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A COMPARATIVE STUDY OF ENERGY USE IN THE US AND OTHER INDUSTRIALIZED COUNTRIES

An Interactive Qualifying Project Report

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by

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Abstract

This project is concerned with the problems and consequences of energy use and its impacts on economic well-being in the United States and various European countries. We gathered and analyzed energy consumption, greenhouse gas emissions, and economic output data over the recent past using the common benchmarking method of Data Envelopment Analysis. We then ascertained the possibilities of reduction in both the energy consumption and greenhouse gas emission without negative consequences upon the economic output.

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Authorship

The write-up of this project was distributed in the following manner:

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1 Introduction

Developments since the industrial revolution saw great increases in the energy consumption of the world which served to improve our lives, but also posed serious problems to our continual growth. While new technologies improve the efficiency at which the world operates, the long term and future requires the use of alternative energy sources. The feasibility of alternative sources of energy as replacement for current dwindling fossil fuel supplies is the central focus of our project.

No one can deny the benefits and improvements bestowed upon society by the changes brought forth during the industrial revolution. The load of work has been taken from the back of man and animal and put upon machinery. Large power plants lit up cities and new modes of transportation let more people and goods move around faster than ever before.

While the machinery opened up vast frontiers of new possibilities and achievement, it also brought along a host of new problems. Not only does the consumption of energy used by the machinery produce potentially harmful side effects, the energy requirements of the overall machinery use have been increasingly demanding. Today’s most used energy sources such as fossil fuels are finite and being consumed at an alarming rate while at the same time the reliance on these sources has been increasing.

The burning of fuels such as oil or coal not only releases energy but also various gases into the atmosphere. Some of these cause localized effects on the environment while others such as the greenhouse gases are believed to have global consequences which cannot be effectively addressed by a single community, state, or even nation.

While emission policy and technologies aimed at reducing the harmful byproducts can be used to alleviate the problem of emissions, they do nothing in terms of supply. No matter how effective fossil fuel use is, it does not change the fact that the fossil fuel supply is finite. While alternate energy sources exist, they are generally a very small fraction of the current energy use in the world today.

Whether or not the efficiency at which energy is consumed can be improved both in terms of harmful side effects and final output per unit consumed is an important question in the short term, but the only viable long term solutions involve alternative energies. Therefore the important question becomes whether or not alternatives can be viably used as replacement for today’s rapidly growing industrial world and its growing reliance of fossil fuels.

A large number of studies have been done to attempt to address these questions. Analyses using the decomposition method such as those done by Jenne & Cattell (1983) and Marlay (1993) were used to determine the factors that influence energy use in the industry. Ang & Zhang (1999) among others used the method to point out sources of change in energy-related CO2 emissions. These studies, however, do not directly address the issue from a point of view of efficiency or consumption reduction. Furthermore, they do not assess the potential substitutability between different sources of energy.

To gain new insight into the issues we employ a commonly used method of Data Envelopment Analysis. We analyze the history of energy consumption in the United States and a few European countries in terms of efficiency. As a forerunner for a general replacement of fossil fuels with alternate sources, we determine whether historical evidence suggests energy consumption of fossil fuels can be reduced while maintaining the gross domestic product which serves as a general measure of the standard of living.

While no decisive results present themselves, we do find that the fossil fuel consumption in the United States has been less than optimal at various points in the recent past. Given the available technology we find that there is no evidence of potential reduction of energy consumption that can be achieved for the most recent years. In terms of energy use, production in these years is found to be optimal.

We speculate, however, that present situation in the United States may be very similar to that of the United States before the oil crisis in the 1970’s. In both cases the observed efficiency of energy use has been seen to be optimal from the perspective of only the present and the past. In the case of the 1970’s though, a very large and overall inefficiency soon followed. We conclude that a present optimality is not a viable proof of well being in the near future.

We also find that in the European community, France and Germany are significantly more efficient than United Kingdom if compared against each other. The French use of nuclear energy and the German renewable energy initiatives should be a good model for other countries including the United States but direct comparisons between Europe and the United States were not possible in this project given wide differences in the structure and formulation of the available data between the countries. We recommend further study of Europe and the United States within a single point of view using compatible data such that quantitative comparisons between the two are possible.

2 Background

In this chapter we begin with a brief history of energy use in the world starting with the industrial revolution. The consequences of the changes brought upon the world follow and a few potential solutions to the problems stemming from energy use are described. An overview of policies used in the United States and Europe to address energy use and its harmful effects is provided. To conclude we describe some common methods used for analysis of energy use as well as their shortcomings that we address in this project.

2.1 Energy History

2.1.1 World

Before the dawn of industrialization, humans relied on sources such as fire, the sun, water, wind, and compost as forms of energy. When there were tasks that were physically impossible for humans to perform, they employed the use of animals. For thousands of years it was through those previous means that most humans were provided with energy. It wasn't until the late 1800's with the oncoming of the industrial revolution, that great advancement in the area of energy took place.

For centuries wood/biomass was the dominant energy source in the world. It wasn't until around the 1890's in which we see fossil fuels accounting for more than half of the world's energy, a figure that rose from around 15 to 22*10^18 Joules/Year. A century later the numbers have changed significantly. Households and Industry in low income countries are mainly responsible for the 25*10^18 J/Year provided from biomass, but fossil fuels now account for the use of about 360*10^18 J/Year (Smil, 2000). The 20th century would be the first time when energy was dominated by fossil fuels. Figure 1 shows the World Energy Consumption of primary energy by source.

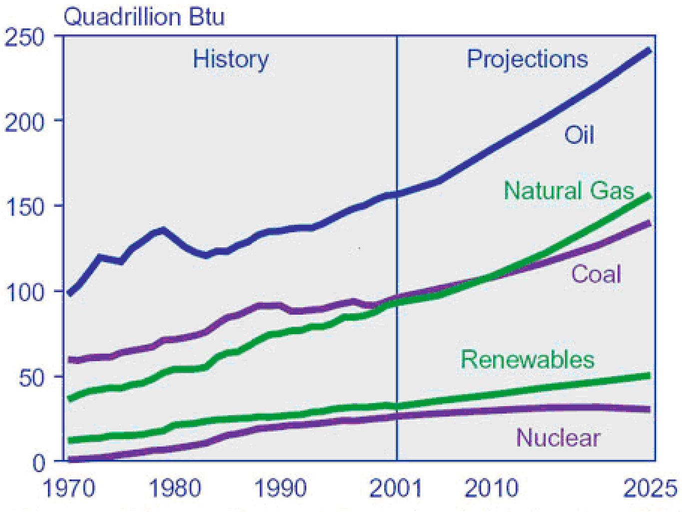

Figure 1: World Energy Consumption By Source [source: EIA]

2.1.2 United States

The global trend of increased use of fossil fuels at the end of the 19th century held true with the U.S. There was widespread use of fossil fuels such as coal, oil, and natural gas. The concentrations of energy that these natural resources harnessed allowed a higher rate of energy to be instilled within the U.S. economy (Energy Information Administration [EIA], n.d.).

Coal quickly became the primary source of energy in the U.S. around 1885. In 1951 petroleum overtook coal as the most highly consumed energy source and a few years later natural gas surpassed coal (EIA, n.d.). Renewable energy sources which include biomass, solar, geothermal, and hydroelectric energy have also been implemented, but have not had the widespread success of fossil fuels.

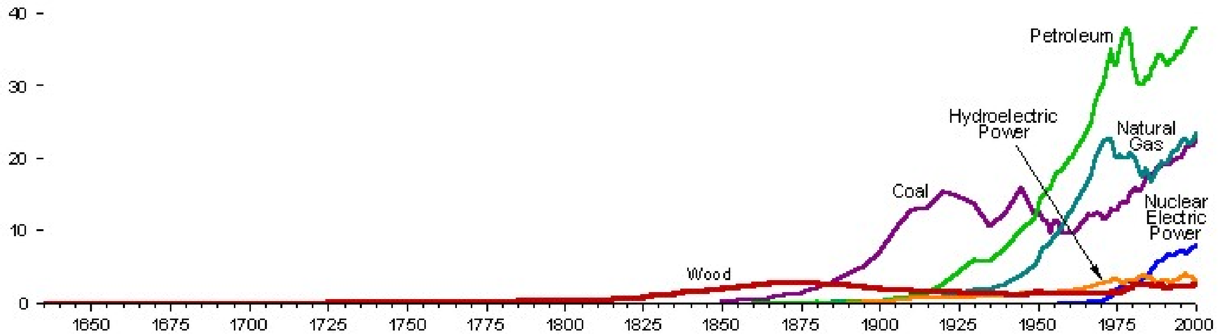

Figure 2: Energy Consumption by Source, 1635-2000 (Quadrillion Btu) [source: EIA]

The U.S. is the world's largest energy producer. It is also the largest consumer of energy as well as its largest importer. According to the EIA (2003), the U.S. consumed approximately 22.7, 22.5, and 39.07 quadrillion Btu's of coal, natural gas, and petroleum energy respectively in 2003.

2.2 Energy and the Economy

According to Smil (2000), the relationship between the economy and the use of energy is dynamic and multifaceted. As Brown et al. (1998) point out, before the 1970's and the oil embargo that OPEC instilled on the U.S. and Denmark for two years, the energy demand and gross domestic product (GDP) would increase at similar rates which led people to think that there was a direct correlation between the two.

After the embargo, instead of a stagnant or dwindling GDP, it instead rose by 35% from 1973 to 1986. During this time Americans purchased automobiles, housing products, heaters, and motors among other technologies that were more efficient, showing that there was not necessarily the connection between energy use and GDP that was previously thought of (Brown et. al, 1998). This comparison is known as energy intensity.

Smil (2000) argues that energy intensity is a function of country size, climate, the composition of the primary supply, difference in industrial structure, and discretionary personal consumption of energy. Figure 3 compares the U.S. energy intensity with other industrialized nations over the last century.

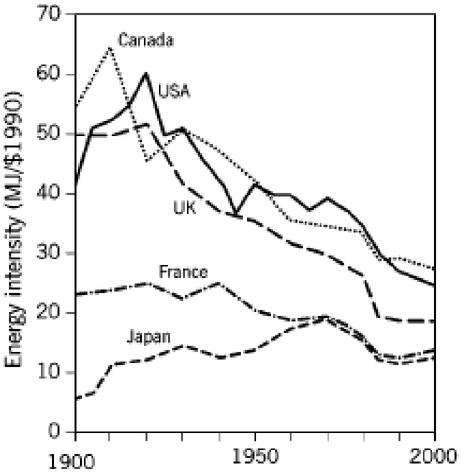

Figure 3: Energy Intensity of Industrialized Countries [source: EIA]

2.3 Energy Types

2.3.1 Fossil Fuels

2.3.1.1 Coal

Nearly a quarter of the world's coal reserves are located in the Unites States (Department of Energy [DOE], n.d.). Before both petroleum and natural gasses, it was this combustible black rock that powered the United States and as of 2002, 22.698 quadrillion Btu's of coal energy was produced while 21.980 quadrillion Btu's was consumed.

The U.S. produces more coal than they consume, so the exportation accounts for 37 percent of the United States' energy exports in term of Btu's (DOE, n.d.) Within the United States, coal is now primarily used in the production of electricity. Over the last 50 to 60 years there has been a trend of decline of coal use in the residential, transportation, commercial, and industrial sectors (Figure 4).

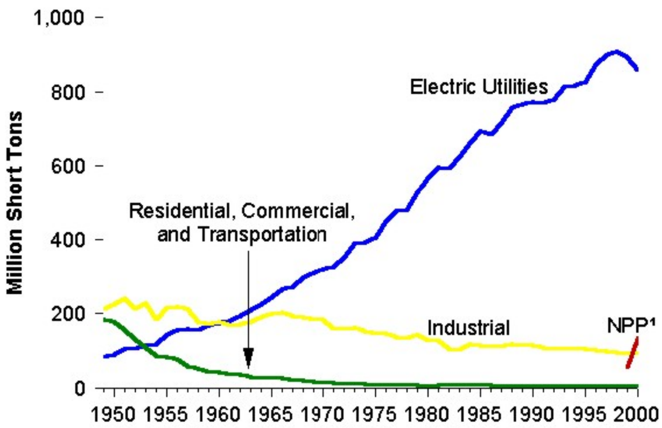

Figure 4: Coal Consumption by Sector [source: EIA]

In the U.S. many electric units are coal-fired based and more than 50 percent of all electricity generated comes from coal (Figure 5).

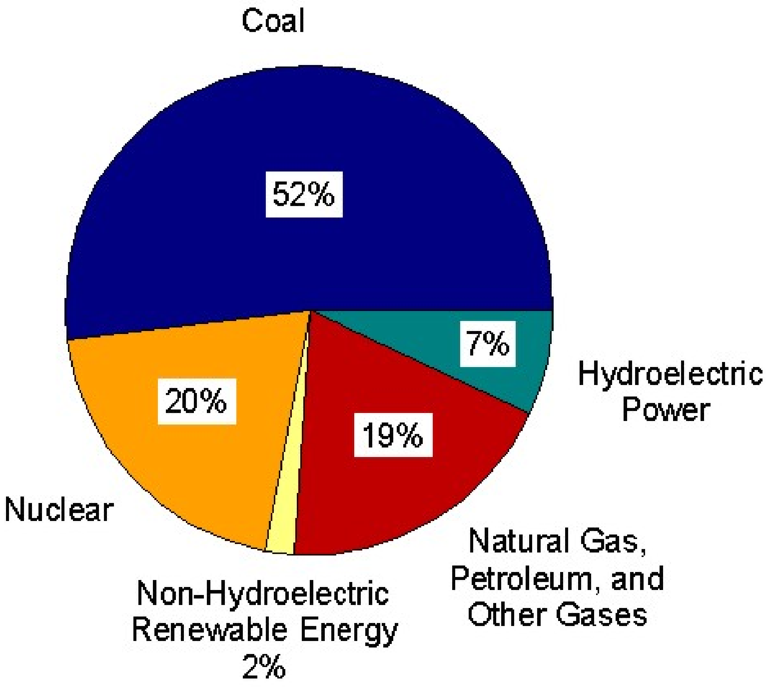

Figure 5: Electricity Net Generation in the US by Source for 2000 [source: EIA]

2.3.1.2 Oil/Petroleum

Currently the U.S. imports more oil than they produce, meaning they have to rely on Arab nations and others that export the product. An example of this reliance was during the OPEC embargo that raised oil prices to over $55 per barrel, the highest in US history. In 2003, the U.S. imported nearly 12.2 million barrels a day. Total, the US produces (including imports) over 20 million barrels a day. Most of which is used for the transportation sector which consumes nearly 9 million barrels a day (Figure 6).

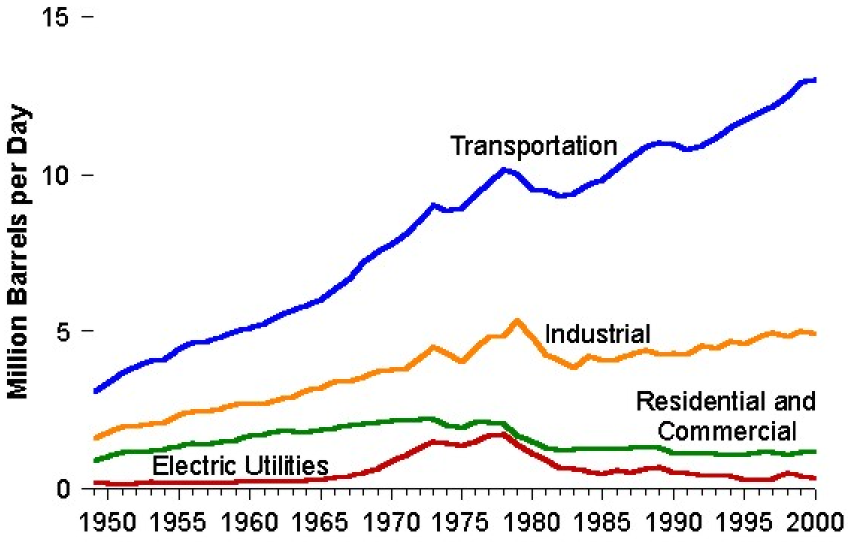

Figure 6: Petroleum Consumption by Sector [source: EIA]

2.3.1.3 Natural Gas

Like crude oil, the consumption of natural gas now exceeds its production in the U.S. According to the Energy Information Administration, natural gas accounts for 24 percent of the total energy consumed by the U.S., of which 32 percent is consumed by the industrial sector. Like coal and oil, natural gas is a non-renewable resource and irreplaceable.

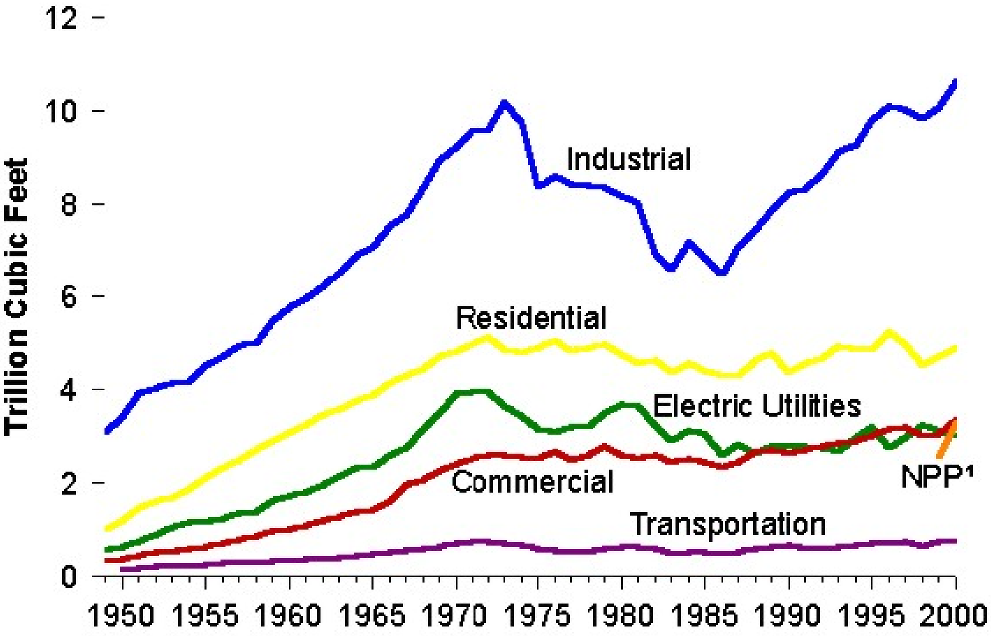

Figure 7: Natural Gas Consumption by Sector [source: EIA]

2.4 Consequences

No one can doubt the benefits and opportunities provided by the technologies and methods developed as a result of the industrial revolution. The quality of life has been steadily improving. There are, however, some negative consequences arising from the techniques that have been put in effect all over the world. Some of these negative effects are a direct consequence of the increased energy use and especially the sources of the energy. The problems created as a result can be categorized into two main types: issues dealing with the adverse effects of the emissions released during burning of fossil fuels and issues dealing with dwindling fossil fuel supply.

2.4.1 Emissions

The process of burning of fuels releases not only energy but also various gases. The biggest combustion sources include electric utilities, industrial boilers and internal combustion engines, smelters, natural gas engines and turbines, industrial process heaters, iron and steel furnaces, kilns, incinerators, residential fuel combustion, and transportation sources (Clement & Kagel, 1990). Most significant of these gases include SO_2 (Sulphur Dioxide), NO_x (Nitrogen Oxides), and CO_2 (Carbon Dioxide).

Many of these gases are naturally present within the atmosphere. Some such as CO_2 (carbon dioxide), CH_4 (methane), and N_2O (nitrous oxide) are released and absorbed by naturall processes. Human activities, however, are known to cause additional quantities of these gases to be emitted, and therefore change their concentrations in the atmosphere (Environmental Protection Agency [EPA], 2004).

Sulphur dioxide is released from smelters, gas processing plants, tar sands plants, coal-fired electrical generating plants, and vehicles while oxides of nitrogen come from the same sources, but especially from trains, cars, and trucks (Alberta Environment, 1993). As of 1985, the largest two emitters of SO_2 and NO_x were the utilities and transportation sectors. The utilities contribute 69% of all U.S. SO_2 emissions while the transportation sector is responsible for over 43% of total NO_x emissions (Clement & Kagel, 1990). Coal burning is the primary source of SO_2 and NO_x emissions in the utilities sector with 95% of utility emissions of SO_2 and 87% of NO_x accounted for. The rest is released by utilities comes from oil and natural gas burning (Clement & Kagel, 1990).

The other major gas released during combustion is CO_2 (Carbon Dioxide). Coal burning releases the most CO_2 per unit energy followed by oil and gas (Keepin et al., 1986). Recent EPA (2002) report places oil burning as the main source of CO_2 emissions in the United States followed by coal and natural gas. The disparity is a result from a higher use of oil fuels than coal. Utilities are the main source of CO_2 emissions from coal burning while transportation is the main contributor to CO_2 by oil burning (EPA 2004). A limited amount of carbon dioxide is also released by non-energy uses of fossil fuels such as fossil fuel use in manufacture or use of various products.

The emissions arising from combustion have a direct effect on the atmospheric composition and atmospheric processes (Smith, 1993). As a result, processes such as acid deposition and global warming have arisen. Furthermore, the air pollution has widespread consequences on human health.

2.4.1.1 Acid Deposition

Driscoll et al. (2001) describe acid deposition as an emergent critical environmental stress with adverse effects on landscapes and aquatic ecosystems. The process occurs when sulphur dioxide (SO_2) and oxides of nitrogen (NO_x) in the air are deposited on the surface of the earth (Alberta Government, 1993). The process “alters the interaction of many elements … contributes directly and indirectly to biological stress and to the degradation of ecosystems” (Driscoll et al, 2001).

2.4.1.2 Global Warming

The effect of global warming or “greenhouse effect” is described as the warming of the atmosphere as the result of increased concentrations of various gases in the atmosphere. The essential idea is that the earth traps some of the energy released by the sun. The retention rate depends on the composition and concentration of gases in the atmosphere.

The major gas known to increase energy retention rate in the atmosphere is carbon dioxide but Bolle et al. (1986) notes that other influential gases such as chlorofluorocarbons, methane, and nitrous oxide are recently increasing in concentration.

Although scientists generally agree on the statistical data relating to fossil fuel burning and the concentrations of greenhouse gases in the atmosphere, and historical changes in global temperature, they do not, however, agree on how all this data should be interpreted (Newton, 1993). Opinions range from interpretations that global warming has already begun to notions that there is no evidence to justify anything consequential (Newton, 1993).

Despite the lack of agreement on the topic, there is no shortage of analyses of the effects of global warming if it were to occur. These include predictions of changes of sea-level, water resources, agriculture, forests, ecological systems, and human societies (Newton, 1993). The most drastic and potentially threatening of these is the increase in sea-level, the result of which, would put certain populated regions of the world under water.

2.4.2 Health

Environmental impacts are not the only consequences of fossil fuel burning. Combustion processes that release greenhouse gases also produce air pollutants, which have adverse effects on public health (Working Group on Public Health and Fossil-Fuel Combustion, 1997). These substances have varying degrees of toxicity and ill-effect on human health (Ozkaynak et al., 1985).

Sulfur dioxide (SO2) has been found to affect the airway especially in patients with asthma and the gas has been linked to changes in hospital admissions and mortality (Ayres, 1998). Carbon monoxide, on the other hand, is known to cause loss of consciousness and death in high concentrations. Various studies of the ambient or low concentration effect of this gas have shown links with heart failure (Ayres, 1998). Particulate matter (PM) has been shown to have a wide range of effects including procuring inflammation, weakening of the immune system, and cardiovascular effects (EPA, 2002).

In addition to direct health consequences, emissions pose some long term health implications. McMichael et al. (1997) notes that the eventual exposures to higher temperatures such as those eventually caused by global warming will increase the rate of illness and death. Furthermore the changes in frequency and intensity of weather events can promote death and injuries. The disturbances in ecological systems such as those caused by acidic deposition can cause changes in food production, which in turn cause malnutrition and hunger. He generalizes that “Changes in the environment to which human biology and culture are adapted or disturbances of ecosystems that set the conditions for health would generally have adverse effects on health.” (McMichael et al., 1997)

2.4.2.1 Supply

A popularly overlooked problem with fossil fuels is their limited supply. Currently the United States imports 63% of its oil while 25% come from the Middle East. Given such large dependence, Cannon (2002) argues that the United States is “more vulnerable than any other country in the world to the pricing dictates of Organization of Petroleum Exporting Countries (OPEC).” Canon also reminds us that if the U.S. were to supply all of its oil needs by domestic sources; it would run out of its oil reserves in less than three years. Furthermore, the increased consumption of oil by emerging industrial countries in Asia is putting a strain on existing oil supplies. Canon threatens that “if current transportation and oil use trends continue … within the decade, it could well set off a resource grab on a scale unparalleled in history” (Canon, 2004, pp. 3).

