | Energy consumption by type of energy per person | All data available / compiled |
| Expenditures for Clean Coal Research | $/yr | Total amount spent on clean coal research | Limited data available / compiled |
| Expenditures for Clean Coal Implementation | $/yr | Total amount spent on clean coal implementation | Limited data available / not compiled |
| Investment Percentage of Coal Profit | $/$ | Investment in new technology as a percentage of profits | Limited data available / compiled |
| Sustainable Development Spending | $/yr | Sustainable development spending by coal companies | Limited data available / not compiled |
| Renewable Energy Sources vs Nonrenewable | % | Amount of renewable energy source vs nonrenewable | All data available / compiled |
| Particulate Emissions | units/yr | Total releases of particulate emissions per year | All data available / compiled |
| Natural Resource Accounting | tons/yr | The accounting of the material flow cycle of natural resources for a given year | Limited data available / not compiled |

# APPENDIX B

# FUTUREGEN PENETRATION AND COAL MFA’S SPREADSHEET

# 1. INTRODUCTION

Included with this Dissertation is a CD-ROM, which contains calculations and data for the FutureGen penetration cases and the coal MFA's. All spreadsheets have been prepared using Microsoft Excel 2003.

# 2. CONTENTS

FutureGen Penetration Case 1

FutureGen Penetration Case 2

FutureGen Penetration Case 3

FutureGen Penetration Case 4

BIBLIOGRAPHY

American Society of Mechanical Engineers (ASME). The Need for Additional U.S. Coal-Fired Power Plants. ID: 05-16. http://www.asme.org/NewsPublicPolicy/GovRelations/PositionStatements/Need_Additional_US_CoalFired.cfm. 4-5-07.

Anderson, J.W. "Coal—Dirty Cheap Energy." Resources for the Future. Winter 2005. Issue Number 156. pp. 31-34.

Brunner, Paul H. and Helmut Rechberger. Practical Handbook of Material Flow Analysis. Lewis Publishers, 318 pp. 2004.

Buck, Stuart and David Gerard. "Cleaning Up Mining Waste." 2001. www.perc.org.

Burgelman, Robert A., Clayton M. Christensen, and Steven C. Wheelwright. Strategic Management of Technology and Innovation. Fourth Edition. New York: McGraw-Hill, 2004.

Burke, Frank. "Emissions Control Technologies." The Coal Utilization Technologies Workshop. Morgantown, WV. September 22, 2004.

California Energy Commission. Final Report Compilation for Impact Assessment Framework. October 2003.

California Fuel Cell Partnership. http://www.fuelcellpartnership.org/fuel-vehl_cars.html. 1/11/07.

Charnes, A., W. Cooper, and R. Ferguson. "Optimal Estimation of Executive Compensation by Linear Programming." Management Science, 1, 138-151.

Coal News. www.coalnews.net. 11/27/06.

Courtright, Hank. Prepared witness testimony for the House Committee on Energy and Commerce. June 24, 2003.

Dakota Gasification Company. http://www.dakotagas.com. 1/10/07.

Darmstadter, Joel and Palmer, Karen. "Renewable Sources of Energy—Safe Bet or Tilting at Windmills?" Resources for the Future. Winter 2005. Issue Number 156. pp. 24-27.

David, Jeremy and Howard Herzog. "The Cost of Carbon Capture." 2000.

Emmons, Hamilton, A. Dale Flowers, Chandrashekar M. Khot, and Kamlesh Mathur. Storm 4.0 for Windows Quantitative Modeling for Decision Support. Euclid: Lakeshore Communications, 2001.

Energy Calculator—Common Units and Conversions. http://www.eia.doe.gov/kids/energyfacts/science/energy_calculator.html#coalcalc. 1/10/07.

Energy Information Administration (EIA). U.S. Department of Energy. *Annual Energy Outlook 2005 with Projections to 2025.* February 2005.

Energy Information Administration (EIA). U.S. Department of Energy. *Annual Energy Outlook 2006 with Projections to 2030.* February 2006.

Energy Information Administration (EIA). U.S. Department of Energy. Annual Coal Report. 2005. http://www.eia.doe.gov/cneaf/coal/page/acr/acr_sum.html. 1-10-07.