Hubbert had successfully predicted in 1958 that United States oil production would peak around 1970. Since then, production has declined steadily which has in turn affected policy with the nations of the Middle East (Duncan &Youngquist, 1999).

Although production in the United States has peaked long ago, the United States has been able to supply its demand through imports. Unfortunately when the World oil production peaks, there will be no place to go to get more oil. Duncan and Youngquist believe that when this inevitable event occurs, the final competition for the remaining oil reserves will take place, most notably between the industrialized nations.

Since the World oil production peaks could very well be one of the most important events in recent human history, many forecasts have been made which predict when the peak will happen. Duncan and Youngquist predict that the world peak will happen during 2007. This is also the time that they predict that the crossover between OPEC and non-OPEC countries will take place where OPEC countries will supply the world with over half of the remaining oil.

Other forecasts on peak production provide different results. Douglas-Westwood Ltd. (2002) predicts that the production peak will be around 2010. Bentley’s (2000) analysis yields a peak around 2010. Similar results were made by Campbell (1991), Campbell and Laherrere (1998), Duncan (1997), Hatfield (1997), Ivanhoe (1997), and MacKenzie (1996).

One forecast that has an extremely different timeline with regard to peak oil production is the Energy Information Association’s forecast. They predict that peak will happen around 2030 if there is a 3.0% increase in oil demand. A demand of 0% would result in a peak around 2075.

In any case, the data shows that there will be an inevitable oil shortage that will have major implications within most of our lifetimes.

2.5 Potential Solutions

In the case of global warming, the immediate solution is to reduce carbon dioxide emission, which in turn means reducing the dependence on fossil fuels (Newton, 1993). Proposals for achieving this reduction take form of two common types: increased conservation or development of alternate energy sources (Newton, 1993). A reduced consumption of fossil fuels, would also serve to alleviate the economic and political dependence as well as other environmental problems including acid deposition. Other solutions attempt to limit the emissions of harmful gases without necessarily limited the burning of fossil fuels.

2.5.1 Alternatives

The use of alternative fuels or energy sources can have a large impact on emissions and political dependence. Nuclear, Solar, Wind, and Hydroelectric energy sources can, if used aggressively, can reduce emissions and at the same time lower the dependence on fossil fuels. The various alternate energy sources and renewable fuels are summarized here.

2.5.1.1 Nuclear

Nuclear power is potentially the most immediately available alternative to fossil fuels. The energy is derived from strong nuclear bonds inside atoms. A nucleus of an atom, upon breaking up, releases energy in the process known as nuclear fission (DOE, 2004). Nuclear reactors release this energy by maintaining a chain reaction of continuous fission in which the break up of atoms releases particles (and energy) which themselves hit other atoms causing them to break up. Nuclear energy is popularly regarded as dangerous as the very same reaction, if unchecked, is the same process used in nuclear weapons.

2.5.1.2 Solar

The earth is continuously bombarded by energy emanating from the sun. The entire biological structure on earth relies directly on this energy. Plants, which stand at the bottom of the food chain, require the sun to produce oxygen and survive. Humans have also used the sun’s rays for their own purposes. Romans were known to use black tiles under water ducts to heat the water (Deudney & Flavin, 1983). Sunlight is still used to heat bathwater today and the devices used to trap this energy have been improved. The oil prices of the 1970’s have greatly increased the economics of solar energy in the recent past. In 1983 most solar collectors un use were part of building heating systems (Duedney & Flavin, 1983).

Sunlight is also being used to generate electricity. The photoelectric effect takes place on the surface of photovoltaic solar cells as the photons from the sun dislodge electrons that orbit atoms in the cells' material. Small solar cells are being used in small devices that do not require much energy such as pocket calculators. On a larger scale, there are photovoltaic systems in Japan, Europe, and the United States with outputs as high as 500 kWe. An experimental solar power with 150 MWe output exists in Japan.

2.5.1.3 Biomass

According to the U.S. Department of Energy Efficiency and Renewable Energy, Biomass refers to such organic matter as woods, plants, residue from agriculture or forestry, and organic wastes.

Biomass, similarly to petroleum, can be used for fuels. The two most common fuels include ethanol and biodiesel fuels. Ethanol or ethyl alcohol is produced through the fermentation of sugars, a process very similar to making beer. Currently there are three main types of ethanol in use today, E95, E85, and E10. E95 is pure ethanol and is mostly used as a mixing agent with petroleum. E85 and E10 are ethanol fuels mixed with 15 and 90 percent gasoline respectively, and have the advantage of better engine combustion and lower emissions (Ethanol Blended Fuels). Biodiesels are used in a similar fashion to ethanol as a fuel additive, but the chemical makeup is of methal esters, and it must be mixed with petroleum diesel fuels.

Biomass can also be used to generate electricity. The most common form in this case is direct combustion in which biomass is burned with excess air which in turn heats up steam within a steam turbine generator.

2.5.1.4 Wind Energy

A near infinite source of energy that has been utilized for years is wind energy. This type of energy uses giant wind turbines that typically are designed with either three or two blades to produce upwards of 5MWs of electrical energy. Wind turbines are giant structures and there tower height and blade diameters can exceed over 80 meters. The reason that these wind turbines are so massive is that larger turbines can harness more energy because of the area of wind that passes through them. The turbines are quite high off the ground as well because wind speeds are greater at higher elevations. This means that wind turbine placement is very important. They cannot be put in areas full of high tress or within cities where objects on the ground and in the air can create friction with the wind and create turbulence. Instead the ideal placement locations for wind turbines include typically flat areas with fairly consistent wind patterns.

2.5.1.5 Geothermal Energy

Geothermal energy is a greatly underused energy/electricity resource. This energy resource taps the earth’s geothermal heat to drive electric turbines. Wells and reservoirs of steam and hot water are located below the earth’s surface much like oil. Unlike oil, however, geothermal energy is renewable.

According to the Geothermal Technologies Program sector of the U.S. Department of Energy, there are three types of geothermal power plants; dry steam, flash steam, and binary-cycle plants. The dry steam plant operates by using steam directly from the earth to turn turbines. Flash plants use hot water at high pressure within a low pressure tank. The result is the water “flashing” and changing phases to steam which turns a turbine. The last type of plant uses a warm water to heat up another type of liquid with a lower boiling point. When this other liquid turns to steam in works similarly to the previous types and operates a turbine.

Since the temperature of the ground is fairly consistent throughout the year, geothermal heat pumps that use a heat exchange can provide heat for water during the summer as well as heating during the winter and air conditioning in the summer to residential as well as industrial buildings. According to the EPA geothermal, heat pumps are the best alternative space conditioning systems available due to cost savings and emissions

2.5.2 Impact of Alternatives

Although there are many clean alternatives to fossil fuels, they are not widely used. As of 2002 the use of all of the alternate fuels and sources accounts to less than 15% of United States energy consumption (EPA, 2004). Nuclear power, which seemed to be have been the answer to all of humanity’s energy problems, suffered a large setback in the U.S. where safety issues have almost eliminated nuclear power as a viable alternative (Newton, 1993). Despite the setbacks, electricity generated from nuclear power now accounts to 21% of all electricity production in the U.S. surpassing oil and natural gas (DOE, 2004).

2.5.3 Policy

Given that some of the driving forces behind energy use include market and corporate competition, the problems associated with energy use cannot be left to their own devices. Government intervention in form of policies and law is naturally required as a voice of reason in a competitive world economy.

Recently the United States government and others around the world began using economic incentives as means to reduce or cap emissions. Economic incentives are defined as “instruments that use financial means to motivate polluters to reduce the health and environmental risks posed by their facilities, processes, or products” (EPA, 2001, pp. ii). These incentives are meant to use market forces as a means of emission reduction and include such policies as tradable pollution permits and taxes.

Fullerton and West (1999) propose a tax on cars and gasoline. They argue that measurement of every car’s emissions would be too expansive and inaccurate. Their proposal is a tax that depends only on the fuel type, engine size, and pollution control equipment. A tax on vehicle’s estimated efficiency would provide incentives for users to more efficient fuels and vehicles.

Environmental policies, of course, vary from nation to nation. Following is an overview of some important policies existing in the United States and the European nations that are subject to our analysis further in the project.

2.5.3.1 United States

The major environmental policy in the United States is contained within the Clean Air Act. Originally adopted in 1955 but not made effective until 1970, it had major amendments in 1977 and 1990. It is intended to set federal standards for air pollution. Designed to improve air quality in areas below standards and prevent deterioration in areas above federal standard (New Mexico Center for Wildlife Law [NMCW], n.d.).

The Act requires permits for “construction or operation of stationary sources of hazardous air pollutants” (NMCW, n.d.). The 1990 amendment brought forth an emission trading program for sulfur dioxide (NMCW, n.d.). It contains obligations to control substances that deplete the ozone layer as per Montreal Protocol (NMCW, n.d.). Federal facilities are not exempt from regulations imposed by Clean Air Act (NMCW, n.d.). The act contains provisions for monitoring greenhouse gases but does NOT address the problem directly (Renewable Energy Policy Project [REPP], 2000).

The Energy Policy Act of 1992 (or EPACT) is another large piece of legislation aimed at energy use. The act has a potential of increasing energy efficiency and reducing the emissions of global warming gasses (Regulatory Assistance Project [RAP], 1992). With tax credits and subsidies, the act attempts to make renewable resources more cost competitive (RAP, 1992). The act initiated the Renewable Energy Production Incentive (REPI) program to subsidize electricity generated from renewable sources (American Public Power Association [APPA], 2005). The program, however, has expired in 2003 and is currently pending reauthorization in congress (APPA, 2005).

In addition to national policies, much of the regulation in the United States is left to individual states. This translates to the existence of varied policies across the states. California is one of the more regulated states. The 1994 California Energy policy outlines steps to alleviate the relevant problems described in this project. The policy outlines recommendations such as a promotion of “competitive markets and energy efficient technologies” (California Energy Commission [CEC], 1994). Furthermore it encourages a balance in energy, economic, and environmental goals which include vehicle emission regulations. Provisions for pursuing transportation alternatives are also in place (CEC, 1994).

2.5.3.2 Germany

One of Germany’s efforts of the 1990’s was the development and application of a strategy for the protection of global climate. They are one of the leading proponents and strong supporters of the United Nations Framework Convention on Climate Change and the Kyoto Protocol.

The United Nations Framework Convention on Climate Change was introduced in the 1990’s to evaluate ways to reduce global warming. The Kyoto Protocol was adopted as part of the Convention in 1997 to create a more powerful and legally binding framework to reduce greenhouse gas emissions and curb global warming. It calls for all greenhouse gas emissions to be reduced by at least 5% from 1990 levels to a commitment period from 2008-2012 (United Nations Framework Convention on Climate Change).

Germany has taken the most drastic measures of any country to reduce greenhouse gasses in an attempt to reach the goal of 5% reduction. The European Union, of which Germany is part, determined to reduce emissions by 8% by 2008-2012. Germany's actual contribution to this goal is greenhouse gas reductions of 21% over the period of the protocol (The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety).

For years Germany relied on nuclear energy as its primary source for electricity at nearly 30% (Aitken 2005). Germany has set forth a plan to transit to 100% renewable energy, a goal they believe is economically and technically possible primarily through the use of wind and solar energy.

Starting in the late 1980's the German government started a "100 megawatts of wind" program which served to jumpstart the German wind industry. By the end of September 2004, wind turbines accounted for about 6.2% of Germany's electrical energy, with over 15,688 MW of installations a number that is roughly 125% more installations than the United States which has the second highest amount (Aitken 2005).

The "100 megawatts of wind" program allowed utilities to purchase renewable generated electricity from independent power producers at a minimum price of 90% of the average electric rate for wind energy (Aitken 2005).

Other policy that the German government has implemented that has enhanced the use of wind energy was the Federal Building Construction Law that allowed the building of wind turbines in natural areas. Also under the Renewable Energy Sources Act, onshore turbines erected in 2005 will receive no less than 8.53 euro cents per kilowatt hour for the first five years and 5.39 euro cents afterwards for 20 years of commissioning. The act also encourages the use of biomass for electricitry (The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety).

Other programs that have been implemented to reduce carbon dioxide emissions include carbon taxing, renewable energy portfolio standards, and the Electric Feed law which allows the purchase of renewable energy at a discounted price (Dooley & Runci 1999).

2.5.3.3 France

France has the largest and most integrated nuclear power system in the world, but as global and national pressure has increased there has been debate on whether to continue a strong based policy around nuclear energies. Currently, France is planning on replacing numerous nuclear plants in 2015 (Boulesteix 2004).

France has been able to exploit energies such as biomass, hydroelectricity, wind, and thermal energies to become the leading producer and consumers of renewable sources in Europe (Boulesteix 2004). Hydroelectricity accounts for the second highest amount of energy production in France, and due to France’s Kyoto Protocol commitment, they hope to increase the amount of electricity produced by wind turbines from the 1997 level of 15% to 21% by 2010 (Boulesteix 2004).

France’s obligation to the Kyoto Protocol is for the stabilization of greenhouse gas emissions to 1990 levels. France also set forth to reduce carbon dioxide levels by 20% by 2005 compared to 1988 levels (European Renewable Energy Council 2004). Data from 2001 illustrate that France’s greenhouse gas emissions were, at the time, 0.4% above the Kyoto Protocol target (Egenhofer, 2005).

France has implemented what is known as the EOLE program which has greatly increased the production of wind energy instillations in recent years (European Renewable Energy Council 2004). Between 2001 and 2002 energy produced by wind turbines doubled. France is hoping by 2010 to reach a goal of 3000MW in capacity (Boulesteix 2004).

France is also increasing renewable use through solar power which previously had not been a major source of energy. According to the European Renewable Energy Council (2004) policies that have been implemented to promote and increase the use of solar and thermal energy instillations are the “Plan Soleil” and the “Batiment Bleus”. France also has promotional fiscal measures for renewable energies which include tax rebates, favorable depreciation schemes, and feed-in tariffs to help promote the use of renewable energy sources (United Nations Framework Convention on Climate Change 2005).

2.5.3.4 United Kingdom

According to the United Kingdom's Department of Trade and Industry (2005), currently only 3% of the United Kingdom's electricity is supplied by renewable energies. Since the introduction of the United Nations Framework Convention on Climate Change and the rising concern for global climate change, the United Kingdom has been striving to reduce carbon dioxide emissions as well as increase the use renewable energies and decreasing other energy sources.

Renewable energies in the United Kingdom account for far less in terms of energy and electricity supply than other European Union countries at 1.1% and 2.5% in 2001 respectively (European Renewable Energy Council 2004). Energies from biofuels and waste are the major contributor to renewable sources at 86% (European Renewable Energy Council 2004).

It is likely that wind energy is going to play a key role in the future of United Kingdom energy production and the reduction of greenhouse emissions. According to the European Renewable Energy Council (2004) the United Kingdom has around 15% of European Union's potential wind resources.

The United Kingdom is following the framework of the 2003 Energy White Papers by which 10% of electricity is expected to come from renewable energy sources by the year 2010 and 20% by 2020. Another goal of the White Papers is to reduce carbon dioxide by 60% by 2050 (United Kingdom Department of Trade and Industry 2005). The United Kingdom is also ratified the Kyoto Protocol which has set a goals of a 12.5% reduction of greenhouse gasses by 2008-2012, with a national goal of 20% reduction of carbon dioxide by 2010 (United Kingdom Department of Trade and Industry 2005).

The United Kingdom has also introduced policies such as the Climate Change Levy which is a tax on the use of non-renewable energy sources used in the industrial, commercial and public sectors and the Renewable Obligation which guarantee that suppliers must purchase a certain percentage of energy from renewable resources (United Kingdom Department of Trade and Industry 2005).

2.6 Analysis Methods

Attempts at discovering solutions or current inefficiencies require various analyses of the energy use patterns and trends. Simply reducing emissions or reducing dependency isn't a simple task. In order to have realistic impacts, one needs to consider factors in the economy in far-reaching and often complicated analyses. Two of the most common methods used are the Data Envelopment Analysis (DEA) and the Decomposition Analysis. Both of these analyses have the advantage of not requiring specific knowledge of the interrelationship between the quantities used in the analysis.

2.6.1 Decomposition

The Decomposition method is a common tool to analyze sources of change or difference. Decomposition analysis functions on the principle of splitting an identity into component parts (Rose & Casler, 1996). The method has been widely used to quantify contributions of various factors such as energy intensity to changes in energy and environmental indicators (Ang & Zhang, 1999). It can also be used to identify sources of change in areas such as economic growth and energy use (Rose & Casler, 1996).

The decomposition method is also a generally accepted tool for policy making in OECD countries, Eastern Europe, and many developing countries (Ang, 2004). Common areas in which the method has been applied are energy demand and supply as well as energy-related gas emissions.

Jenne & Cattell (1983) analyzed trends in energy use within industry in the United Kingdom while Marlay (1983) did the same for the United States. Ang & Zhang (1999) used the decomposition technique to compare energy-related CO2 emissions between countries and regions. They found that the major sources of change included fuel share, energy intensity, income, and population.

2.6.2 Data Envelopment Analysis

Data Envelopment Analysis (or DEA) is generally a method for evaluating the performance of various entities. These entities take in various inputs and produce some outputs (Cooper, Seiford, & Zhu, 2000). The major benefit of the method lies in its ability to handle entities that produce outputs or consume inputs of no or unknown market prices (Ray, 2000). The method has recently proven flexible enough to be used in many different applications. It has been used to evaluate the performance of hospitals, universities, cities, business firms, and even whole countries (Cooper, Seiford, & Zhu, 2000). A small cross section of the many studies with DEA is summarized below.

In analysis of education, DEA has been used to determine the cost efficiency of schools as units given widespread concerns that public education is not efficient (Ruggiero, 2000). It was determined that despite the proposed $1 billion increase in spending for schools, the school system contained over $800 million in inefficiency. Ruggiero (2000) also notes a wide range of other schools and districts that have been used as subjects of an efficiency analysis using DEA across the United States and Europe.

According to Paradi,Vela, & Yang (2000), the banking industry is the most heavily studied of all business sectors. They note that in a rapidly changing world, continuous improvement is vital for any successful organization. Yang et al. (2000) describes three main measures over which bank performance is evaluated: production, intermediation, and profitability and notes large number of bank studies in the United States, Asia, and Europe.

Likewise, in the field of health care, the task has been generally the reduction of costs and increase in performance. The performance of health-care, however, has been noted to be harder to measure and quantify (Chilingerian & Sherman, 2000). Chilingerian and Sherman (2000) find that in the past, studies to determine amount and source of inefficiencies in the field have been scarce but they note that hundreds of efficiency studies have been recently conducted across the United States and Europe. As an example, they note, it has been found that billions of “wasted” dollars result from inefficiency in the United States health care system per year (Chilingerian & Sherman, 2000).

Further interesting uses of DEA include the analysis of the performance of baseball players in terms of their “input” salary (Howard & Miller, 1993) and determining the most dominant baseball player (Anderson, 2000). In other fields Charnes et al. (1989) used the method to analyze the relative efficiencies of the economic performance of entire Chinese cities.

Analysis of nations in terms of their energy use and their output using Data Envelopment Analysis, however, has been scarce. To our knowledge no other study has utilized DEA to study this issue. Because of the advantages of using DEA over the commonly used decomposition methods in this regard, we adopt DEA to investigate the issues of potential energy conservation and emission reduction. In the next chapter we provide the details of our methodology and our motivation.

3 Methodology

The two sides of the issues involved with energy use are the energy consumption and the byproducts on one hand and the results or products of this energy use on the other hand. In the simplest form, using energy enables us to produce GDP. Being naïve, one can say that the solution to all the energy problems is simple: stop using energy. This, of course, ignores the fact that the GDP, a basic measure that tells us much about economic well-being and quality of life, depends heavily on energy use.

What other options are there? Can a nation's energy use be decreased while its GDP does not suffer? Looking at the recent history of the United States, we see that both energy use and the GDP are steadily rising as seen in Figure 1 and Figure 11 respectively. Looking at their ratio or the "energy intensity", however, we can see that the energy intensity is decreasing. Energy intensity is defined as energy use per unit GDP. While it may not be realistic to simply stop energy consumption, it is more reasonable to have as efficient of a use of the energy as possible.

Is it enough that energy intensity is decreasing and hence the efficiency at which energy is used is getting better? We know that it took a lot more energy in the 1970's to produce the same amount of GDP as it does now but does knowing that a certain year in the recent past experienced a higher energy intensity than some other year help us give meaningful advice or come to interesting conclusions? Specifically does this information give any insight into potentially solving or alleviating the problems of emissions and supply? While overall efficiency is increasing, the consumption is itself still increasing and this cannot itself be good for our current problems.

In the simple measure of energy intensity, more than one source of energy consumed is broadly binned into an overall energy consumption. Furthermore, solar energy produces no pollution and the renewable energy sources have no major problem of depletion (though they have problems of their own). We also know that some energy sources produce more CO2 and other potentially harmful side effects than others. It could also be that some energy sources have a higher payout in GDP than others. Is it not possible, then, to structure our energy use to keep GDP high while keeping the harmful side effects low?

How can we answer such a question? If the relationship between each energy type is known and how much pollution each type causes then perhaps a mathematical analysis might be enough to tell us everything there is to know. But what if the relationships are unknown and constantly changing from year to year as technologies improve or economies shift?

This is where the Data Envelopment Analysis comes in. It allows us to analyze efficiency defined in many ways without knowing the strict relationship between the economy's inputs and its output. Using the recent history of the energy consumption and GDP, it can be used to compose measures of efficiency in terms of various maximization or minimization problems. For example, one might wish to know if there is evidence in the recent past that can suggest that the GDP can be increased or at least maintained while the energy consumption is reduced. The method could then determine the efficiency of each time period in regards to this measure. Furthermore it can be used to determine if bad outputs of the economy can be theoretically reduced.

3.1 Data Envelopment Analysis

Data Envelopment Analysis is based on a set of entities or Decision Making Units. The method attempts to evaluate the performance of each of these units using others as the benchmark. In general the real goal is to somehow define optimal efficiency of the DMU's. The problem is that the exact relationship between what the DMU is given as input and the output it produces is unknown. The model is good at handling such problems as it uses observed DMUs to create a benchmark performance or efficiency without given relationships between input and output other than those derived from the DMU's themselves.

Given are n decision units, each with m inputs and s outputs.

1. DMU_j - Decision Making Units (DMU) $j \in \{1...n\}$
2. x_{ij} - i^th input to the j^th DMU $i \in \{1...m\}$
3. y_{rj} - r^th output of the j^th DMU $r \in \{1...s\}$
4. $x_{ij} \geq 0 \qquad \forall i, j$

5. $y_{rj} \geq 0 \qquad \forall i, j$

Definition 1 DEA Data Basis

The strength of the general group of methods that follow lies in the fact that there is no limit given on the number of inputs or outputs and more importantly there is no relationship between inputs and outputs provided as part of the model. These relationships almost always exist in the areas being modeled but these are only inferred from the DMU input and output levels themselves. For example the DMUs might be economy inputs and outputs of a given year of a given country. The inputs might be the consumptions of various energy sources while the outputs could be the GDP and CO2 emissions.

While the ability of the system itself to infer relationships is invaluable, the deeper difference between a simple analysis of energy intensity over time and DEA derives itself from the capability of multiple inputs. It can be seen that in the case the DEA methods are used with single inputs and outputs, the conclusions we can draw are only as intricate as those derivable from energy intensity as seen in Figure 3.

3.1.1 Input vs. Output Based Models

An essential property of DEA models and the ones described further in this section is the notion of input based or output based models. The difference between the two is the main focus or intention of the model. The input based model is used to determine potential reductions in the inputs of a DMU while the output based models do the same for outputs of the DMU.

3.1.1.1 Input Based

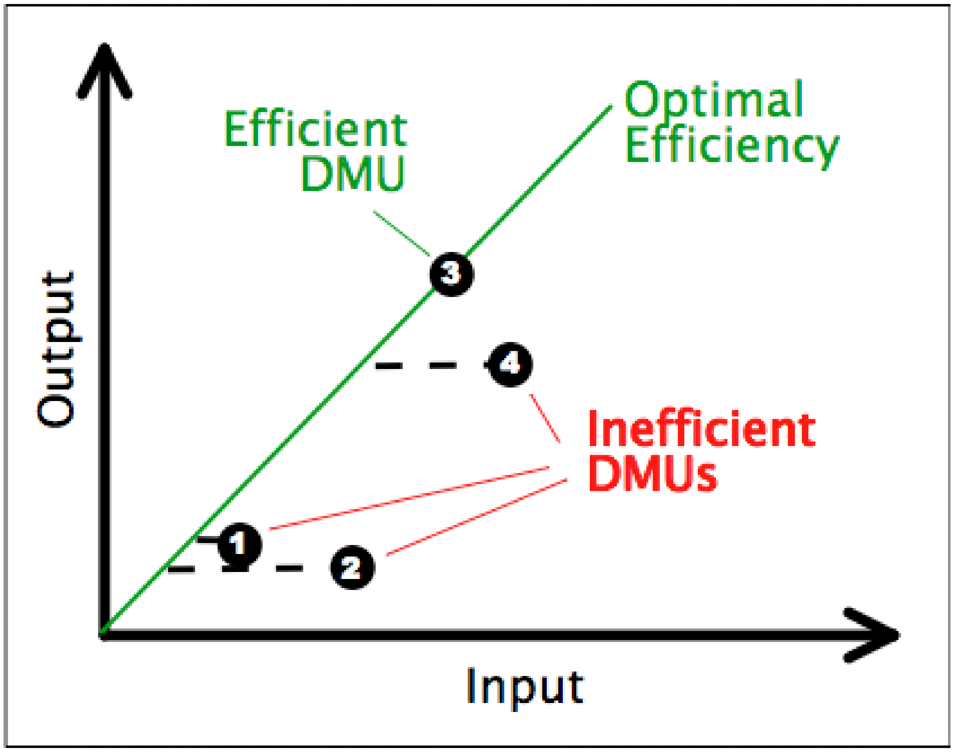

Figure 8 Input Based DEA

The hypothetical example in Figure 8 Input Based DEA shows 4 DMUs of varying amounts of inputs and outputs. In a case of input minimization, we are concerned with determining the most efficient use of some resource or otherwise the highest ratio of input to output. In our project this is the ratio between GDP and energy consumption which also happens to be the reciprocal of energy intensity.

According to the demonstration, example DMU #3 observes the most efficient use of its input. That DMU therefore defines an optimal efficiency frontier. The other DMUs are less efficient since their output to input ratio is lower. The model shows us that each of these other DMUs can potentially use less input and produce the same amount of output. This means that all the inefficient DMUs can reduce their input by some proportion. If the inputs to DMUs #1 and #4 were reduced by their proportions then they would be both optimal. The values of the proportional decrease tell us how efficient each DMU is compared to the others. In more complicated models containing more than one input, further reductions in individual inputs are possible in the form of “slacks” which demonstrate the relative inefficiency of various inputs as opposed to the inefficiency of the entire DMU.

3.1.1.2 Output Based

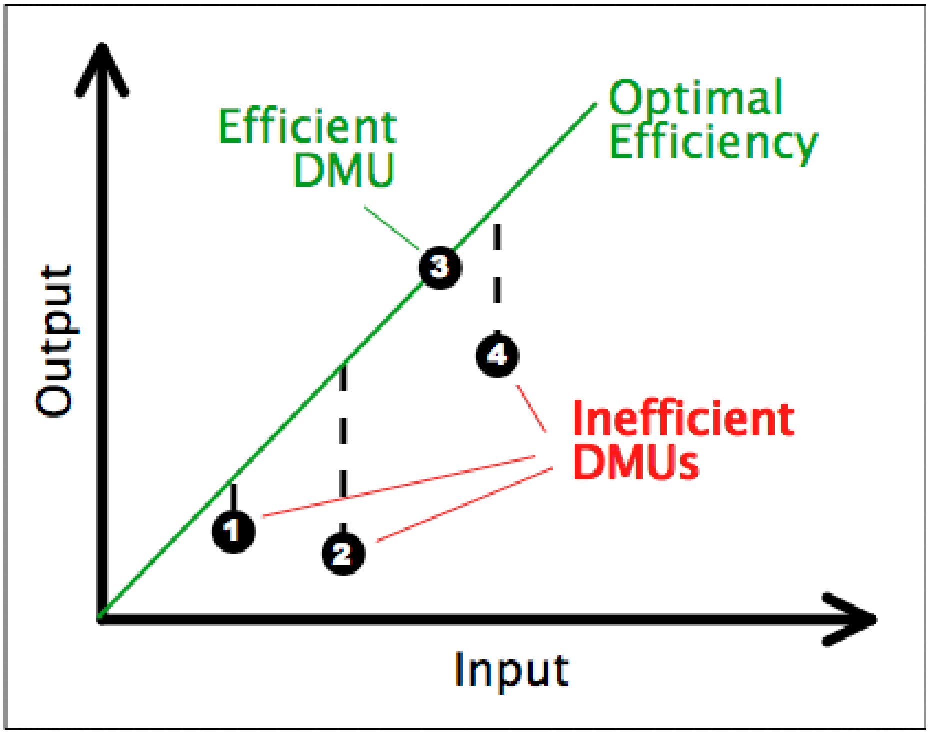

Figure 9 Output Based DEA

In the case of output maximization, the same idea of efficiency takes effect. One still desires the best ratio of output to input for the reason that the output is the real focus and important part of the entities being modeled. In the toy example, DMU #4 still observes optimal efficiency in this regard. All the other inefficient DMUs can increase their output by some proportion to be considered at par with DMU #3.

3.1.2 Our Models

Both input minimization and output maximization strive for essentially the same thing: optimal ratio between input and output. In the case of a single input and single output, the two approaches tend to be extremely congruent in their results but the real strength of DEA lies in its ability to handle multiple inputs and outputs. Furthermore, there are many more options than input minimization and output maximization. The general paradigm allows for easy tweaking of constraints for a variety of uses. Our models and their intentions are summarized below:

- **Model 1: Input Minimization**
    - minimize energy consumption
- **Model 2: Input Minimization**
    - minimize energy consumption
    - allow renewable energy consumption to remain
- **Model 3: (undesirable) Output Minimization/ (desirable) Maximization**
    - minimize CO2 emissions
    - maximize GDP
- **Model 4: (undesirable) Output Minimization**
    - minimize CO2 emissions

3.1.3 Basic Input-Based Model (MODEL 1)

The first DEA model used is the Charnes, Cooper, Rhodes (1978) or CCR input-based model. The model strives to minimize the inputs while maintaining the outputs. That is the optimal value of theta as seen in the model represents the largest “radial contraction” in all the inputs while maintaining the output.

Given:

1. the DMUs as above
2. $o \in \{1...n\}$ or the index of a specific DMU to be considered

$\theta^* = \min \theta$ under the constraints:

1. $\sum_{j=1}^{n} x_{ij}\lambda_j \leq \theta x_{io} \qquad \forall i$
2. $\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{ro} \qquad \forall r$
3. $\lambda_j \geq 0 \qquad \forall j$

Definition 2 Model 1

The θ in the model ranges in [0,1] and represents a radial contraction in all inputs that is theoretically possible while maintaining the output level. If, for example, an optimal value of θ resulted in 0.85, the conclusion would be to note a potential reduction of all the inputs simultaneously by 15% and still produce at least the original level of output.

The θ is always guaranteed to be at most 1. Such a value would represent a general incapability to reduce the DMU inputs. The guarantee is in place because for any DMU being evaluated, it could be made to be its own benchmark in which case $\lambda_o = 1$ and $\lambda_i = 0$ for all other i. This also represents an optimal efficiency of the DMU in question as it's output is incapable of being constructed by a linear combination of other DMU outputs while the inputs are reduced.

3.1.3.1 Slacks

The θ described by the model so far only provides a theoretical reduction of all the inputs by the same ratio. It may be, however, that the various individual inputs can be theoretically reduced by further amounts. This occurs because of the inequality present in the first conditional in Definition 2 Model 1.

To account for this, "slacks" are provided as measures of further potential reduction beyond the proportional reduction by the optimal theta ratio. They are inferred by the difference between the proportional reduction introduced by θ and the linear combination of the individual inputs:

Equation 1 Input Slack Definition

$$s_i = \theta x_{io} - \sum_{j=1}^{n} x_{ij} \lambda_j \qquad \forall i$$

3.1.4 Input-Based Modified Model (MODEL 2)

In the first model, the reduction in inputs is all encompassing. The optimal theta serves to reduce all the inputs by the same proportion. It might be interesting to consider a model in which some inputs need not be reduced. For example the renewable energy consumption may be considered not as problematic as other sources. This can be seen in Figure 14.

To handle this kind of case, we define a second model and partition the DMU inputs into two sets: those that are to be reduced and those that need not be.

Define a set of inputs which need not be reduced:

- $G \subseteq \{1...m\}$

The minimization problem remains the same except a small change.

$\theta^* = \min \theta$ under the constraints:

1. $\sum_{j=1}^{n} x_{ij}\lambda_j \leq \theta x_{io} \qquad \forall i \notin G$
2. $\sum_{j=1}^{n} x_{ij}\lambda_j = x_{io} \qquad \forall i \in G$
3. $\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{ro} \qquad \forall r$
4. $\lambda_j \geq 0 \qquad \forall j$

Definition 3 Model 2

3.1.5 Directional Distance Function Model (MODEL 3)

In our third model we look at the model introduced by Chung and Färe (1995) and later modified by Weber and Domazlicky (2001). The model uses a “directional distance” to measure technical efficiency. Their model served to maximize the outputs while minimizing the inputs. They proposed the same proportion of increase and reduction. This proportion (or β) is then the measure of the technical efficiency of the DMU.

Weber and Domazlicky (2001) adapted Chambers, Chung, and Färe’s (1996) model to study productivity in manufacturing. They proposed DMUs that produce good or desired outputs and at the same time produce bad or undesired outputs. Their study of states in the USA included the desired output of manufacturing output while the undesired output they considered was pollution.

Weber and Domazlicky's (2001) essential change is to consider reduction of undesirable outputs because they are really bad as opposed to reducing inputs which aren't intrinsically bad to use but rather are reduced because it is always a nice idea to reduce inputs. Their model still enforces a reduction or at least not an increase of inputs however. Depending on the model it might be unrealistic to require enormous inputs (or consumption) in order to reduce or increase outputs.

Define a set of desirable outputs:

$$G \subseteq \{1 ... m\}$$

$\beta^* = \max \beta$ under the constraints:

1. $\sum_{j=1}^{n} x_{ij}\lambda_j \leq x_{io}$ $\quad \forall i$
2. $\sum_{j=1}^{n} y_{rj}\lambda_j \leq (1-\beta)y_{ro}$ $\quad \forall r \notin G$
3. $\sum_{j=1}^{n} y_{rj}\lambda_j \geq (1+\beta)y_{ro}$ $\quad \forall r \in G$
4. $\lambda_j \geq 0$ $\quad \forall j$

Definition 4 Model 3

The β here is a measure of both an increase in desirable outputs and decrease in undesirable inputs. If the reduction and increase proportions were allowed to be different, the model wouldn't be able to represent their respective values to the users of the model (is reduction of undesirable outputs better than increase in desirable outputs?) In our analysis, the desired output will remain GDP while the undesirable output will be CO2 emissions.

3.1.6 Output-Based Model with Undesired Outputs (MODEL 4)

Our fourth model is much like the first two models but takes into account undesirable outputs as does our third model. Intuitively this model is equivalent to the second model except in the fact that this one is output-based while the second model was input based. The intent of this model is to focus on the negative or undesirable outputs.

Define a set of “good” or “desirable” outputs that are not to be reduced:

- $G \subseteq \{1 \ldots s\}$

$\theta^* = \min \theta$ under the constraints:

1. $\sum_{j=1}^{n} x_{ij}\lambda_j \leq x_{io} \qquad \forall i$
2. $\sum_{j=1}^{n} y_{rj}\lambda_j \geq y_{ro} \qquad \forall r \in G$
3. $\sum_{j=1}^{n} y_{rj}\lambda_j \leq \theta y_{ro} \qquad \forall r \notin G$
4. $\lambda_j \geq 0 \qquad \forall j$

Definition 5 Model 4

The θ in this case tells us by how much can undesirable outputs be reduced. In our case this will be greenhouse gas emissions. Once this is made the focus of the model, the rest of the outputs are maintained while the inputs are kept at below or at the normal levels.

4 Results and Analysis

4.1 Data Selection

The countries chosen for our analysis included the United States, Germany, France, Italy, and the United Kingdom. We wanted to choose countries where it was possible to recommend policy changes as well as other ideas on how to increase reliance on renewable energies as well as increasing carbon dioxide emissions. Countries still in the developing process have different energy needs than countries with high GDP per capita (a standard measure of living) so all of our selected countries are industrialized and have high GDP per capita. According to the CIA World Factbook, the United States, Germany, United Kingdom, France, and Italy are ranked 1st, 5th, 6th, 7th, and 8th respectively in terms of GDP.

A simple energy analysis commonly used is energy intensity or energy consumption divided by a countries' GDP. Our first two methods are setup extremely similar to energy intensity except we look at multiple inputs for a given output. For this we chose to look at the energy consumption from a number of different sources. Our output, similar to energy intensity would be GDP.

For our first two methods we chose to look at the initial break-up of energy sources. These are the consumption of coal, gas, oil, nuclear, and renewable energy. We wanted as many data points as available since it would provide more valuable results. Therefore we obtained United States consumption data from the Energy Information Administration. The data years ranged from 1949 to 2003 and measurements of energy were in quadrillion BTUs. Data regarding Real GDP was obtained from the Economic Report of the President 2004, and GDP figures were given for years starting in 1959. The data is in Billions of chained 2000 dollars.

Ideally we were hoping to find similar data for our European Countries over similar periods of time as the United States, but that proved to be extremely difficult. We found eurostat (see data sources in appendix A for more information) to be a valuable resource regarding our European countries' data. This website allowed us to obtain energy consumption as well as GDP data for the countries that we chose. Unfortunately, this data did not cover the same period of time as United States data. Instead the period included years between 1985 and 2002. Additionally, the European data was in different units of measurement which led us to conduct analysis for the United States and the European countries separately.[1]

For the European analysis we decided to compare all countries together since their period of time for which data was available was shorter. Also there was no GDP information for Germany until 1991 and no data for nuclear consumption within Italy after 1987 so we had to truncate the valuable data for Germany and Italy. For Germany only data from 1991 to 2002 was used and for Italy only data from 1985 to 1987 was used.

The third method used [directional distance function] looks at a desirable (positive) output and an undesirable (negative) output and increases and reduces both respectively by a certain factor. The last method we used also looks at this same data but manipulates it differently. Naturally, we chose the good input to be represented by GDP and the bad output in this case is represented by pollution. For the United States we used carbon dioxide emissions data, measured in million metric tons of carbon dioxide, from the Energy Information Administration as the negative output. The data period was 1949 to 2002 so that our usable data range was 1959 to 2002.

We utilized eurostat to access data concerning our European countries' carbon dioxide emissions. We had to use data of greenhouse gas emissions which included not only carbon dioxide emissions but other air pollutants as well since data exclusively for carbon dioxide was not available. The emission measurements were in 1000 tonnes carbon dioxide equivalent and data was only available from 1990 through 2002. This limiting the time period we could study with the last two methods and prevented us from conducting analysis for Italy since 1985 to 1987 were our only usable years.

4.2 Model 1: U.S. Energy Consumption to GDP

An initial analysis involves the energy consumption and the Gross Domestic Product of the United States (GDP). The assumption is that the energy is consumed as input and produces the GDP as output. While energy consumption is in need of minimization, the GDP needs to be maintained.

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[1] European consumption measurements were in thousands tons of oil equivalent. GDP measurement was in millions of 1995 Euro.

This model is a first step above a simple energy intensity analysis. Instead of considering the total energy consumption of the entire country in relation to the GDP, the model lets us consider the GDP as a product of more than one input.

4.2.1 Model Setup

- n = 45 – 45 years
- m = 5 – 5 inputs
- s = 1 – 1 output
- DMU_j - jth year
- x_{1j} - energy consumption from coal in the jth year
- x_{2j} - energy consumption from gas in the jth year
- x_{3j} - energy consumption from oil in the jth year
- x_{4j} - energy consumption from nuclear plants in the jth year
- x_{5j} - energy consumption from renewable sources in the jth year
- y_{1j} - U.S. GDP in the jth year

Years range from 1959 (n=1) to 2003 (n=45)

4.2.1.1 DMU Inputs:

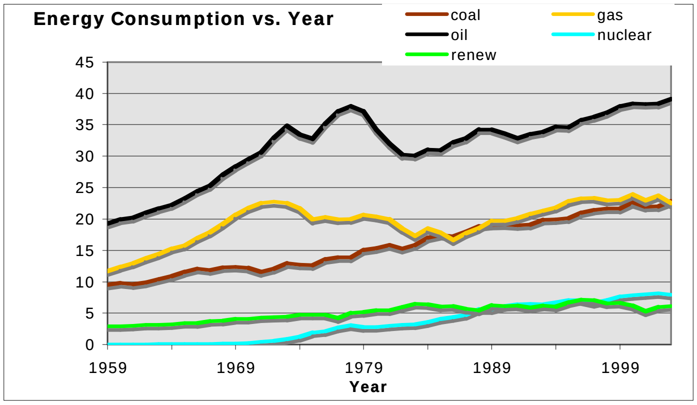

Figure 10: Energy Consumption vs. Year [source: EIA]

4.2.1.2 DMU Outputs:

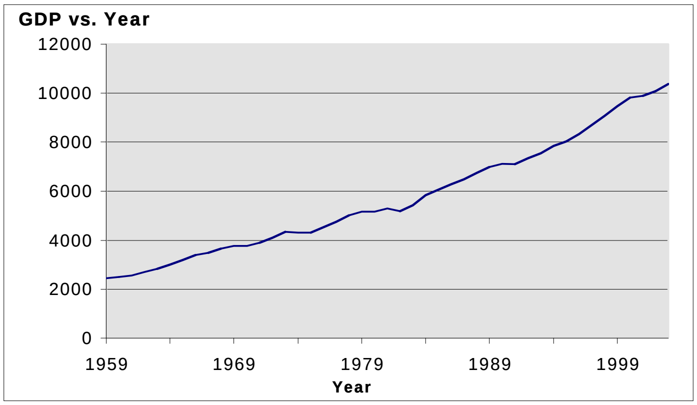

Figure 11: GDP vs. Year [source: Economic Report of the President]

4.2.2 Results

The results show high efficiency during the period between 1959 through 1975. Following this period is a long frame of inefficiency lasting through the year 1999. High efficiency follows this rough period.

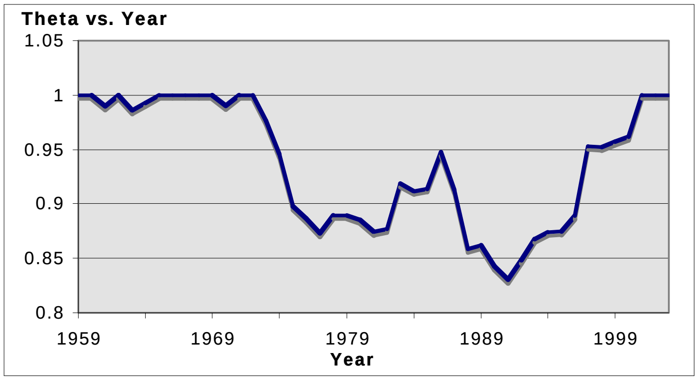

Figure 12: Theta vs. Year [author's calculations]

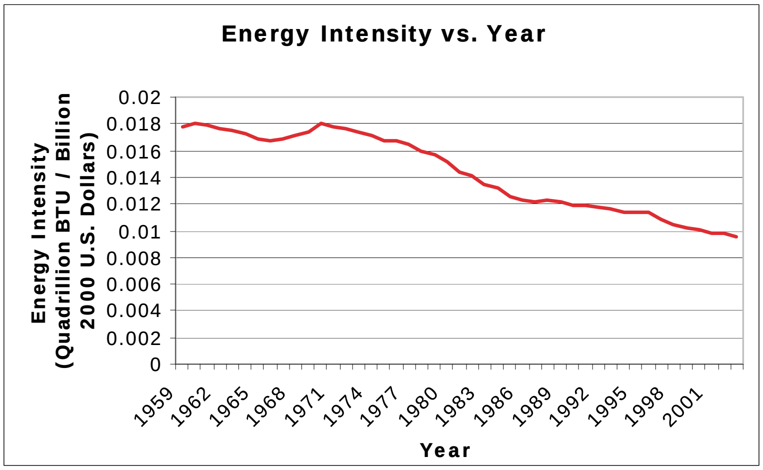

Figure 13: U.S. Energy Intensity [author's calculations]

The results in Figure 12 show the radial efficiency, also known as theta for each year. These results show a significantly different picture than the energy intensity as in Figure 13. The figure shows the energy intensity of all primary energy consumptions combined and it has an observed steady decline between 1959 and 2003. On the other hand the results obtained from the DEA program show that between 1973 and into the late 90’s there were varying inefficiencies in energy consumption.

The reason we obtain these results are because the DEA program takes not only the energy consumed but also looks at the different inputs and tries to find their optimal combinations. The program does this by finding benchmarks within the years of our technology set which are used to produce a desired level of GDP with a different and “more efficient” combination of energy consumptions. So for every year of assessment, there are years (or year) that make the benchmarks. An example is the year 2003 which serves as one of the most common benchmark years. These benchmark years can be observed in Lambda Table B.1.1.4 in our Appendix.

Figure 14 along with data tables in B.1.1 of the Appendix show that taking into account our theta efficiencies as well as additional slacks in energy consumptions we can compare the actual energy consumptions by source against the optimal consumptions that are calculated by this method. The results show that for all data, efficiency is near 100% until 1973. The average efficiency across all sources from 1959 to 2003 was calculated to be 90.89%. The source breakup of the average efficiencies for coal, gas, oil, nuclear, and renewables was 92.99%, 91.74%, 90.63%, 93.61%, 85.45% respectively. The low efficiency for renewables represents a flaw with using the simple input oriented DEA model. The way the method is setup it looks at reducing renewable energy in lieu of the other energies which slightly disregards our goal of increasing reliance on renewables.