Energy Information Administration (EIA). U.S. Department of Energy. Electric Power Monthly. June 2007 Edition.

Energy Information Administration (EIA). U.S. Department of Energy. Existing Capacity by Energy Source. October 4, 2006. http://www.eia.doe.gov/cneaf/electricity/epa/epat2p2.html. 4-5-07.

Energy Information Administration (EIA). U.S. Department of Energy. U.S. Coal Consumption by End-Use Sector. December, 20, 2006. http://www.eia.doe.gov/cneaf/coal/quarterly/html/t28p01p1.html. 1-10-07.

Environmental Protection Agency (EPA). Material Flow Accounts: How They Can Be Use As An Information Tool for 21st Century Public Policy. 2004.

Eurostat. Economy-Wide Material Flow Accounts and Derived Indicators: A Methodological Guide. Luxembourg: Office for Official Publications of the European Communities. 92 pp. 2001.

Federal Highway Administration (FHWA) Asset Management Website. www.fhwa.dot.gov/infrastructure/asstmgmt. 5/7/07.

FutureGen Alliance Website. http://www.futuregenalliance.org/about/timeline.stm. 1/11/07.

Gass, Saul I., Linear Programming Methods and Applications: Fifth Edition. Danvers: Boyd & Fraser Publishing Company, 1995.

Graedel, T.E. and B.R. Allenby. Industrial Ecology. Second Edition. New Jersey: Prentice Hall, 2003.

Grayson, R. Larry. University of Missouri at Rolla Mining Engineering 403 Class notes. Lecture 19. Winter Semester 2005.

Hart, Maureen. Sustainable community Indicators: Trainers' Workshop. North Andover, Massachusetts, 86 pp. 1998.

Holt, Neville. *"IGCC Technology Status, Economics and Needs."* Presentation at the International Energy Agency and Zero Emission Technologies Technical Workshop. February 17, 2004.

IEA Clean Coal Centre. *Life Extension of Coal-Fired Power Plants*. March, 2006. http://www.iea-coal.org.uk/content/default.asp?PageId=830. 4-5-07.

Ignizio, J.P. *Goal Programming and Extensions*. Lexington, MA: Lexington Books. 1976.

Inflation Calculator.
http://www.westegg.com/inflation/ 11/15/06.

Internal Revenue Service (IRS). *Tax Credit for Hybrid Vehicles*. www.irs.gov. 8-27-07.

Kahn, James R. The Economic Approach to Environmental and Natural Resources, Third Edition. Mason: South-Western, 2005.

Kiernan, Peter. "Getting Real about U.S. Dependence on Foreign Oil." World Politics Watch. September 25, 2006. www.worldpoliticswatch.com/article.aspx?id=206.

KurzweilAI Website.
http://www.kurzweilai.net. 1/11/06

Kurzweil, Ray. "Re: Singularity Counterarguments."
http://www.kurzweilai.net/mindx/frame.html?main=/mindx/show_thread.php?rootID%3D782. 6/5/01.

Lee, S. M. *Goal Programming for Decision Analysis.* Philadelphia: Auerbach Publishers. 1972.

Litynski, John. "Summary of DOE's Regional Carbon Sequestration Partnerships." North American Coalbed Methane Forum. October 31, 2007.

Lowrie, Raymond L., ed. SME Mining Reference Handbook. Littleton: Society for Mining, Metallurgy, and Exploration, Inc. (SME), 2002.

Merriam-Webster Online Dictionary.
http://m-w.com/dictionary/sustainability. 1/10/06.

MSNBC.com. "Gore, U.N. Climate Panel Win Nobel Peace Prize." October 12, 2007.

Murray, Jan. "Global Energy: the Questions Ahead." Royal Sydney Yacht Squadron, Neutral Bay, Australia. 2004.

National Energy Policy Development Group. *National Energy Policy*. May 2001.

National Energy Technology Laboratory (NETL). *Tracking New Coal-Fired Power Plants—Coals Resurgence in Electric Power Generation.* January 24, 2007.

National Energy Technology Laboratory (NETL). *Cost and Performance Baseline for Fossil Energy Plants. Volume 1: Bituminous Coal and Natural Gas to Electricity Final Report.* May 2007.