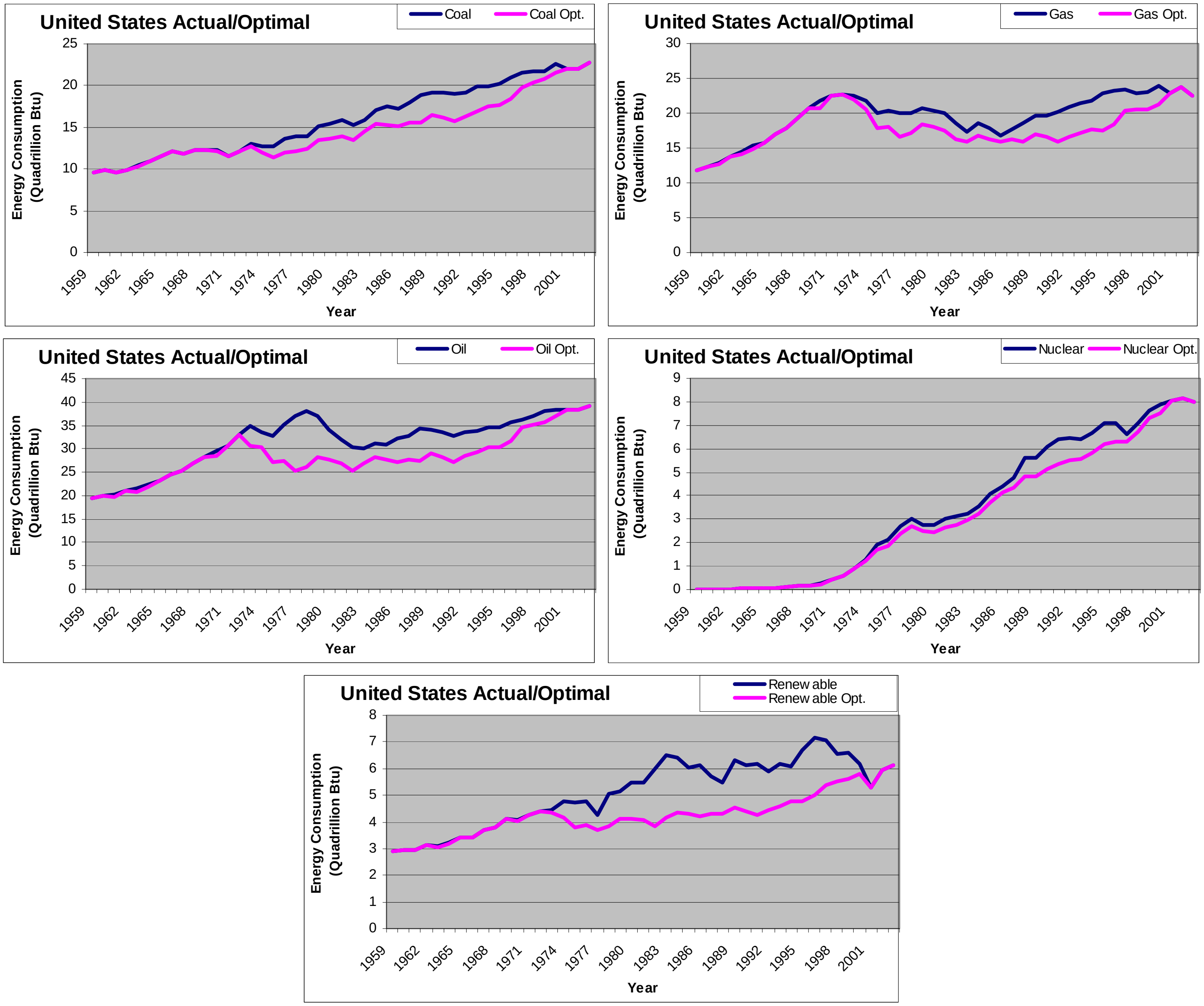

Figure 14: United States Actual/Optimal Consumptions [author's calculations]

Additional analysis was also done using this method, but with the total of all energy consumptions as the input. Given a single input and single output this would result in determining how close to optimal energy intensity (as an aggregate measure) each year is . One of the years is most certainly the most efficient in terms of energy intensity.

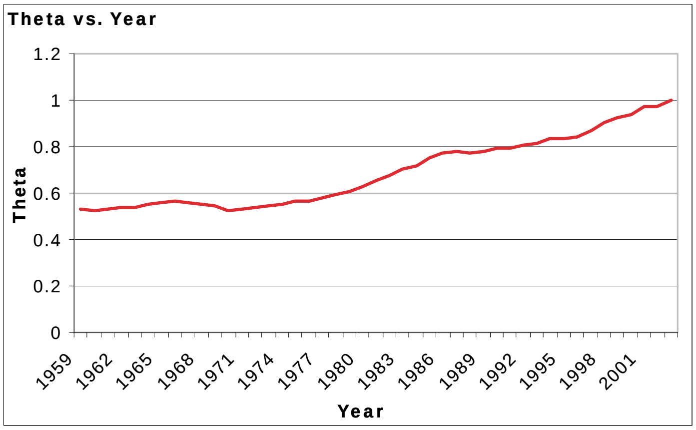

Figure 15: Theta vs. Year [author's calculations]

The results are simply as expected (see Figure 15). While a lower energy intensity is the desired outcome, a higher theta is desired in terms of our DEA model. As you see that higher (or closer to 1) theta values in Figure 15 are entirely correlated with better (lower) energy intensities in Figure 13.

4.3 Model 1: European Energy Consumption to GDP

The first model was tested again but in this case used data from the European Nations; Germany, France, Italy, and the United Kingdom. There was no data for Italy’s nuclear consumption beginning the year of 1988. Because of this, only the years of 1985 to 1987 were used and the DEA program yielded no results so they will not be shown.

4.3.1 Model Setup

- n = 51 – 51 years
- m = 5 – 5 inputs
- s = 1 – 1 output
- DMU_j - j^th year
- x_{1j} - energy consumption from solid in the j^th year
- x_{2j} - energy consumption from gas in the j^th year
- x_{3j} - energy consumption from oil in the j^th year
- x_{4j} - energy consumption from nuclear plants in the j^th year
- x_{5j} - energy consumption from renewable sources in the j^th year

- y_{1j} - European (Germany, France, United Kingdom) GDP's in the j^{th} year

Years range from Germany 1991 (n=1) to United Kingdom 2002 (n=51)

4.3.1.1 DMU Inputs

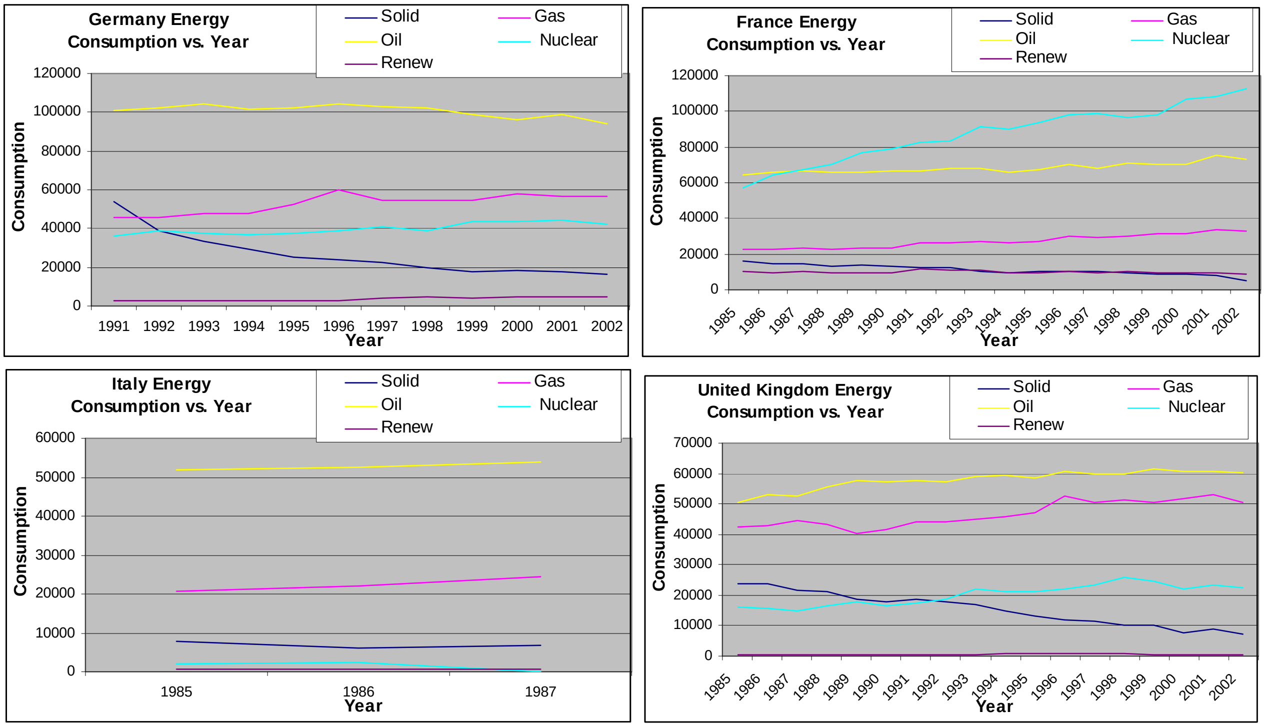

Figure 16: European Energy Consumptions [Eurostat data]

4.3.1.2 DMU Outputs

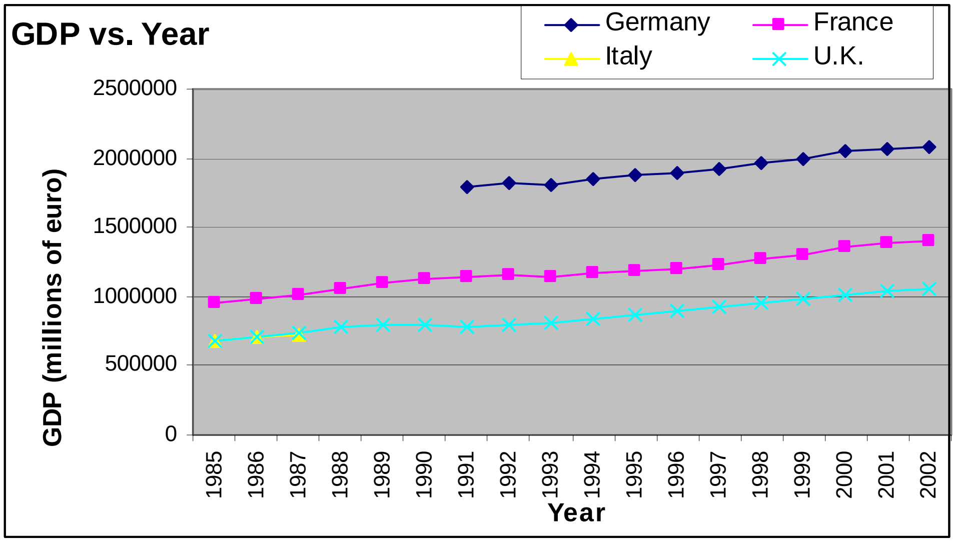

Figure 17: European GDP vs. Year [Eurostat data]

4.3.2 Results

The results in Figure 18 show that for Germany there was high efficiency during the years of 1992, 94, 95, 99, 02. The year that is most inefficient is found to be the 1997 which has an efficiency that is found to be 94.152%, but overall most of the years are highly efficient.

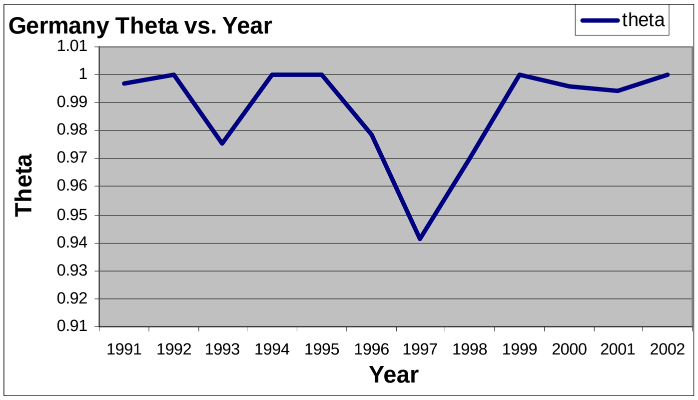

Figure 18: Germany Theta vs. Year [author's calculations]

For France (Figure 19) the results show a much different picture. Only three years are found to have 100% efficiency: 1990, 2000, and 2001. There are numerous periods of inefficiency and some of the lower efficiencies are in 1986 and 1996 where there are efficiencies of 92.3% and 91.48% respectively.

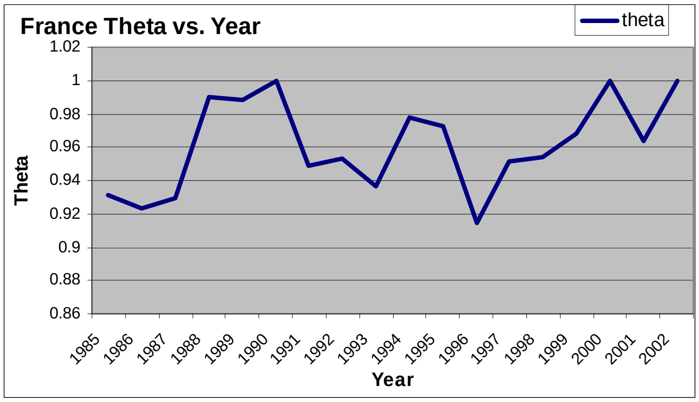

Figure 19: France Theta vs. Year [author's calculations]

The United Kingdom (Figure 20) is found to have lowest efficiencies overall. Only the years of 1987, 1988, and 2002 are 100% efficient. There is a very long period of inefficiency between the years of 1991 to 1999 that reaches its lowest point in 1994 at 80.43%.

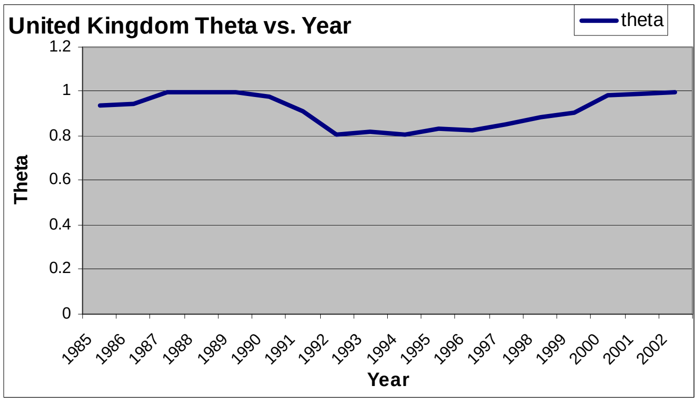

Figure 20: United Kingdom Theta vs. Year [author's calculations]

While the theta values show the overall inefficiency for the years of each country, we must take the slack values of the energies into account to gain a better understanding of how inefficient the consumption of each energy source is. Doing this we calculate the inefficiencies of each source for the four countries over each year. From there each countries' separate inefficiencies, as well as all four combined, are determined. The results of all four countries combined yielded the following inefficiencies;

- Solids – 86.21%
- Gas – 94.67%
- Oil – 94.31%
- Nuclear – 94.44%
- Renewables – 92.23%

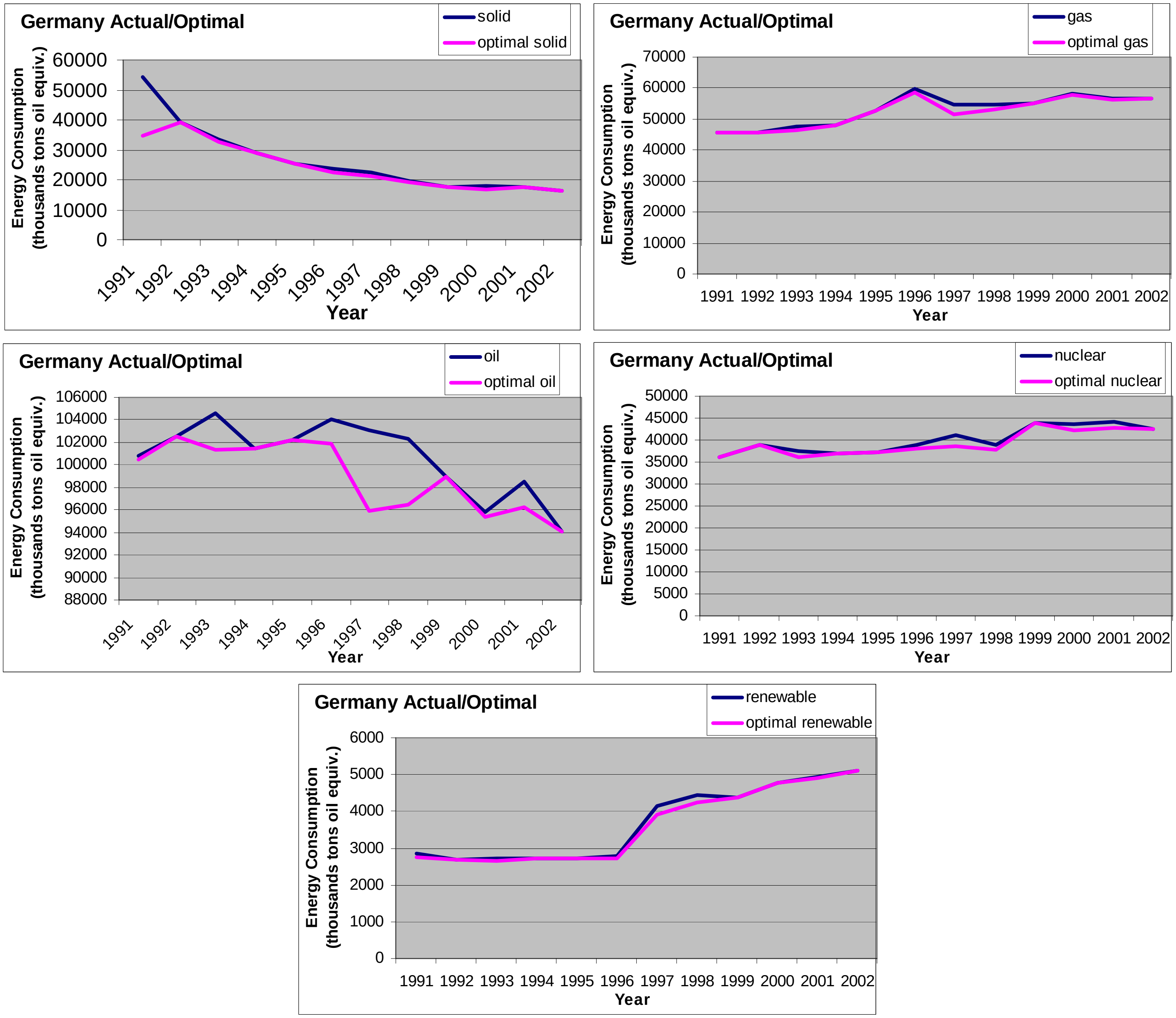

Figure 21: Germany Actual/Optimal Consumptions [author's calculations]

Figure 21 along with data tables in section B.1.2 of the Appendix show that for the given time period there is very high efficiency for Germany. The relatively small radial inefficiency and small slacks indicate that the optimal consumptions of solid and gas energy sources are not far below or different from what the actual consumptions were according to the DEA analysis. This of course assumes full substitutability between the different energy sources. The inefficiency of solids and gas for Germany was found to be 94.94% and 98.78% respectively.

Although, it appears that there are significant differences with the actual and optimal oil consumptions, there is not as much deviation between the sources. The average efficiency for oil is 98.26%. Average nuclear efficiency was found to be 98.18%.

German consumption of renewable energies over the time period of 1991 to 2002 was highly efficient. The inefficiency for the renewable energies is 98.42% according to our analysis. Again, the relatively small radial inefficiency and slacks show us that the optimal consumptions of these energy sources are strikingly similar to the actual consumptions over the period.

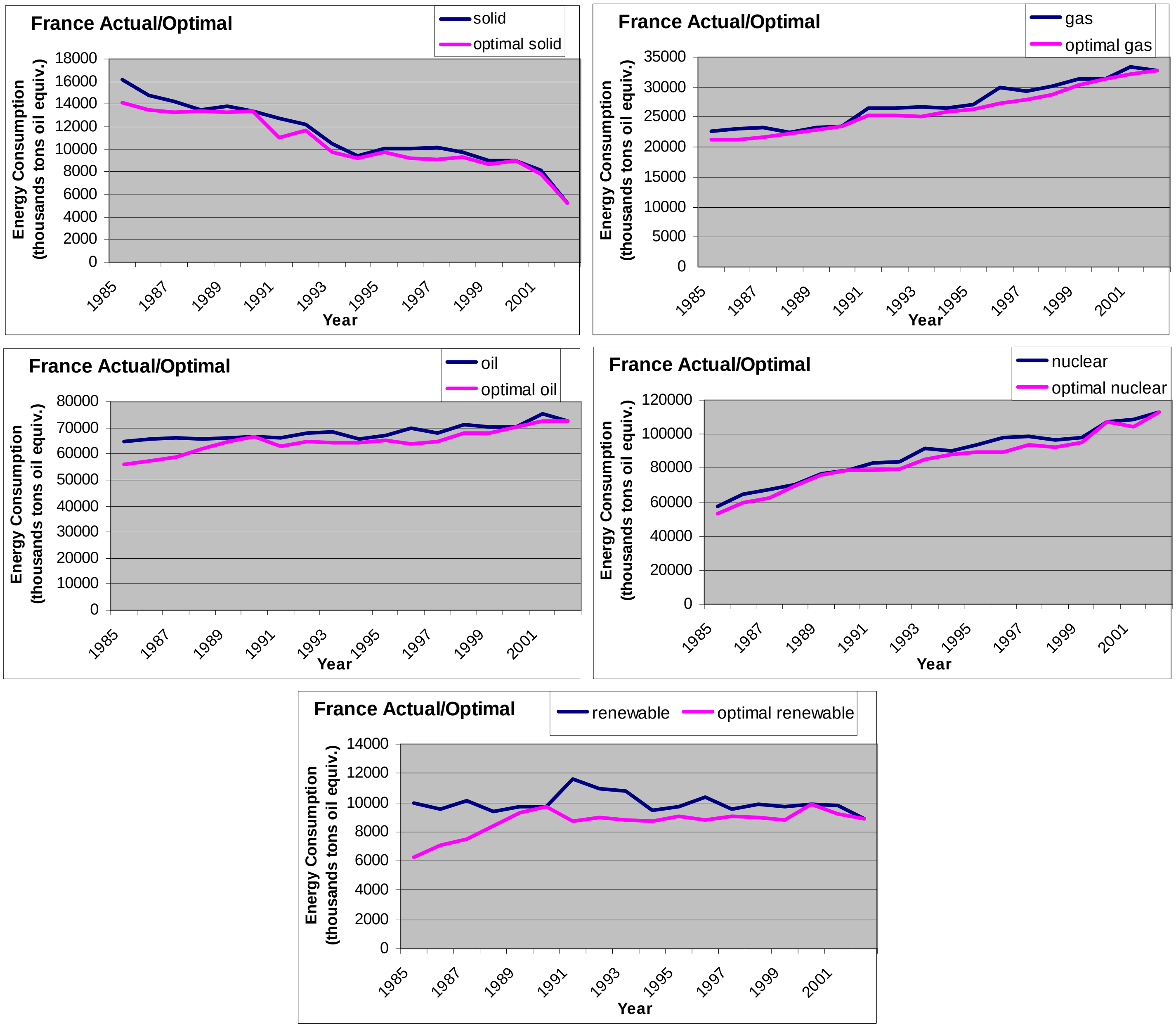

Figure 22: France Actual/Optimal Consumptions [author's calculations]

Similar to Germany, the Figure 22 along with data tables in B.1.2 in the Appendix show that for the given time period there is very high efficiency in France with respect to solid and gas energy consumption. There was slightly more inefficiency however for France than for Germany. For solids and gas, efficiencies are 94.85% and 96.12% respectively.

For oil and nuclear consumption there is still relatively low inefficiency at 94.95% and 96.01% respectively. The only data for France that is relatively inefficient compared to the other energy consumptions that we have looked at is France's renewable energy consumption. An inefficiency of 87.51% demonstrates a distinct difference between the actual energy consumptions and the optimal consumptions for renewable energy. According to the DEA analysis and the assumption that there is full substitutability then there could be possible reductions made in renewable energy use but since we are investigating how to reduce carbon dioxide emissions and increase renewable energy use this result does not go well with our goals.

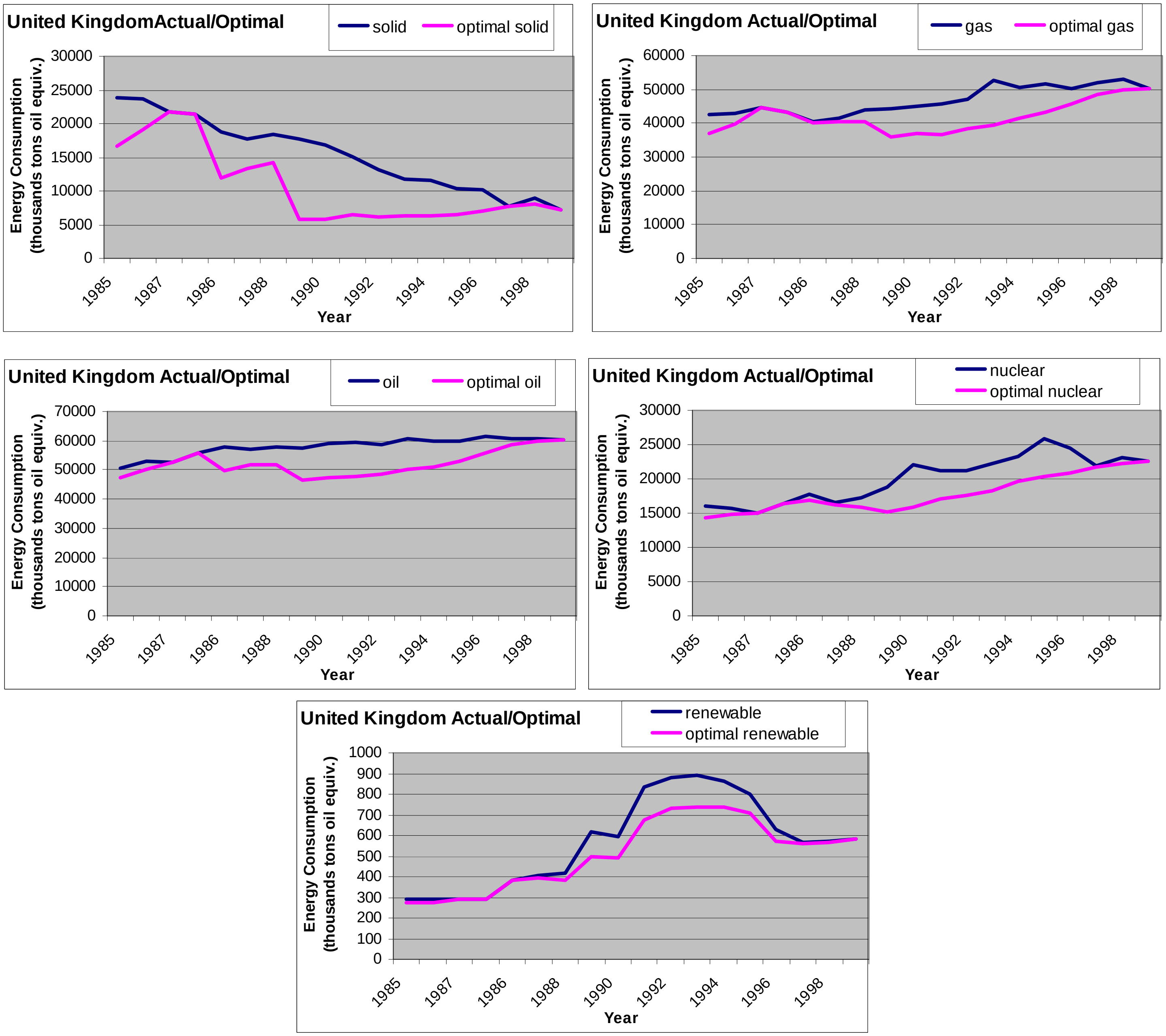

Figure 23: United Kingdom Actual/Optimal Consumptions [author's calculations]

Investigating the United Kingdom (Figure 23) results for Model 1, we notice that using this form of DEA the consumption of solid, gas, oil, and nuclear observe the lowest efficiencies at 69.44%, 89.54%, 90.09%, 89.45% respectively. The efficiency of renewable consumption was found to be 91.54% over the time period, which is around 4% better than France's efficiency.

Data shows that the overall efficiency for Germany, France, and the United Kingdom were 97.72%, 93.89%, and 86.01% respectively. The above results are important because although all countries show lowering energy intensities over the period 1985 to 2002, the DEA analysis shows that there are still large inefficiencies. This is especially important for the United Kingdom which had an intensity drop of 31.95% over the period but of the observed countries had the lowest efficiency. France which has a higher current energy intensity also has higher efficiency than the United Kingdom. Energy intensities are shown in Figure 24.

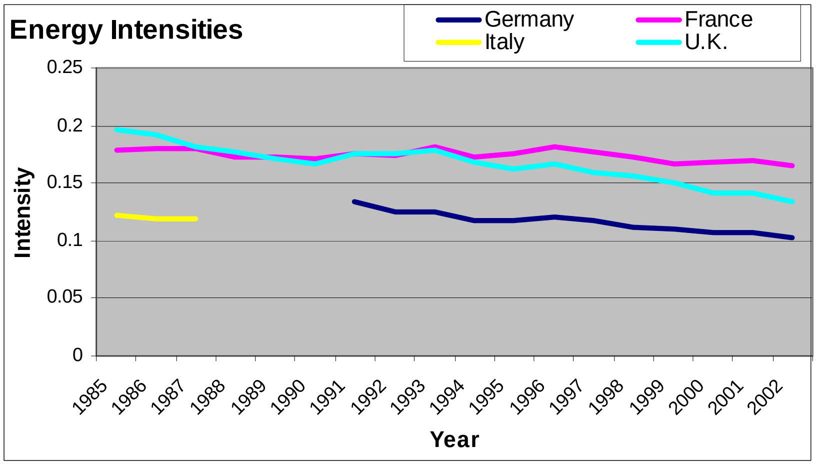

Figure 24: European Energy Intensities [author's calculations]

4.4 Model 2: U.S. Energy Consumption to GDP #2

In the second stage of our analysis we address the shortcoming of the simple DEA model in the context of our application. We construct a modified input oriented model wherein the renewable energy consumption is allowed to remain unchanged while the rest of the inputs are reduced. The inputs and outputs are exactly the same as in the first model. We allow the renewable energy consumption to be excluded from the reduction because renewable energy sources are not subject to dwindling supply problems.

4.4.1 Model Setup

- n = 45 – 45 years
- m = 5 – 5 inputs
- s = 1 – 1 output
- DMU_j - jth year
- x_{1j} - energy consumption from coal in the jth year
- x_{2j} - energy consumption from gas in the jth year
- x_{3j} - energy consumption from oil in the jth year
- x_{4j} - energy consumption from nuclear plants in the jth year
- x_{5j} - energy consumption from renewable sources in the jth year
- y_{1j} - U.S. GDP in the jth year
- $G = \{5\}$

Years range from 1959 (n=1) to 2003 (n=45)

4.4.2 Results

Overall the results show a generally more efficient use of energy despite the relatively inefficient timeframe of the 1970’s through 1995. This general timeframe coincides with that observed in the first model with lower efficiencies compared to earlier and later years.

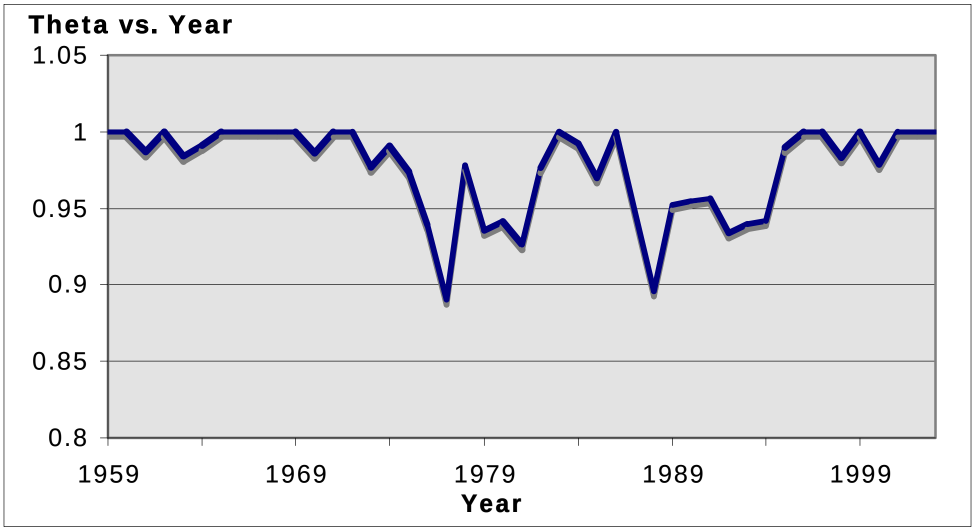

Figure 25: Theta vs. Year [author's calculations]

The results presented in Figure 25 and Figure 26 along with data tables in section B.2.1 of the Appendix show a much different scenario than the first DEA model since we set the program to maintain the same levels of renewable energy consumption. Coal energy average efficiency was 4.41% higher than the first DEA program at 97.40%. Gas efficiency was calculated to be at 96.41% of the actual consumption, a 4.68% increase compared to the previous model. Oil increased in efficiency by 4.41% to 95.04% and nuclear efficiency climbed 2.93% for an average efficiency over the period of time to 96.54%.

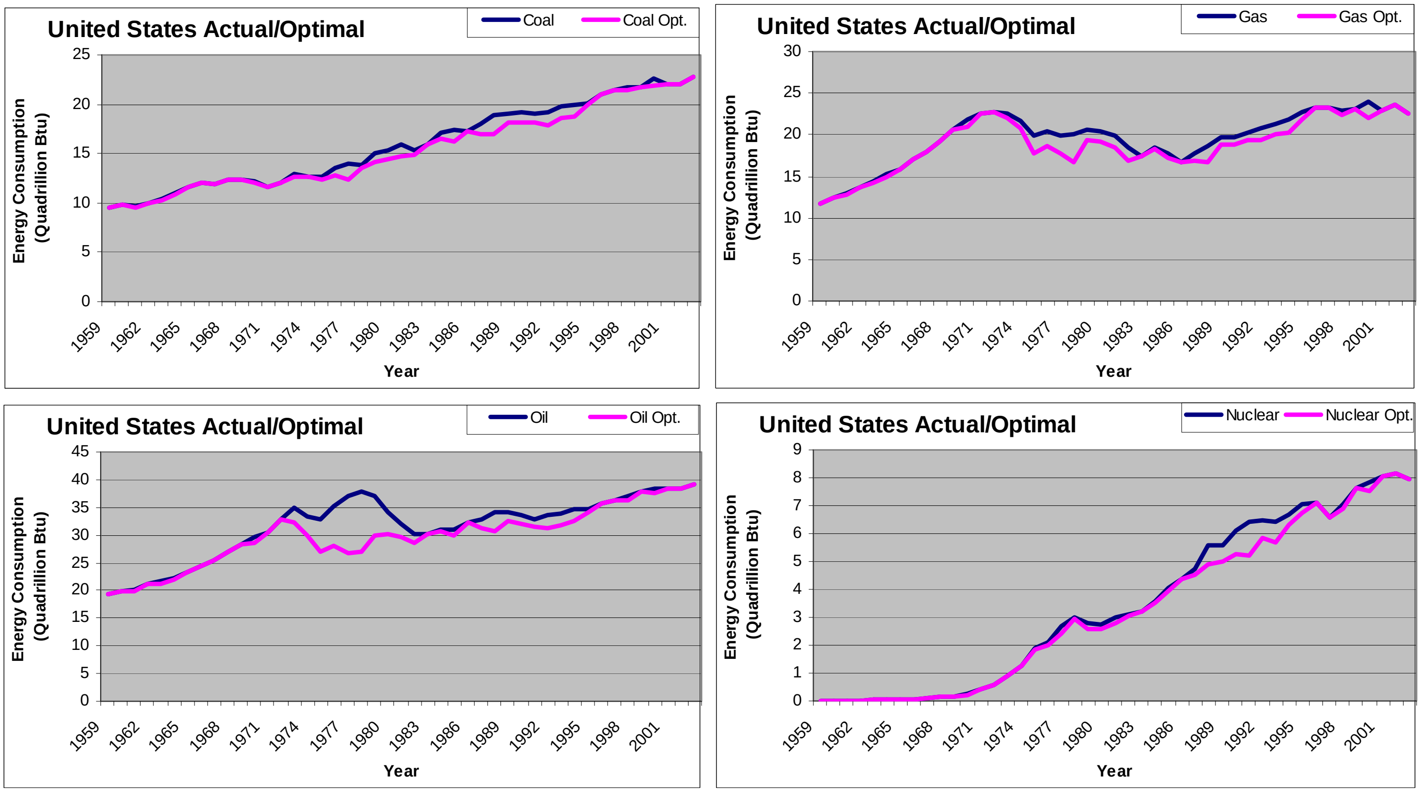

Figure 26: Optimal/Actual Consumptions [author's calculations]

The results show that during the oil crisis there were still high inefficiencies for oil. For the year 1978 we see our lowest efficiency, 70.82% of the actual oil consumption for that year. On the other hand, earlier years show relatively high, if not 100% efficiency, which might indicate that when the oil shock hit the United States there was an immediate lacking in technologies causing the large inefficiencies.

4.5 Model 2: European Energy Consumption to GDP #2

Similarly to the United States, this second model for Germany, France, and the United Kingdom allows the renewable energy consumptions to remain while the rest of the inputs are reduced because we do not want to reduce renewable energies. The inputs and outputs are the same as in the first model for the European countries.

4.5.1 Model Setup

- $n = 51$ – 51 years
- $m = 5$ – 5 inputs
- $s = 1$ – 1 output
- DMU_j - j^{th} year
- x_{1j} - energy consumption from solid in the j^{th} year
- x_{2j} - energy consumption from gas in the j^{th} year
- x_{3j} - energy consumption from oil in the j^{th} year
- x_{4j} - energy consumption from nuclear plants in the j^{th} year
- x_{5j} - energy consumption from renewable sources in the j^{th} year
- y_{1j} - European (Germany, France, United Kingdom) GDP’s in the j^{th} year
- $G = \{5\}$

Years range from Germany 1991 (n=1) to United Kingdom 2002 (n=51)

4.5.2 Results

The results show that for Germany (Figure 27) there were years of high efficiency during 1992, 1994, 1995, 1999, and 2002 like in Model 1. Also, the year that is most inefficient is 1997 similarly to the first model, but the efficiency that is found is only slightly lower at 94.04%. In general, though, the Theta values are extremely similar with respect to the first European model’s thetas.

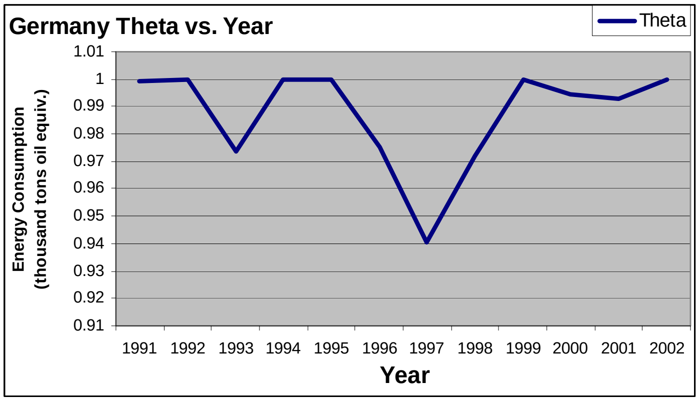

Figure 27: Germany Theta vs. Year [author's calculations]

The results for France (Figure 28), unlike Germany, show much more significant differences in theta values. Instead of three years of 100% efficiency, there are now 7 years; 1985, 1988, 1990, 1991, 1993, 2000, and 2002. Overall, the efficiencies are generally higher than in the first model. The two lowest efficiencies are in 1996 and 1997 with values of 96.58% and 95.93% respectively.

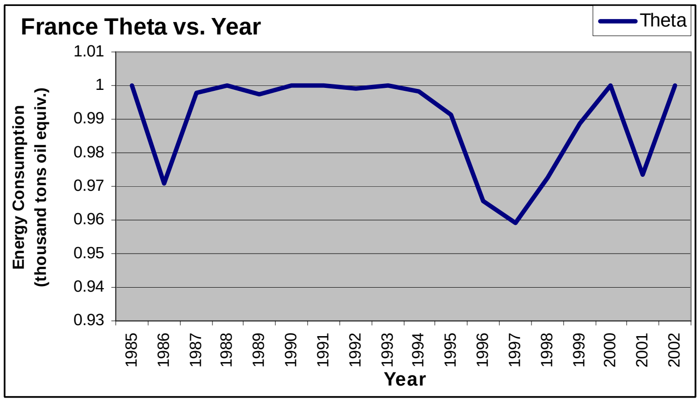

Figure 28: France Theta vs. Year [author's calculations]

The United Kingdom (Figure 29), like Germany, has similar results to the first model's results and in the years of inefficiency the theta values are lower. Again, the years of 1987, 1988, and 2002 are 100% efficient and there is a very long period of lower efficiency between 1991 and 1999. The efficiency is over 3% lower at the low point of 77.5% in 1993.

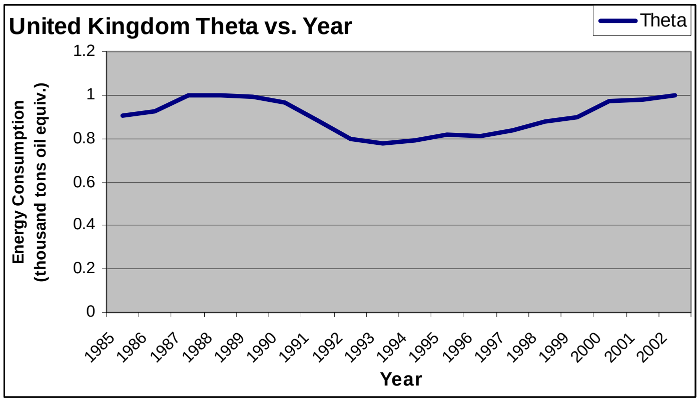

Figure 29: United Kingdom Theta vs. Year [author's calculations]

Taking into account the slack value of each energy, we see how inefficient each energy consumption is. The results of the Model 2 analysis for all four countries combined yielded the following inefficiencies;

- Solids – 86.68%
- Gas – 94.49%
- Oil – 94.31%
- Nuclear – 95.19%

Only nuclear and solids efficiency has risen, while the other energy consumptions have lower efficiencies compared to the first DEA program.

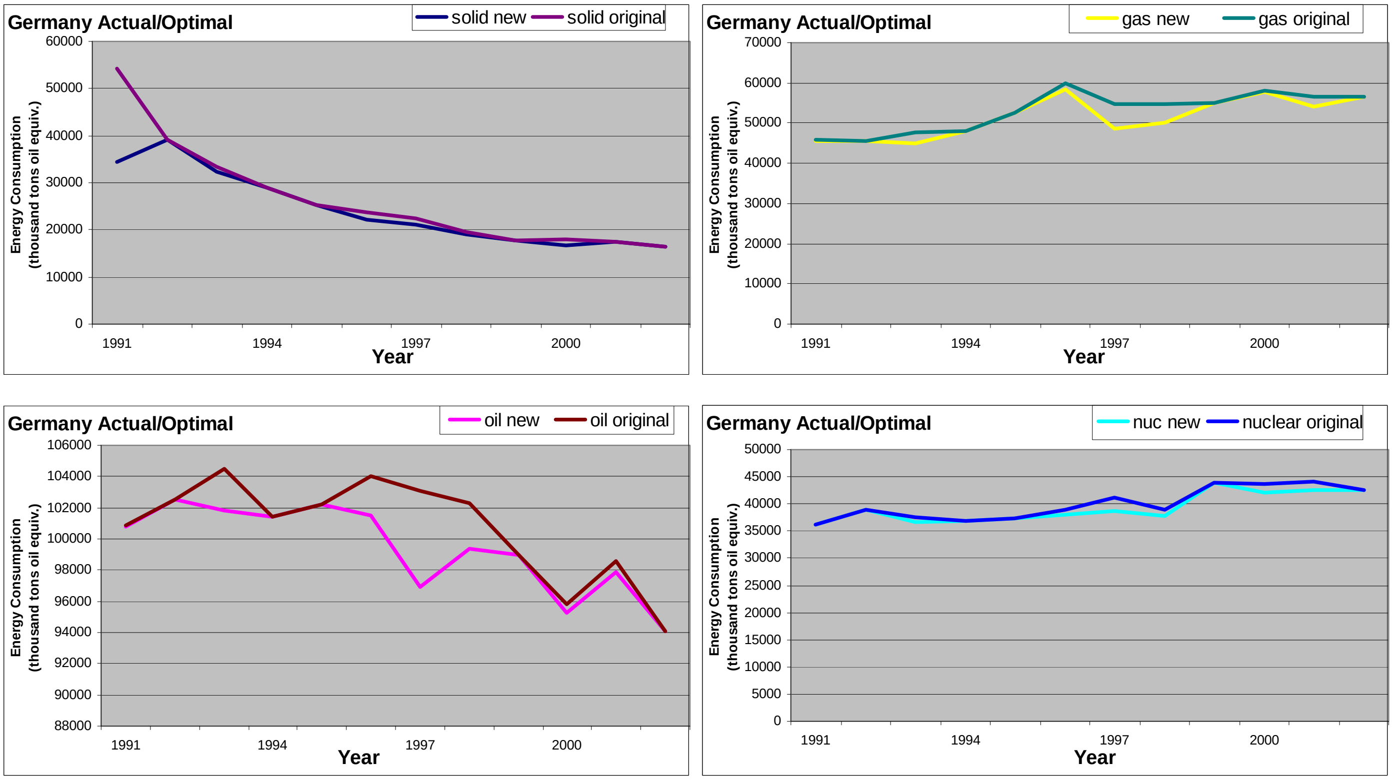

Figure 30: Germany Actual/Optimal Consumptions [author's calculations]

Figure 30 along with data tables in section B.2.2 of the Appendix show that there is only a slightly higher inefficiency for Germany in solid and gas energy consumption than in Model 1. Solid efficiency is now 94.73% and gas efficiency is 97.23%. Inversely, oil and nuclear consumption was a little more efficient than before at 98.73% and 98.23% respectively. The reason for these differences stems from this DEA program's inability to substitute renewable energies for others.

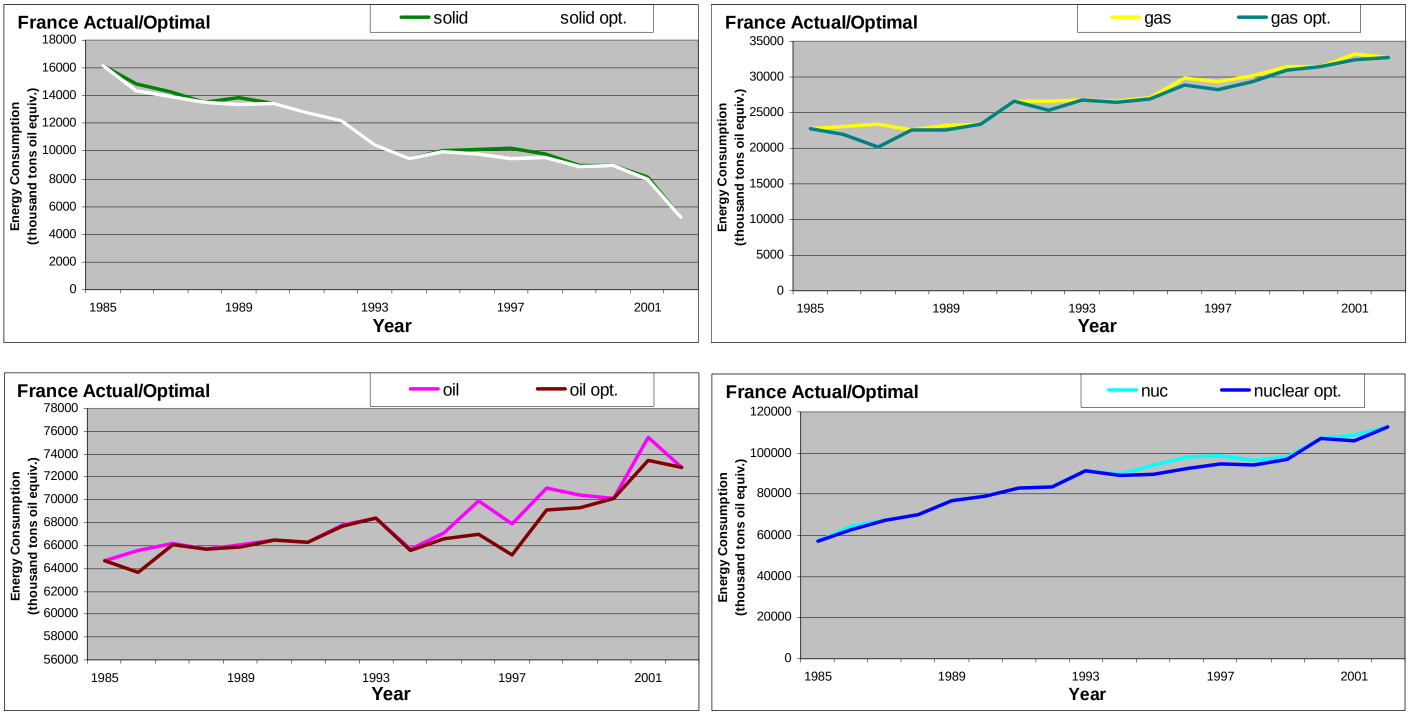

Figure 31: France Actual/Optimal Consumptions [author's calculations]

The results for France shown in Figure 31 demonstrate a fairly significant increase in efficiencies over all consumption spectrums when renewable energies are not minimized. The efficiency for solids increases over the time period by 3.6% for an efficiency of 98.45%. Gas efficiency increases by 1.61% on average and oil efficiency by 3.96% resulting in efficiencies of 97.73% and 98.91% respectively. For nuclear energy consumption efficiency was 98.59%, a 2.58% increase.