National Renewable Energy Lab (NREL). Hydrogen and Fuel Cells Research. http://www.nrel.gov/hydrogen/proj_fuelcells.html. 12/7/06.

National Research Council (NRC) Committee on Material Flows Accounting of Natural Resources, Products, and Residuals. Materials Count: The Case for Material Flows Analysis. Washington, D.C.: The National Academies Press, 124 pp. 2004.

Newell, Richard. "The Hydrogen Economy—Laying Out the Groundwork." Resources for the Future. Winter 2005. Issue Number 156. pp. 28-30.

New Zealand Ministry for the Environment. Environmental Performance Indicators: Proposals of indicators of the environment effects of energy. Wellington: Ministry for the Environment, 98 pp. 2000.

Osborne, Richard J. "Carbon Tax as an Element of Tax Reform Agenda." Duke Energy. April 29, 2005.

Olson, David L., "Comparison of Four Goal Programming Algorithms." Journal of the Operational Research Society. Volume 35. Number 4. pp. 347-354, 1984.

Pascoe, S. and S. Mardle. European Review of Agriculture Economics. 28.2. 2001: 161-185.

Phillips, Jeff. Electric Power Research Institute (EPRI). "Integrated Gasification Combined Cycle with CO2 Capture." Presentation. 2005.

Piller, Dan. "TXU Chief Touts Coal as a Solution." Star-Telegram.com. http://www.dfw.com/mld/dfw/business/15959597.htm. 11/08/06.

Portney, Paul R. "Nuclear Power—Clean, Costly, and Controversial." Resources for the Future. Winter 2005. Issue Number 156. pp. 28-30.

Ramage, Janet. Energy: A Guidebook. 1st Edition. New York: Oxford University Press, 1983.

Raymond Kurzweil--Wikipedia Online Encyclopedia. http://en.wikipedia.org/wiki/Raymond_Kurzweil. 1/11/07.

Research Reports International. "Towards a Hydrogen Economy." 1st Edition. June 2004.

Roberts, James. Testimony before Senate Committee on Coal Gasification and Liquefaction Technology. April 24, 2006. http://energy.senate.gov/public/index.cfm?FuseAction=Hearings.Testimony&Hearing_ID=1546&Witness_ID=4373.

Rocky Mountain Institute (RMI). http://www.rmi.org/sitepages/pid556.php. 12/7/06.

Romero, C. *Handbook of Critical Issues in Goal Programming*. Oxford: Pergamon press. 1991.

Rose, Adam Z. and Dan Wei. "The Economic Impacts of Coal Utilization and Displacement in the Continental United States, 2015." Report prepared for The Center for Energy and Economic Development, Inc. July 2006.

Schniederjans, Marc J. and Jamie L. Hamaker. "A New Strategic Information Technology Investment Model." Management Decision. 41.1. February 2003: 8-17.

Schniederjans, Marc J., James J. Hoffman, and G. Stacy Sirmans. The Journal of Real Estate Finance and Economics. 11.2. September 1995: 167-176.

Simbeck, Dale. "Future of U.S. Coal-Fired Power Generation: "Band-Aids" or "Corrective Surgery." Annual Gasification Technologies Conference. San Francisco, California. October 28, 2002.

Strazisar, Brian R., Chen Zhu, and Sheila W. Hedges. "Preliminary Modeling of the Long-Term Fate of $CO_2$ Injection into Deep Geological Formations." Environmental Geosciences. March 2006. Volume 13. Number 1. pp. 1-15.

Sustainable Minerals Roundtable (SMR). Sustainable Minerals Roundtable Presentations – Overview. 2003. http://www.unr.edu/mines/smr/Overview.pdf

University of Utah. Institute for Combustion and Energy Studies. "ICES Black Liquor Gasification Research Activities." http://www.eng.utah.edu/~whitty/utah_blg/index.shtml 11/27/06.

U.S. Climate Change Technology Program. Technology Options for the Near and Long Term. "Reducing Emissions from Energy Supply." August, 2005. http://www.climatetechnology.gov/library/2005/tech-options/tor2005-211-213.pdf

U.S. Department of Energy (DOE). "Draft Environmental Impact Statement for FutureGen Project." DOE/EIS-0394D. 2007b.