Similar to Model 1, the United Kingdom displays the most inefficiency in the Model 2 DEA program. Unlike the Germany and France, the United Kingdom data points toward greater inefficiencies between actual and optimal energy consumption. Solids are found to have a 67.32% efficiency which is 2.12% lower than Model 1. Oil efficiency drops 1.07% to an average of 88.51%. Gas efficiency drops 1.77% to an average of 88.32%, and the average nuclear efficiency is 89.06%, only a 0.39% decrease. As shown in the Appendix section B.2.2 and Figure 32, we see that between 1992 and 1999 there is period of high inefficiency. The high slack values also suggest high substitutability between energy sources.

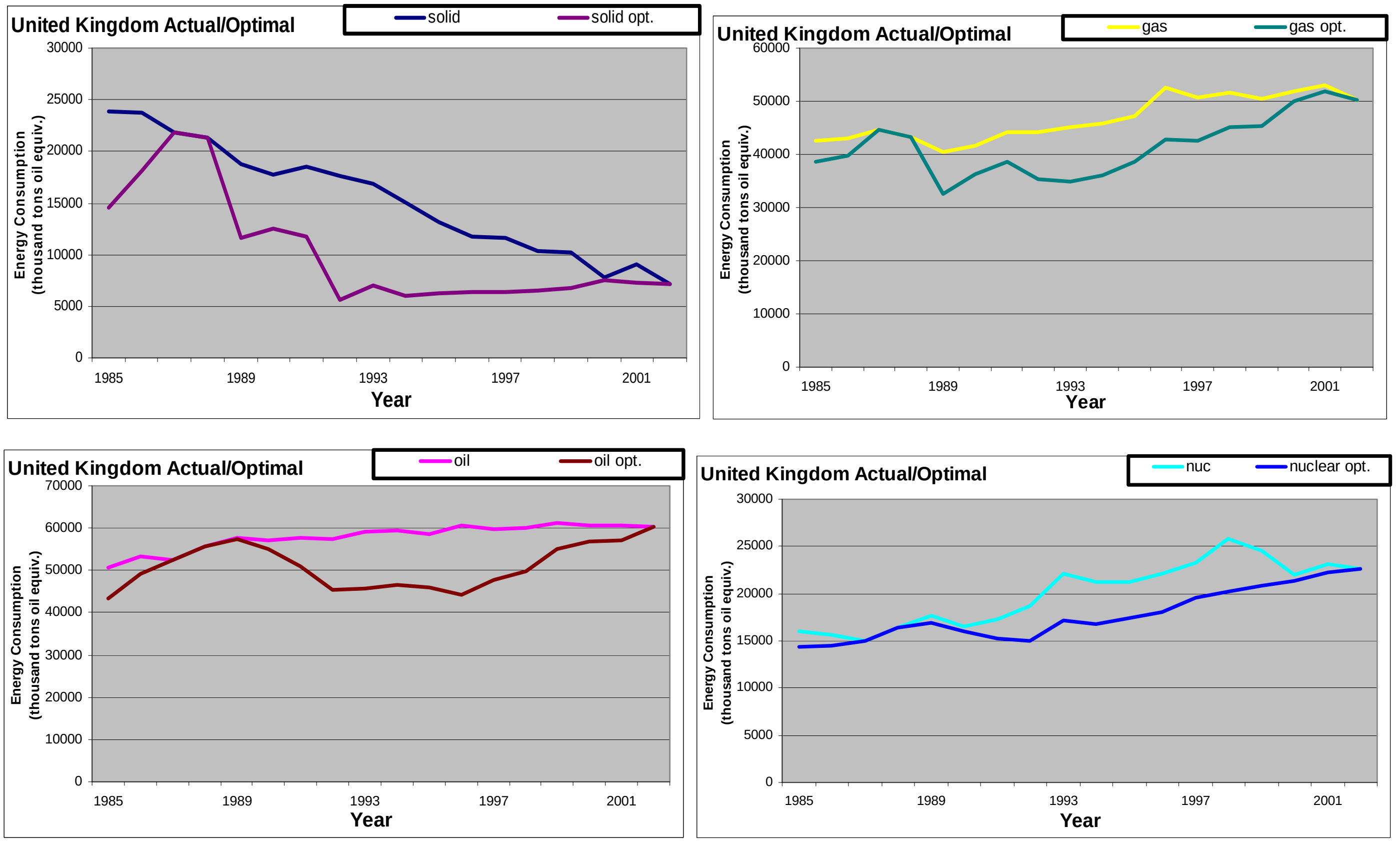

Figure 32: United Kingdom Actual/Optimal Consumptions [author's calculations]

4.6 Model 3: U.S. Energy Consumption to GDP and CO2

This model uses the directional distance function and looks at both GDP and emissions as outputs. It assumes that energy is consumed as input and produces both a positive output of GDP and negative output of CO2 emissions. GDP is to be increased and emissions decreased.

4.6.1 Model Setup

- n = 44 – 44 years
- m = 5 – 5 inputs
- s = 2 – 2 output
- DMU_j - jth year
- x_{1j} - energy consumption from coal in the jth year
- x_{2j} - energy consumption from gas in the jth year
- x_{3j} - energy consumption from oil in the jth year
- x_{4j} - energy consumption from nuclear plants in the jth year
- x_{5j} - energy consumption from renewable sources in the jth year
- y_{1j} - U.S. GDP in the jth year
- y_{2j} - U.S. CO2 emissions in the jth year
- G = {1}

Years range from 1959 (n=1) to 2002 (n=44)

4.6.1.1 DMU Inputs:

The inputs are the same energy consumptions used in the first United States DEA program.

4.6.1.2 DMU Outputs:

In the case of this program, we are looking at GDP being a positive output which has been used in earlier programs. Adversely, there is also a negative output that is produced and for this we use carbon dioxide emissions data gathered from the Energy Information Administration.

4.6.2 Results

From 1959 to 1972, the beta value shown in Figure 33, demonstrate that GDP and carbon dioxide emissions is for the most part stagnant with small values present in 1961, 1963, 1964, and 1970. Starting in 1973 this value increases rapidly until it peaks in 1977 at 12.92%. From there it decreases to nearly nothing in 1986 and then increases again to another peak during 1991 of 10.06% and declines until the late 1990’s early 2000’s where the beta value once again reaches zero. The average beta value for the period from 1973 to 1986 was calculated as 6.91%. Between the period of 1986 to 2000 it was calculated to be 5.66%. The results in Figure 34 as well as the data table B.3.1.1 in the Appendix show that during the time of the oil crisis there was economic impact on the United States GDP, but more importantly carbon dioxide emissions could have been reduced as well.

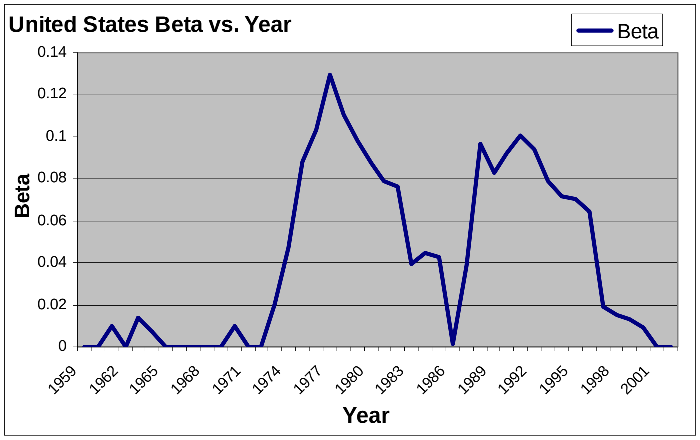

Figure 33: Beta vs. Year [author's calculations]

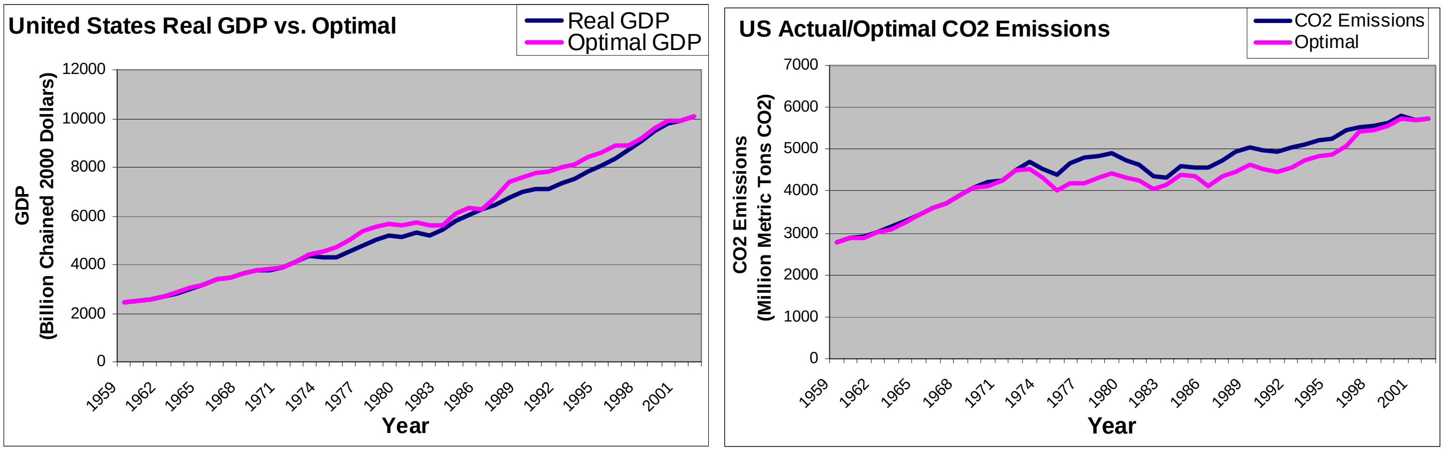

Figure 34: Actual/Optimal GDP and CO2 Emissions [author's calculations]

4.7 Model 3: European Energy Consumption to GDP and CO2

This is the same program as used for the United States Model 3 DEA with the addition that it benchmarks all three European countries (Germany, France, and United Kingdom) comparatively to one another.

4.7.1 Model Setup

- n = 38 – 38 years
- m = 5 – 5 inputs
- s = 2 – 2 output
- DMU_j - jth year
- x_{1j} - energy consumption from coal in the jth year
- x_{2j} - energy consumption from gas in the jth year
- x_{3j} - energy consumption from oil in the jth year
- x_{4j} - energy consumption from nuclear plants in the jth year
- x_{5j} - energy consumption from renewable sources in the jth year
- y_{1j} - European (Germany, France, United Kingdom) GDP's in the jth year
- y_{2j} - European (Germany, France, United Kingdom) greenhouse emissions in the jth year
- G = {1}

Years range from (Germany) 1991 (n=1) to U.K. 2002 (n=38)

4.7.1.1 DMU Inputs:

Same energy data as used in the Model 1 DEA program for Europe.

4.7.1.2 DMU Outputs:

GDP is the positive output, and eurostat greenhouse gas emissions were used as the negative or undesirable output.

4.7.2 Results

The only years that show beta values for Germany are 1993, 1996, 1997, and 2001. This means that only minimal increases in GDP and reductions in greenhouse gas emissions could have been accomplished.

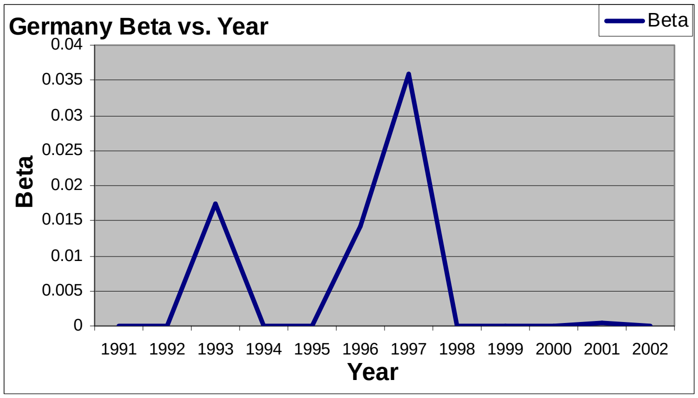

Figure 35: Germany Beta vs. Year [author's calculations]

Figure 35 show that for the following years where a beta value was present, the GDP and greenhouse gas emissions could be increased and lowered by that factor. The data table B.3.2.1 in the Appendix gives the values for beta as well as the actual and optimal GDP and emissions. The results shown in Figure 36 illustrate that in 1993 GDP could increase and emissions decrease by 1.74%. The DEA program also shows that for the short period of 1997 to 1998 the factor would be 1.41% and 3.60% respectively. There is also a very small beta value measured in 2001 of 0.04%.

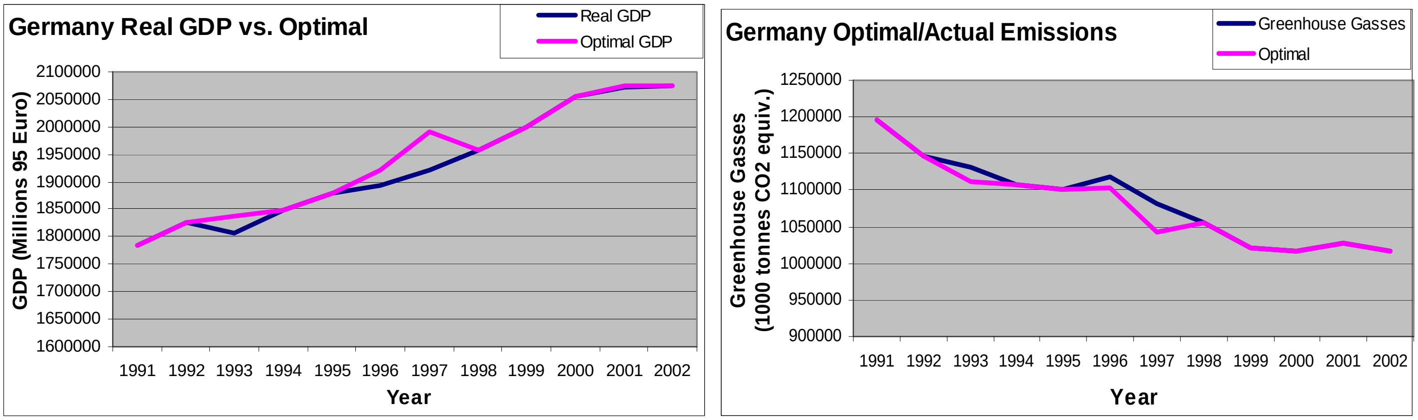

Figure 36: Germany Actual/Optimal GDP and Emissions [author's calculations]

The France results in Figure 37 show that from 1991 to 1999 there was a constantly fluctuating beta factor. There was also a beta measurement in 2001 that was relatively smaller then the other measurements for France at 0.78%. In the period from

1991 to 1999 the beta value reached a maximum in 1996 of 7.31%. The average value for beta over the period was calculated to be 4.13%.

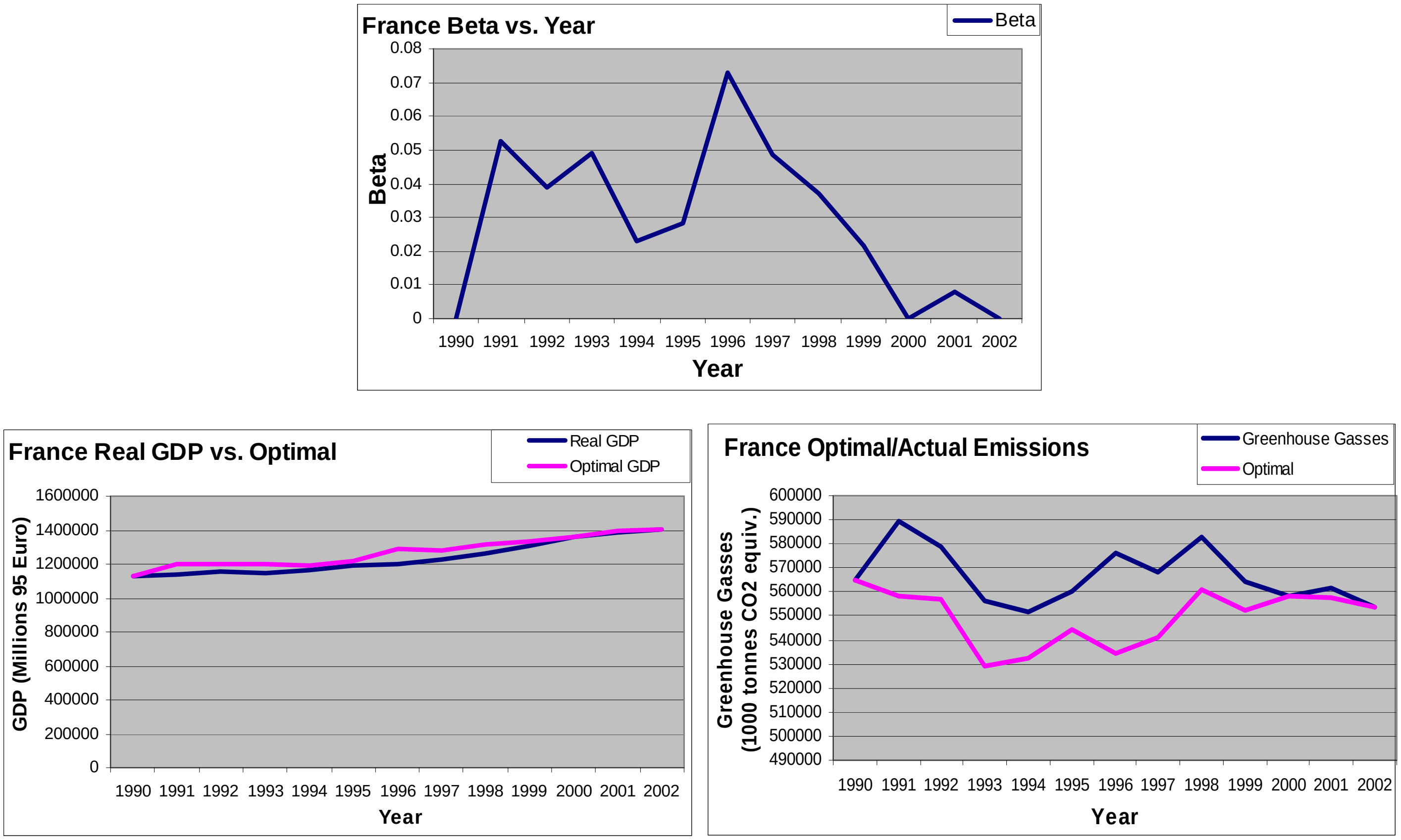

Figure 37: France Beta vs. Year and Actual/Optimal GDP and Emissions [author's calculations]

The United Kingdom displays the largest beta values obtained over our European countries. The beta values peak in 1993 with a value of 18.48%. Further beta values span across the period of 1991 to 2001. The results show that significant gains in GDP could be made according to the model as well as reductions in greenhouse emissions. Overall, the average beta value over the period is calculated as 10.09%.

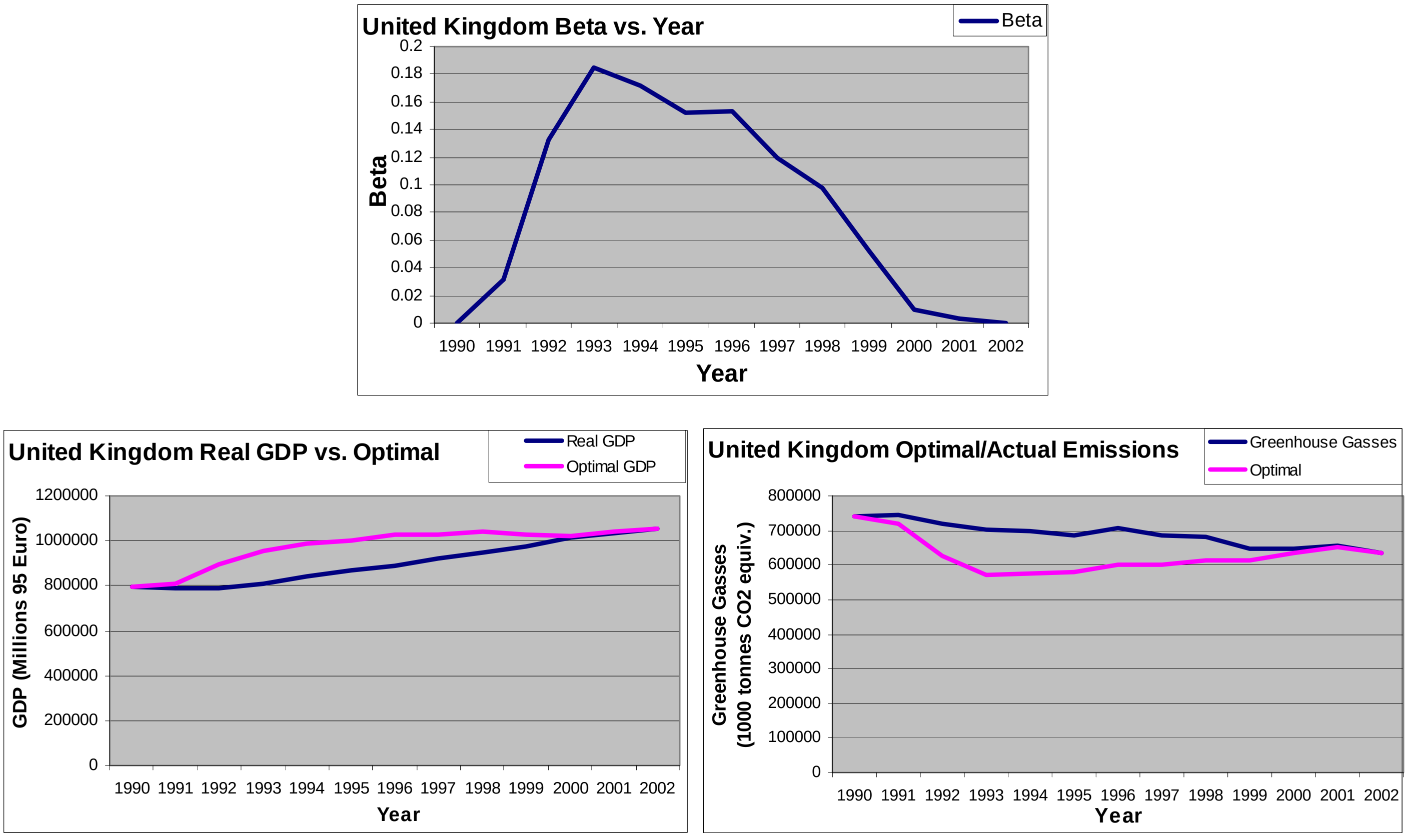

Figure 38: United Kingdom Beta vs. Year and Actual/Optimal GDP and Emissions [author's calculations]

4.8 Model 4: U.S. Energy Consumption to GDP and CO2 #2

While the third model looks at increasing GDP and decreasing CO2 and greenhouse gas emissions, we designed this fourth model to reduce only emissions while maintaining GDP. This is similar in ways to the first and second models but lets us consider the the GDP as well as the emissions as a product the multiple inputs.

4.8.1 Model Setup

- n = 44 – 44 years
- m = 5 – 5 inputs
- s = 2 – 2 outputs
- DMU_j - jth year
- x_{1j} - energy consumption from coal in the jth year
- x_{2j} - energy consumption from gas in the jth year
- x_{3j} - energy consumption from oil in the jth year
- x_{4j} - energy consumption from nuclear plants in the jth year
- x_{5j} - energy consumption from renewable sources in the jth year
- y_{1j} - U.S. GDP in the jth year
- y_{2j} - U.S. CO2 emissions in the jth year
- $G = \{1\}$

Years range from 1959 (n=1) to 2002 (n=44)

4.8.2 Results

The results in Figure 39 and in Appendix data table B.4.1.1 show a similar pattern to the results for the United States using the third DEA model. From 1959 to 1972, carbon dioxide emissions could either not be minimized or were minimized slightly in 1961, 1963, 1964, and 1970. Afterwards, there is a long period starting in 1973 that lasts until 2000 where we find varying degrees of theta values. There are two distinguishable points in which we obtain our lowest theta. In 1977 and 1988, the thetas of 71.22% and 77.38% respectively were found. The values indicate that optimal emissions were, at their best, 71.22% of the actual carbon dioxide emissions.

For the United States and in fact the European countries as well, the DEA model finds that by not trying to increase the GDP, greater reductions in emissions can be made. Between the periods of 1973 to 2000 for both the third and fourth DEA models we calculated that the average amount of the optimal emissions were 93.52% and 84.96% of the actual.

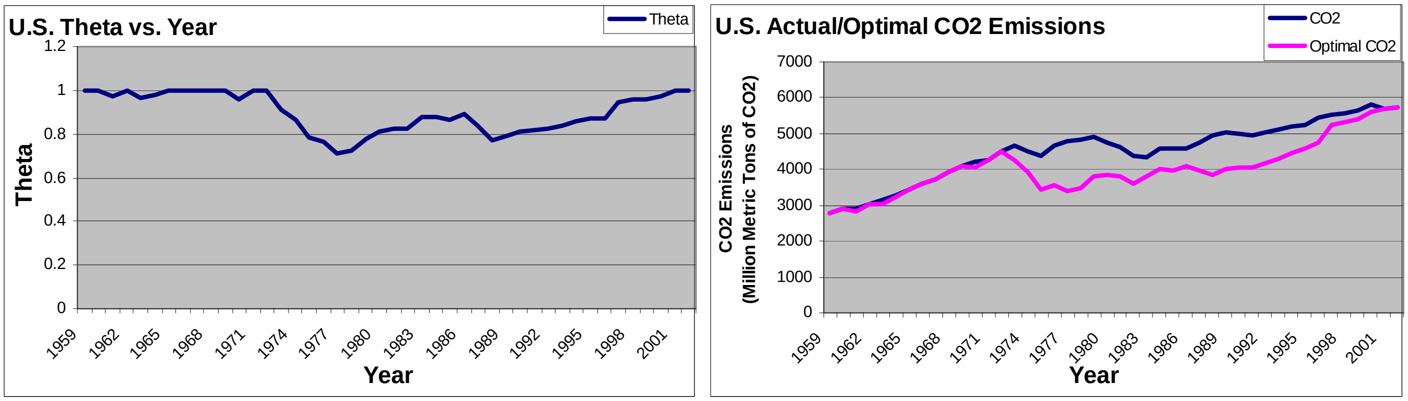

Figure 39: Theta vs. Year and Actual/Optimal CO2 emissions [author's calculations]

4.9 Model 4: European Energy Consumption to GDP and CO2 #2

The fourth model was also used to analyze Germany, France, and the United Kingdom’s energy data and determine the possibility of reducing CO2 emissions while maintaining a given GDP.

4.9.1 Model Setup

- n = 38 – 38 years
- m = 5 – 5 inputs
- s = 2 – 2 outputs
- DMU_j - jth year
- x_{1j} - energy consumption from solid in the jth year
- x_{2j} - energy consumption from gas in the jth year
- x_{3j} - energy consumption from oil in the jth year
- x_{4j} - energy consumption from nuclear plants in the jth year
- x_{5j} - energy consumption from renewable sources in the jth year
- y_{1j} - European (Germany, France, United Kingdom) GDP’s in the jth year
- y_{2j} - European (Germany, France, United Kingdom) greenhouse gasses in the jth year
- $G = \{1\}$

Years range from (Germany) 1991 (n=1) to U.K. 2002 (n=38)

4.9.2 Results

The results shown in Figure 40 as well as Appendix data table B.4.2.1 report that using this DEA model in the years of 1993, 1996, 1997, and 2001 Germany could have made reductions in greenhouse gas emissions. The largest minimization can be observed in 1997 where optimal emissions were calculated to be 90.55% of the actual emissions. The theta values also point to a larger amount of reduction of greenhouse gas when compared to the reductions made possible in the third model.

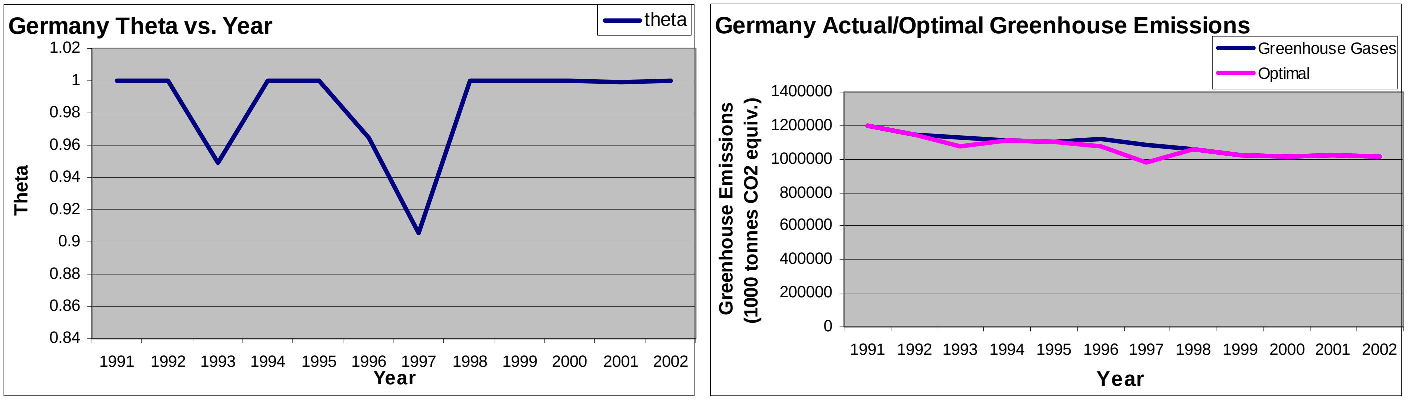

Figure 40: Germany Theta vs. Year and Actual/Optimal Emissions [author's calculations]

A much different picture is painted for France's greenhouse gas emissions which for most years could have been reduced by over 10% when evaluated with this model as shown in Figure 41. The only year besides the first and last year of data when minimization was not possible was in 2000. Over the period studied, the optimal greenhouse gas emissions were calculated as being on average 9.68% less than the actual.

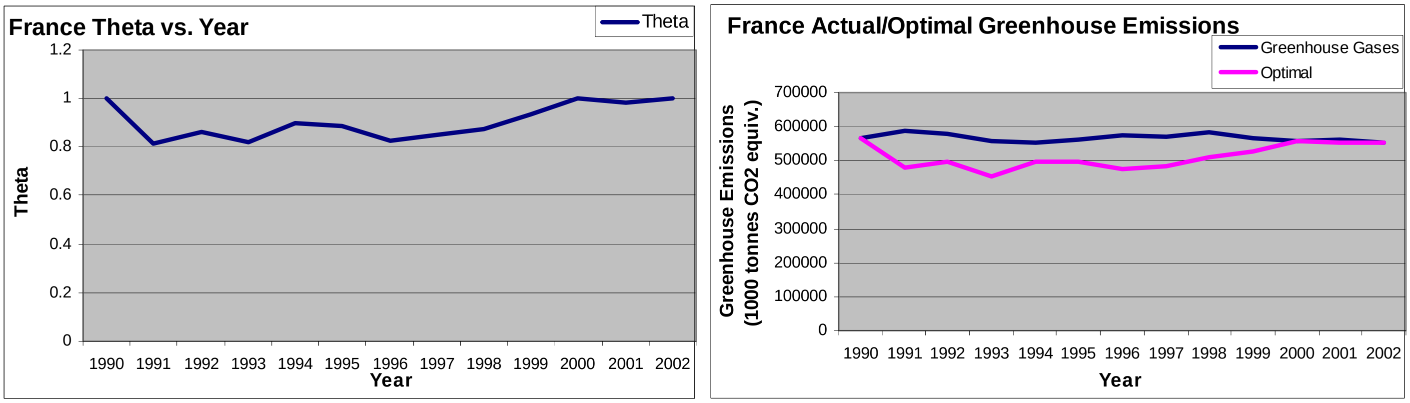

Figure 41: France Theta vs. Year and Actual/Optimal Emissions [author's calculations]

According to this model, the United Kingdom's emissions could have been drastically reduced when compared to the other countries (Figure 42). The DEA program suggests that 1992 could have had the greatest reductions at 35.68% less than the actual emissions of that year. Over the period of time an average reduction of 17.77% was reported by this DEA program.

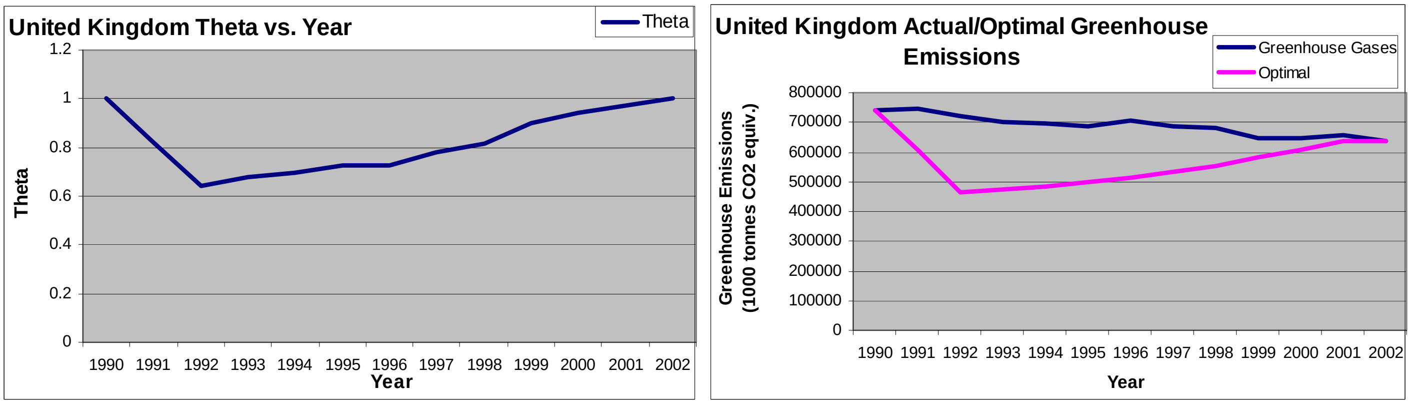

Figure 42: United Kingdom Theta vs. Year and Actual/Optimal Emissions [author's calculations]

5 Conclusions and Recommendations

The world is faced with the problem of dealing with a finite supply of fossil fuels, especially in petroleum production which is expected to peak in the near future. Pressures to decrease or end the use of nuclear power due to the large scale consequences of a nuclear disaster caused by either human error or terrorism have made policy makers rethink its merits in the future of energy use. At the same time, global greenhouse gas emissions continue to increase and are causes for environmental and health concerns. The utilization of renewable energies is currently the most viable means of addressing these problems.

The scope of our analysis uses historical data for the economic indicators, real GDP, carbon dioxide and greenhouse gas emissions, and consumption of major energy sources to obtain insights into the issues of potential energy conservations and emission reductions while maintaining the standard of living, as measured by real GDP.

We analyzed potential energy conservation and emissions reductions for the United States as well as Germany, France, and the United Kingdom, so we could draw insights from the comparative performance of these developed countries. We adopted DEA to investigate these issues. The commonly used decomposition method in the energy literature uses overall energy consumption to measure energy intensities. We extend this line of research by explicitly taking into account the different sources of energy and allow substitutability between the energy sources. In this sense our measure of efficiency also takes into consideration the optimal proportions of different energy sources in defining and measuring efficiency.

The utilization of DEA in conjunction with our data yields many interesting results. Our first model is the basic (and commonly used) DEA model for input-oriented measure of efficiency which measures the proportional reduction in all inputs. While this model gives us an indication of possible energy conservation, in general the minimization of renewable energy is counterintuitive for decreasing reliance on fossil fuels as well as decreasing greenhouse gas emissions. This is why a modified DEA program, Model 2, was created to maintain the given levels of renewable energy and minimize the combination of other energy sources.

The first two DEA programs also shed light on things that simple analysis such as energy intensities do not. The best example would be the United States which experienced an oil crisis in the 1970's and 80's. The energy intensity over that period of time does not show anything out of the ordinary as there is a steady decrease. Looking at the DEA results though, we see things much differently as there are relatively large inefficiencies in oil use during the same period. Years before the oil efficiencies were much higher.

Another observation that is made across all countries is that for the most recent year(s) of data we see 100% efficiency. The reason for this is that during the recent present countries are at the forefront of technological advancement. It is hard to determine what will happen in future but depending on improvements in technology, these recent years that now appear to be 100% efficient may prove to actually not be.

Model 2 results show that the energy efficiency for gas and oil for the United States was 96.41% and 95.04% respectively as compared to 97.23% and 98.73% for Germany and 97.73% and 98.91% for France. While the Unites States seems less efficient than these countries, its performance is better than the United Kingdom with a gas and oil efficiencies of 88.32% and 88.51% respectively. Germany's average efficiency across solid, gas, oil, and renewable energy consumptions is 97.23%, France is 98.42%, and the United Kingdom is 83.30%[2]. Over the period of 1985 to 2002, similarly to the Europe data, the United States' average efficiency across the oil, gas, coal, and nuclear sector is calculated to be 96.01%.

The Model 3 and 4 program results show that larger reductions in emissions were possible when not trying to increase GDP output. Using the third model, optimal United States carbon dioxide emissions averaged 4.22% below actual emissions. Germany and France averaged an average optimal reduction of 0.57% and 2.42% respectively. The United Kingdom reductions averaged 8.54%. Model 4 results show average reductions of 10.17% for the United States. Average reductions for Germany, France, and the United Kingdom were 1.51%, 9.68%, and 17.77% respectively.

Interpreting the results there are some recommendations for future work and likewise for policy. It should be noted that we also have to make some assumptions and

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[2] German results are from 1991 to 2002.

attempt to account for improvements in future technology since all results show that current efficiencies of energy use are 100% and that emissions are at optimal levels that cannot be reduced further.

Possibly the most important and informative work that could be done in the future would be to conduct a study with comparable units between the United States and European countries so that benchmarking between them could be made. This would paint a much clearer picture as to how the United States compares to other industrialized countries. Obtaining such comprehensive data for comparable data construction and for comparable time periods is difficult and expensive and hence was beyond the scope of our project.

We believe that within the United States, more policy and more funding aimed to increase research and development of alternative and renewable energies should be in place. Looking at the actual and optimal energy consumptions before 1973, we see very high efficiencies. Afterwards, when the oil crisis takes place, the efficiency is much lower. What can be interpreted from this is that before the oil crisis, technology was sufficient based on our nation's economic status and energy needs. Once the oil prices were driven up other combinations of energy should have been used for optimal efficiency, but technology was not sufficient for this to happen. Looking at the DEA program results, we see that in recent years, the United States' efficiency is following a similar path to the pre-1973 results. If another oil shock were to occur again, a similar increase in inefficiency could occur, and a way to counteract this from happening is having technologies available that could be used to handle such a scenario.

It is also recommended that the United States rethink its stance regarding the Kyoto Protocol of which it is not obliged to presently. The actual emissions of greenhouse gasses for the European countries have all seen reduction across their studied time periods and are expected to most likely meet their Kyoto Protocol targets, yet the United States continues to see growth in carbon dioxide emissions. Based on the European countries' policies, it appears that wind turbines will have a significant impact on their future energy needs. This has been especially true in Germany which has applied wind energy in policy since the 1980's. The United States, with its thousands of miles of coastline and usable land, has the ability and means to erect numerous large scale wind farms. The wind sector is clearly an area that the United States falls short compared to Europe especially considering that a country the size of Texas has around 125% more wind power installed than the whole United States.

The United States cited that the Kyoto Protocol would hurt the economy if it were to be ratified (Cameron et. al 2001). If this is one of the major contributing reasons to the United States' resistance with the Kyoto Protocol, then we believe that the United States should propose a policy similar in terms to the Kyoto Protocol that is more economically feasible.

At the state level, there are already a number of states and cities that have policies that require certain percentages of energy must be purchased from renewable sources annually. These policies are similar to the European White Papers which require that a certain percentage of energy purchased is renewable. We recommend that if no attempts were made to ratify the Kyoto Protocol or present a national policy similar to it, then a national policy similar to the White Pages could act as a framework around which additional goals such as greenhouse gas emission reductions could be built.

Germany has shown that with dedicated policies that are on the forefront of greenhouse gas emission reduction and renewable energy use, it is possible to have a successful economy while having high energy efficiencies. The same may be said about France, although they have a heavier reliance on nuclear power which presents many concerns.

What is interesting however, are the results we see from the DEA programs regarding the United Kingdom. All results point to the United Kingdom having the highest inefficiencies with respect to optimal consumptions of energy, greenhouse gas emissions, and GDP. Yet, the United Kingdom has been reducing its energy intensity, increasing GDP, and is on target for the 12.5% reduction of greenhouse gasses and 20% reduction of carbon dioxide that have been set. Therefore, future work may want to study which countries and years are setting the benchmarks for the United Kingdom.

The DEA method sheds new light on energy analysis that is not necessarily apparent using simple methods such as energy intensity and decomposition. It shows how in the past energy efficiency has been less than ideal. There are some issues such as the assumption that substitutability is possible between energy sources as well as a lack of results regarding the efficiency of the most recent years. Yet the method definitely does have its merits and proves to be a valuable tool with which past energy and emissions data can be analyzed and comparisons between countries can be made.

References

Aitken, Donald. (2005). Germany Launches Its Transition To All Renewables. *Solar Today Magazine.*

Alberta Environment (1993). *Focus on Acid Deposition* (Online). Retrieved April 21, 2005, from http://www3.gov.ab.ca/env/resedu/edu/focuson/AcidDep.pdf

American Public Power Association (2005). *Issue Brief: Renewable Energy Production Incentive (REPI)* (Online). Retrieved April 25, 2005, from http://appanet.org/files/PDFs/REPI.pdf

Anderson, T.R. (2000).Bonds or Ruth: Determining the Most Dominant Baseball Batter Using DEA. In Cooper, W. W., Seiford, L. M., Zhu, J. (Eds.) *Handbook on Data Envelopment Analysis*. Boston: Kluwer Academic Publishers.

Ang, B.W., Zhang, F.Q. (1999). Inter-regional comparisons of energy-related CO2 emissions using the decomposition technique. *Energy - The International Journal, 24*(4), 297-305.

Ang, B.W. (2004). Decomposition analysis for policymaking in energy: which is the preferred method? *Energy Policy, 32*(9) 1131-1139.

Ayres, J.G. (1998). Health Effects of Gaseous Air Pollutants. In Hester, R.E., Harrison, R.M. (Eds.) *Air Pollution and Health. Issues in Environmental Science and Technology, 10*, UK: The Royal Society of Chemistry.

Bentley, R.W. (2000). Global Oil & Gas: An Overview.*Energy Policy, 30,* 189-205.

Boole, H. J. Seiler, W., Bolin, B. (1986). *Other Greenhouse Gases and Aerosols*. In Bolin, B. et al (Ed.). *The Greenhouse Effect, Climatic Change, and Ecosystems: A Synthesis of Present Knowledge*. (pp. 157-205). New York: John Wiley & Sons.

Boulesteix, C. (2004). Energy Profile - France 2004. *Industry Canada* (Online) Retrieved April 16, 2005, from http://strategis.ic.gc.ca/epic/internet/inimr-ri.nsf/fr/gr124727f.html

Brown, M. et al. (1998). Engineering-Economic Studies of Energy Technologies to Reduce Greenhouse Gas Emissions: Opportunities and Challanges. *Annual Review of Energy and the Environment, 23,* 287-385.

California Energy Commission (1994). *California Energy Policy* (Online). Retrieved April 2, 2005, from http://www.energy.ca.gov/reports/BReport94.html

Cameron, J., Pugliese, M.,Wilder, M. (2001). From Kyoto to Bonn: Implications and Opportunities for Renewable Energy. *Renewable Energy World,* 43-55.

Campbell, C. J. (1991). *The golden century of oil 1950-2050*. Dordrecht/Boston/London: Kluwer Acad. Publ.

Campbell, C. J., and Laherrere, J. H. (1998) The end of cheap oil. *Scientific American, 278*(3), 78-83.

Cannon, J. S. (2004) The Transportation Boom in Asia: Crisis and Opportunity for the United States. *Inform*.

Chambers, R.G., Chung Y., Färe, R. (1996). Benefit and distance functions. *Journal of Economic Theory, 70*, 407-419.

Charnes, A., Cooper. W. W., Rhodes, E. (1978). Measuring the efficiency of decision making units. *European Journal of Operational Research, 2,* 429-444.

Charnes, A., W. W. Cooper, et al. (1989). Using DEA to evaluate relative efficiencies in the economic performance of Chinese cities. *Soci-Economic Planning Sciences*.

Chilingerian, J.A., Sherman, H.D. (2000).Health Care Applications. In Cooper, W. W., Seiford, L. M., Zhu, J. (Eds.) *Handbook on Data Envelopment Analysis*. Boston: Kluwer Academic Publishers.

Chung, Y., Färe, R. (1995). Productivity and Undesirable Outputs: A Directional Distance Function Approach. *Discussion Paper Series* No. 95-24.

Clement R., Kagel R. (1990). *Emissions From Combustion Processes: Origin, Measurement, Control*. Boca Raton: Lewis Publishers.

Cooper, W. W., Seiford, L. M., Zhu, J. (2000). Data Envelopment Analysis: History, Models and Interpretations. In Cooper, W. W., Seiford, L. M., Zhu, J. (Eds.) *Handbook on Data Envelopment Analysis*. Boston: Kluwer Academic Publishers.

Deudney, D., Flavin, C. (1983). *Renewable Energy: The Power to Choose*. New York: W. W. Norton & Company.

Dooley, JJ., Runci, PJ. (1999). *Energy Research and Development in Germany.* PNNL-12207. Washington, DC.

Douglass-Westwood Ltd. (2002). Analyst Claim Early Peak in World Oil Production. *Oil & Gas Journal, 100*(34), 33-34.

Driscoll C.T., Lawrence G.B., Bulger A.J., Butler T.J., Cronan C.S., Eagar C. et al. (2001). Acidic deposition in the northeastern U.S.: sources and inputs, ecosystem effects, and management strategies. *BioScience, 51*, 180–198.

Duncan, R. C. (1997). The world petroleum life-cycle: encircling the production peak: *Proc. 13th SSI/Princeton Conf. Space Manufacturing: Space Studies Inst.*, Princeton, 267-274.

Duncan, R. C., & Youngquist, W. (1999). Encircling the Peak of World Oil Production. *Natural Resources Research, 8*(3).

Egenhofer, C. (2005). Is the Kyoto Protocol ready for the dump? *European Voice* (Online) Retrieved April 16, 2005, from http://www.ceps.be/Article.php?article_id=323&

European Renewable Energy Council (2004). *Renewable Energy Policy Review; France* (Online). Retrieved April 21, 2005, from http://www.erec-renewables.org/documents/RES_in_EUandCC/Policy_reviews/EU_15/France_policy_final.pdf

European Renewable Energy Council (2004). *Renewable Energy Policy Review; United Kingdom* (Online). Retrieved April 21, 2005, from http://www.erec-renewables.org/documents/RES_in_EUandCC/Policy_reviews/EU_15/UK_policy_final.pdf

Fullerton, D., West, S. (1999). Can Taxes on Cars and on Gasoline Mimic an Unavailable Tax on Emissions?. *NBER Working Papers. 7059*.

The German Federal Ministry for the Environment (n.d.). Nature Conservation and Nuclear Safety. *Climate and Energy* (Online), Retrieved April 16, 2005, from http://www.bmu.de/english/climate_and_energy/aktuell/35017.php

Hatfield, C. B. (1997). How long can oil supply grow? *Hubbert Center Newsletter*. #97/4

Howard, L.H., Miller, J.L. (1993). Fair pay for fair play: estimating equity in professional baseball with data envelopment analysis. *Academy of Management Journal, 26*(4), 882-894.

Hubbert, M. K., 1967, Degree of advancement of petroleum exploration in United States. *American Association of Petroleum Geologists Bulletin, 51*(11), 2207-2227.