U.S. Department of Energy (DOE). Energy Efficiency and Renewable Energy (EERE). Hydrogen, Fuel Cells, and Infrastructure Technologies Program. "Hydrogen Production." http://www.eere.energy.gov/hydrogenandfuelcells/production/natural_gas.html. 12/3/06.

U.S. Department of Energy (DOE). "FutureGen—A Sequestration and Hydrogen Research Initiative." Project Update. Office of Fossil Energy. December 2006.

U.S. Department of Energy (DOE). "FutureGen—Tomorrow's Pollution-Free Power Plant." http://www.fossil.energy.gov/programs/powersystems/futuregen/. 11/27/06

U.S. Department of Energy (DOE). FutureGen-Tomorrow's Pollution-Free Power Plant. http://www.fossil.energy.gov/programs/powersystems/futuregen/. 1-10-07a.

U.S. Department of Energy (DOE). Hydrogen Posture Plan. February, 2004.

U.S. Department of Energy (DOE). Hydrogen Program. http://www.hydrogen.energy.gov/production.html. 12/3/06.

U.S. Department of Energy (DOE). Hydrogen Program. Well to Wheels Analysis. http://www.hydrogen.energy.gov/well_wheels_analysis.html. 1/24/07.

U.S. Department of Energy (DOE). "Moving Toward Zero Energy Homes." December 2003. http://www.eere.energy.gov/buildings/info/documents/pdfs/35317.pdf

U.S. Department of Energy (DOE). Today's Hydrogen Production Industry. http://www.fossil.energy.gov/programs/fuels/hydrogen/currenttechnology.html. 1/10/07.

Vine, E. "Regulatory Constraints to Carbon Sequestration in Terrestrial Ecosystems and Geologic Formations: A California Perspective." Mitigation and Adaptation Strategies for Global Change. Volume 9. Number 1, 2004. pp. 77-95.

Warneke, Joel Richard. The Development of a Coal Material Flow Analysis, Indicators, and Models to Facilitate the Creation of Public Policy. University of Missouri at Rolla. 2004.

Weir International, Inc. Mining, Geology and Energy Consultants. *Overview of the United States Coal Mining Industry*. December, 2006.

World Bank. Glossary of terms.
http://youthink.worldbank.org/glossary.php#iii. 1/12/07.

www.biodiesel.org. 11/27/06

www.cia.gov/cia//publications/factbook/geos/us.html. 11/26/06

www.eia.doe.gov/neic/rankings/crudebycountry.htm. 11/26/06.

www.ethanol.org. 11/27/06.

www.fuelcells.org. The Online Fuel Cell Information Resource. 12/7/06.

www.hydrogen.com. 11/28/06.

Yu, Oliver. Notes from Business 264: Introduction to Technology Planning and Mangement at San Jose State University. *Getting Started with Technology Trend Analysis: Part 1*.
http://www.cob.sjsu.edu/yu_o/bus264/Technology%20Trend%20Analysis.htm.
2/16/07.

Zwaniecki, Andrzej. "Secretary Bodman Sees Active Role for Governments in Developing New Technologies." November 14, 2006.
<http://usinfo.state.gov/utils/printpage.html>

# VITA

Shannon Perry Lusk was born on February 1, 1979 in Cape Girardeau, Missouri. She received the degree of Bachelor of Science cum laude in Civil Engineering at the University of Missouri-Rolla, Rolla, Missouri, in 2002.

After graduation she went to work for Professional Engineering Consultants, P.A. in Wichita, Kansas where she worked as a Land Development Engineer. In 2003, she joined Elgin Surveying and Engineering, Inc. in Rolla, Missouri, as a Land Development Engineer. She was awarded a GAANN Fellowship in Energy Research Linked to Sound Public Policy Making in 2004 and returned to UMR to work on her Ph.D. in Mining Engineering.

In 2006, Shannon moved to Lexington, Kentucky and joined Engineering Consulting Services, Inc. as a project manager. She is also involved with Project Lead the Way (PLTW) through the University Kentucky. PLTW is a program designed to promote interest in engineering disciplines through specialized curriculum developed for middle school and high school.

Shannon has been a member of the Society for Mining, Metallurgy, and Exporation (SME), International Society of Explosives Engineers (ISEE), and Women in Mining (WIM) since 2003.