Ivanhoe, L. F. (1997). Get ready for another oil shock! *The Futurist, 31*(1), 20-23.

Jenne, J., Cattell, R. (1983). Structural change and energy efficiency in industry. *Energy Economics, 5*(2), 114–123.

Keepin, W. et al. (1986). *Emission of CO_2 into the Atmosphere*. In Bolin, B. et al (Ed.). *The Greenhouse Effect, Climatic Change, and Ecosystems: A Synthesis of Present Knowledge*. (pp. 35-91). New York: John Wiley & Sons.

MacKenzie, J. J. (1996). Oil as a Finite Resource: When is Global Production Likely to Peak? *A Paper of the World Resources Institute,* Washington, D. C.

Marlay, R. (1984). Trends in industrial use of energy. *Science, 226,* 1277–1283.

McMichael, A. J., Haines, A. (1997). Global climate change: the potential effects on health. *British Medical Journal, 315,* 805-809.

New Mexico Center for Wildlife Law (n.d.) *Clean Air Act: Summary from Federal Wildlife Laws Handbook* (Online). Retrieved April 2, 2005, from http://ipl.unm.edu/cwl/fedbook/cleanair.html

Newton, D. E. (1993). *Global warming: a reference handbook*. Denver: ABC-Clio.

Ozkaynak, H., Spengler, J.D. (1985) Analysis of Health Effects Resulting from Population Exposures to Acid Precipitation Precursors. *Environmental Health Prospects, 63,* 45-55.

Paradi, J.S., Vela, S., Yanh, Z. (2000).Assessing Bank and Bank Branch Performance. In Cooper, W. W., Seiford, L. M., Zhu, J. (Eds.) *Handbook on Data Envelopment Analysis*. Boston: Kluwer Academic Publishers.

Ray, S. C. (2004). *Theory and Techniques for Economics and Operations Research.* Cambridge: Cambridge University Press.

Renewable Energy Policy Project (2000). *A Guide to the Clean Air Act* (Online). Retrieved April 2, 2005, from http://www.repp.org/repp_pubs/articles/issuebr15/02intCAA.htm

Rose, A., Casler, S. (1996). Input-Output Structural Decomposition Analysis: A Critical Appraisal. *Economic Systems Research, 8*(1).

Ruggiero, J. (2000). Performance Evaluation in Education. In Cooper, W. W., Seiford, L. M., Zhu, J. (Eds.) *Handbook on Data Envelopment Analysis*. Boston: Kluwer Academic Publishers.

Smil, V. (2000). Energy in the Twentieth Century: Resources, Conversions, Costs, Uses, and Consequences.*Annual Review of Energy and the Environment, 25,* 21-51.

Smith, K. R. (1993). Fuel Combustion, Air Pollution Exposure, and Health: The Situation in Developing Countries. *Annual Review of Energy and the Environment, 18,* 529-566.

United Kingdom Department of Trade and Industry (2005). *Renewable Energy Policy* (Online). Retrieved April 16, 2005, from http://www.dti.gov.uk/renewables/ renew_2.htm

United Nations Framework Convention on Climate Change (n.d.). *Essential Background* (Online), Retrieved April 16, 2005, from http://unfccc.int/essential_background/items/2877.php

United Nations Framework Convention on Climate Change (2005). *UNFCCC Country Profile; France* (Online). Retrieved April 16, 2005, from http://unfccc.int/files/parties_and_observers/parties/annex_i/country_profiles/application/pdf/c-brief-ext_france_a1__ 24_feb.2005_.pdf

U.S. Department of Energy. (2004). *Nuclear Energy: Answers to Questions.* DOE/NE-0068.

U.S. Department of Energy. (n.d.). *Energy Sources* (Online). Retrieved January 29, 2005, from http://www.energy.gov/engine/content.do?BT_CODE=ENERGYSOURCES

U.S. Environmental Protection Agency. (2001). *The United States Experience with Economic Incentives for Protecting the Environment*. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency. (2002*). The EPA's Particulate Matter (PM) Health Effects Research Centers Program: A Mid-Course (2 ½ year) Report of Status, Progress, and Plans*. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency. (2004) *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2002*. Washington, DC: U.S. Government Printing Office.

U.S. Energy Information Administration (2004), *Annual Energy Review 2003* (Online). Retrieved April 21, 2005, from http://www.eia.doe.gov/emeu/aer/contents.html

U.S. Energy Information Administration (n.d.). *History of Energy in the United States*. (Online) Retrieved January 29, 2005, from http://www.eia.doe.gov/emeu/aer/eh/frame.html

Weber, W., Domazlicky, B. (2001). Productivity Growth and Pollution in State Manufacturing, *The Review of Economics and Statistics, 83*(1).

Working Group on Public Health and Fossil-Fuel Combustion (1997). *The Lancet, 350,* 1341-1349.

Appendices

A Data Sources

A.1 United States

Most of the U.S. data was retrieved from the Energy Information Administration website.

Source: Energy Information Administration
URL:
http://www.eia.doe.gov/

A.1.1 Energy Consumption

Source: EIA Annual Energy Review
URL:
http://www.eia.doe.gov/emeu/aer/overview.html
Tables:
Table 1.3: Energy Consumption by Source, 1949-2003

A.1.2 GDP

Source:
Economic Report of the President (2004). Washingtom, DC: U.S. Government Printing Office.
Tables:
Table B-2: Real gross domestic product, 1959-2004

A.1.3 CO2 Emissions

Source: EIA: Emissions of Greenhouse Gases in the United States
URL:
http://www.eia.doe.gov/oiaf/1605/ggrpt/index.html
Tables:
Table B1: Energy-Related Carbon Dioxide Emissions from the Residential and Commercial Sectors, by Fuel Type, 1949-2003
Table B2: Energy-Related Carbon Dioxide Emissions from the Industrial and Transportation Sectors, by Fuel Type, 1949-2003
Table B3: Total Energy-Related Carbon Dioxide Emissions by End-Use Sector, and the Electric Power Sector, by Fuel Type, 1949-2002

A.2 Europe

All European data used on this project was retrieved using the eurostat web utility.

Data Source: Eurostat
URL:
http://epp.eurostat.cec.eu.int/portal/page?_pageid=1090,1&_dad=portal&_schema=PORTAL

A.2.1 Energy Consumption

Eurostat Tables:

Supply, transformation, consumption – solid fuels – annual data
Supply, transformation, consumption – oil – annual data
Supply, transformation, consumption – gas – annual data
Supply, transformation - nuclear energy – annual data
Supply, transformation, consumption – renewables (hydro, wind, photovoltaic) – annual data
Supply, transformation, consumption – renewables (biofuels) – annual data
Supply, transformation, consumption – renewables and wastes (total, solar heat, biomass, geothermal, wastes) – annual data

A.2.2 GDP

Eurostat Tables:

GDP and main components - Constant prices

A.2.3 CO2 Emissions

Eurostat Tables:

Air pollutant/greenhouse gas

B DEA Results

B.1 Model 1

B.1.1 United States

B.1.1.1 Model 1: United States: Theta and Slacks

		Slack				
Year	Theta	Coal	Gas	Oil	Nuclear	Renew
1959	1	0	0	0	0	0
1960	1	0	0	0	0	0
1961	0.990065	0	0.123371	0.310505	0	0
1962	1	0	0	0	0	0
1963	0.986064	0	0.128148	0.547395	0	0
1964	0.992718	0	0.350515	0.232295	0	0
1965	1	0	0	0	0	0
1966	1	0	0	0	0	0
1967	1	0	0	0	0	0
1968	1	0	0	0	0	0
1969	1	0	0	0	0	0
1970	0.990426	0	0.849908	0.641476	0	0
1971	1	0	0	0	0	0
1972	1	0	0	0	0	0
1973	0.976746	0	0.056737	3.39521	0	0

1974	0.946152	0	0	1.243062	0	0.351009
1975	0.897637	0	0	2.319227	0	0.463132
1976	0.886359	0	0	3.845311	0	0.34833
1977	0.872923	0	0.748697	7.237335	0	0
1978	0.889152	0	0.595949	7.723769	0	0.62724
1979	0.889487	0	0	4.723416	0	0.470429
1980	0.88508	0	0	2.550333	0	0.767346
1981	0.874272	0	0	0.957287	0	0.725962
1982	0.87686	0	0	1.1477	0	1.393052
1983	0.919123	0	0	0.611366	0	1.803841
1984	0.911757	0.179972	0	0	0	1.508385
1985	0.913786	0.638998	0	0.467054	0	1.208333
1986	0.947952	1.156592	0	3.381686	0	1.590736
1987	0.913225	0.861146	0	2.224673	0	0.867093
1988	0.858552	0.590433	0	1.936938	0	0.421614
1989	0.861782	0	0	0.374275	0	0.885282
1990	0.842768	0	0	0.017819	0	0.755512
1991	0.830418	0	0.881322	0	0	0.839593
1992	0.848247	0	1.042001	0	0	0.561589
1993	0.867796	0.320457	1.355548	0	0	0.75542
1994	0.873765	0	1.411803	0	0	0.550555
1995	0.874899	0.02822	2.520706	0	0.021439	1.07663
1996	0.889005	0.262393	2.200744	0	0	1.356919
1997	0.953138	0.683591	1.867313	0	0	1.366061
1998	0.952517	0.398171	1.315937	0	0	0.749123
1999	0.957179	0	1.444316	0.676623	0	0.706257
2000	0.96214	0.2743	1.726971	0	0.024739	0.109158
2001	1	0	0	0	0	0
2002	1	0	0	0	0	0
2003	1	0	0	0	0	0

B.1.1.2 Model 1: United States: Actual and Optimal Consumption

	Actual					**Optimal**				
Year	**Coal**	**Gas**	**Oil**	**Nuclear**	**Renew**	**Coal**	**Gas**	**Oil**	**Nuclear**	**Renew**
1959	9.510	11.717	19.323	0.002	2.901	9.510	11.717	19.323	0.002	2.901
1960	9.832	12.385	19.919	0.006	2.929	9.832	12.385	19.919	0.006	2.929
1961	9.615	12.926	20.216	0.020	2.953	9.519	12.674	19.705	0.020	2.924
1962	9.900	13.731	21.049	0.026	3.119	9.900	13.731	21.049	0.026	3.119
1963	10.406	14.403	21.701	0.038	3.098	10.261	14.074	20.851	0.037	3.055
1964	10.954	15.288	22.301	0.040	3.228	10.874	14.826	21.906	0.040	3.204
1965	11.563	15.769	23.246	0.043	3.398	11.563	15.769	23.246	0.043	3.398
1966	12.118	16.995	24.401	0.064	3.435	12.118	16.995	24.401	0.064	3.435
1967	11.899	17.945	25.284	0.088	3.694	11.899	17.945	25.284	0.088	3.694
1968	12.314	19.210	26.979	0.142	3.778	12.314	19.210	26.979	0.142	3.778
1969	12.346	20.678	28.338	0.154	4.102	12.346	20.678	28.338	0.154	4.102
1970	12.207	21.795	29.521	0.239	4.076	12.090	20.736	28.597	0.237	4.037
1971	11.565	22.469	30.561	0.413	4.268	11.565	22.469	30.561	0.413	4.268
1972	12.051	22.698	32.947	0.584	4.398	12.051	22.698	32.947	0.584	4.398
1973	12.964	22.512	34.840	0.910	4.433	12.663	21.932	30.635	0.889	4.330

1974	12.719	21.732	33.455	1.272	4.769	12.034	20.562	30.410	1.204	4.161
1975	12.677	19.948	32.731	1.900	4.723	11.379	17.906	27.061	1.706	3.776
1976	13.584	20.345	35.175	2.111	4.768	12.040	18.033	27.332	1.871	3.878
1977	13.937	19.931	37.122	2.702	4.249	12.166	16.650	25.167	2.359	3.709
1978	13.891	20.000	37.965	3.024	5.039	12.351	17.187	26.033	2.689	3.853
1979	15.103	20.666	37.123	2.776	5.166	13.434	18.382	28.297	2.469	4.125
1980	15.388	20.394	34.202	2.739	5.494	13.620	18.050	27.721	2.424	4.095
1981	15.892	19.928	31.931	3.008	5.471	13.894	17.422	26.959	2.630	4.057
1982	15.300	18.505	30.232	3.131	5.985	13.416	16.226	25.362	2.745	3.855
1983	15.878	17.357	30.054	3.203	6.488	14.594	15.953	27.012	2.944	4.159
1984	17.060	18.507	31.051	3.553	6.431	15.375	16.874	28.311	3.239	4.355
1985	17.465	17.834	30.922	4.076	6.033	15.320	16.296	27.789	3.725	4.305
1986	17.243	16.708	32.196	4.380	6.132	15.189	15.838	27.139	4.152	4.222
1987	18.017	17.744	32.865	4.754	5.687	15.592	16.204	27.788	4.341	4.326
1988	18.886	18.552	34.222	5.587	5.489	15.624	15.928	27.444	4.797	4.291
1989	19.100	19.712	34.211	5.602	6.294	16.460	16.987	29.108	4.828	4.539
1990	19.178	19.730	33.553	6.104	6.133	16.163	16.628	28.260	5.144	4.413
1991	19.002	20.149	32.845	6.422	6.158	15.780	15.851	27.275	5.333	4.274
1992	19.157	20.835	33.527	6.479	5.907	16.250	16.631	28.439	5.496	4.449
1993	19.862	21.351	33.841	6.410	6.156	16.916	17.173	29.367	5.563	4.587
1994	19.967	21.842	34.670	6.694	6.065	17.446	17.673	30.293	5.849	4.749
1995	20.150	22.784	34.553	7.075	6.669	17.601	17.413	30.230	6.168	4.758
1996	21.025	23.197	35.757	7.087	7.137	18.429	18.422	31.788	6.300	4.988
1997	21.491	23.329	36.266	6.597	7.075	19.800	20.368	34.567	6.288	5.377
1998	21.723	22.936	36.934	7.068	6.561	20.293	20.531	35.180	6.732	5.500
1999	21.681	23.010	37.960	7.610	6.599	20.753	20.580	35.658	7.284	5.610
2000	22.645	23.916	38.404	7.862	6.158	21.513	21.284	36.950	7.540	5.816
2001	21.981	22.906	38.333	8.033	5.286	21.981	22.906	38.333	8.033	5.286
2002	22.041	23.662	38.401	8.143	5.963	22.041	23.662	38.401	8.143	5.963
2003	22.758	22.507	39.074	7.973	6.150	22.758	22.507	39.074	7.973	6.150

B.1.1.3 Model 1: United States: Efficiencies

	Efficiency				
Year	**Coal**	**Gas**	**Oil**	**Nuclear**	**Renew**
1959	1	1	1	1	1
1960	1	1	1	1	1
1961	0.9900654	0.980521001	0.974706046	0.9900654	0.9900654
1962	1	1	1	1	1
1963	0.9860642	0.977166866	0.960839786	0.9860642	0.9860642
1964	0.9927175	0.969790027	0.982301142	0.9927175	0.9927175
1965	1	1	1	1	1
1966	1	1	1	1	1
1967	1	1	1	1	1
1968	1	1	1	1	1
1969	1	1	1	1	1
1970	0.9904259	0.951430332	0.968696436	0.9904259	0.9904259
1971	1	1	1	1	1
1972	1	1	1	1	1
1973	0.9767461	0.974225795	0.879294613	0.9767461	0.9767461
1974	0.9461522	0.9461522	0.90899596	0.9461522	0.872549977

1975	0.8976373	0.8976373	0.826780103	0.8976373	0.799578354
1976	0.886359	0.886359	0.777039577	0.886359	0.813303316
1977	0.8729227	0.835358263	0.677961898	0.8729227	0.8729227
1978	0.8891521	0.85935467	0.685707638	0.8891521	0.764674942
1979	0.8894869	0.8894869	0.762249988	0.8894869	0.798424356
1980	0.8850797	0.8850797	0.810512909	0.8850797	0.745409824
1981	0.8742722	0.8742722	0.844292347	0.8742722	0.741579402
1982	0.8768599	0.8768599	0.838896828	0.8768599	0.64410274
1983	0.9191225	0.9191225	0.898780249	0.9191225	0.641095219
1984	0.901207568	0.9117569	0.9117569	0.9117569	0.677207903
1985	0.87719876	0.9137861	0.898681851	0.9137861	0.713498929
1986	0.880875587	0.9479516	0.842917245	0.9479516	0.688536124
1987	0.865428991	0.9132253	0.845534048	0.9132253	0.760755966
1988	0.827288785	0.8585518	0.801952592	0.8585518	0.781741069
1989	0.8617815	0.8617815	0.850841294	0.8617815	0.721126654
1990	0.842768	0.842768	0.842236927	0.842768	0.71958005
1991	0.8304179	0.786677685	0.8304179	0.8304179	0.694076036
1992	0.8482472	0.798235163	0.8482472	0.8482472	0.753175472
1993	0.851661739	0.804307183	0.8677959	0.8677959	0.745083164
1994	0.8737647	0.809127606	0.8737647	0.8737647	0.782989003
1995	0.873498389	0.764263994	0.8748989	0.871868681	0.713460873
1996	0.876524962	0.794133081	0.889005	0.889005	0.698880424
1997	0.921330041	0.873095739	0.9531383	0.9531383	0.76005553
1998	0.934187224	0.895142419	0.9525167	0.9525167	0.83833848
1999	0.9571793	0.894410226	0.939354677	0.9571793	0.850154402
2000	0.950027368	0.889930528	0.9621404	0.95899372	0.944414125
2001	1	1	1	1	1
2002	1	1	1	1	1
2003	1	1	1	1	1

B.1.1.4 Model 1: United States: Benchmark Years / Lambdas

Year	Is Efficient	Times Used as Benchmark	Benchmark Years
1959	yes	10	1959
1960	yes	1	1960
1961	no	0	1962 1959 1965
1962	yes	4	1962
1963	no	0	1965 1962 1967
1964	no	0	1965 1962 1959
1965	yes	9	1965
1966	yes	6	1966
1967	yes	13	1967
1968	yes	4	1968
1969	yes	2	1969
1970	no	0	1968 1971 1969
1971	yes	7	1971
1972	yes	7	1972
1973	no	0	1971 1968 2003
1974	no	0	1972 2003 1967

1975	no	0	1972 2003 1967
1976	no	0	1972 2003 1967
1977	no	0	1971 2003 1968
1978	no	0	1971 2003
1979	no	0	1972 2003 1967
1980	no	0	1967 2003 1972
1981	no	0	1967 2003 1972
1982	no	0	1967 2003 1965
1983	no	0	1959 2003 1965
1984	no	0	1959 2003 1965
1985	no	0	1959 2003
1986	no	0	2003 1959
1987	no	0	2003 1959
1988	no	0	2003 1959
1989	no	0	2003 1959 1965
1990	no	0	2003 1965 1967
1991	no	0	2003 1966 1967
1992	no	0	2003 1971 1967
1993	no	0	2003 1966
1994	no	0	2003 1967 1971
1995	no	0	2003
1996	no	0	2003 1966
1997	no	0	2003 1966
1998	no	0	2003 1966
1999	no	0	2003 2002
2000	no	0	2003
2001	yes	1	2001
2002	yes	2	2002
2003	yes	29	2003

B.1.2 Europe[3]

B.1.2.1 Model 1: Europe: Theta and Slacks

	Year	Theta	Slack				
			Solid	**Gas**	**Oil**	**Nuclear**	**Renew**
Germany	1991	0.9968221	19229.455	0	0	0	89.669285
	1992	1	0	0	0	0	0
	1993	0.9754705	0	0	621.98805	544.87107	0
	1994	1	0	0	0	0	0
	1995	1	0	0	0	0	0
	1996	0.9787557	950.92714	0	0	0	0
	1997	0.9415194	0	0	1193.211	0	0
	1998	0.9704617	0	0	2800.3559	0	50.782828
	1999	1	0	0	0	0	0
	2000	0.9960024	1196.1714	0	0	1443.944	0
	2001	0.9940713	0	0	1690.7592	1044.9303	0

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[3] European Energy Consumption measurements are in thousand tons oil equivalent.

	2002	1	0	0	0	0	0
France	1985	0.9313176	872.93454	0	4419.1147	0	3030.5327
	1986	0.9230039	147.94131	0	3119.1932	0	1745.0951
	1987	0.9296247	0	0	2647.7321	0	1905.9829
	1988	0.9901172	0	0	3091.9279	0	843.58128
	1989	0.9880647	347.03608	0	568.06419	0	268.41963
	1990	1	0	0	0	0	0
	1991	0.9489835	1064.7373	0	0	0	2345.5941
	1992	0.9528319	0	0	0	0	1454.1956
	1993	0.9364009	0	0	0	171.64019	1281.6695
	1994	0.9775644	0	0	0	0	540.64959
	1995	0.9722446	0	0	0	1656.917	402.45316
	1996	0.9148112	0	0	0	0	738.41506
	1997	0.9510986	573.68088	0	0	0	33.842122
	1998	0.9540997	0	0	0	0	515.05217
	1999	0.9684986	0	0	0	0	570.77918
	2000	1	0	0	0	0	0
	2001	0.9633597	0	0	0	0	205.02239
	2002	1	0	0	0	0	0
Italy	1985	1	0	0	0	0	0
	1986	1	0	0	0	0	0
	1987	1	0	0	0	0	0
United Kingdom	1985	0.9359126	5609.7588	2808.3543	0	597.36656	0
	1986	0.9418363	3307.7941	674.66252	0	0	0
	1987	1	0	0	0	0	0
	1988	1	0	0	0	0	0
	1989	0.9957166	6833.1337	0	7723.2794	773.45861	0
	1990	0.9746002	4079.6582	0	4036.0972	0	0
	1991	0.9145485	2603.7551	0	907.69812	0	0
	1992	0.8098167	8578.5191	0	0	0	0
	1993	0.8228399	8069.4977	0	1032.5971	2299.8004	0
	1994	0.8043128	5621.1115	0	0	0	0
	1995	0.8308165	4847.4018	893.14244	0	0	0
	1996	0.8263597	3469.3093	3915.7167	0	0	0
	1997	0.8534153	3518.1479	1762.8148	0	193.12462	0
	1998	0.8844648	2632.2224	2279.9339	0	2563.5627	0
	1999	0.9074873	2173.0956	0	0	1321.5867	0
	2000	0.9865202	0	2607.4859	1360.984	0	0
	2001	0.9879176	867.17639	2524.1769	0	654.25068	0
	2002	1	0	0	0	0	0

B.1.2.2 Model 1: Europe: Actual and Optimal Consumption

		Actual					Optimal				
	Year	Solid	Gas	Oil	Nuclear	Renew	Solid	Gas	Oil	Nuclear	Renew
Germany	1991	54190	45729	100842	36128	2855	34788.33	45583.68	100521.53	36013.19	2756.26
	1992	39115	45618	102551	39000	2679	39115.00	45618.00	102551.00	39000.00	2679.00

	1993	33307	47590	104539	37543	2704	32490.00	46422.64	101352.72	36077.22	2637.67
	1994	29032	48035	101429	36842	2731	29032.00	48035.00	101429.00	36842.00	2731.00
	1995	25373	52595	102194	37322	2731	25373.00	52595.00	102194.00	37322.00	2731.00
	1996	23776	59831	104061	38925	2777	22319.97	58559.93	101850.30	38098.07	2718.00
	1997	22421	54753	103091	41114	4152	21109.81	51551.01	95868.97	38709.63	3909.19
	1998	19619	54797	102269	38912	4437	19039.49	53178.39	96447.79	37762.61	4255.16
	1999	17635	54875	98969	43853	4388	17635.00	54875.00	98969.00	43853.00	4388.00
	2000	18111	58006	95805	43750	4785	16842.43	57774.12	95422.01	42131.16	4765.87
	2001	17523	56697	98561	44189	4950	17419.11	56360.86	96285.90	42882.09	4920.65
	2002	16334	56455	94084	42522	5109	16334.00	56455.00	94084.00	42522.00	5109.00
France	1985	16149	22703	64674	57273	9937	14166.91	21143.70	55812.92	53339.35	6223.97
	1986	14824	22991	65617	64593	9590	13534.67	21220.78	57445.55	59619.59	7106.51
	1987	14303	23327	66226	67239	10118	13296.42	21685.36	58917.59	62507.04	7499.96
	1988	13521	22514	65670	70182	9373	13387.37	22291.50	61929.07	69488.41	8436.79
	1989	13839	23192	66082	76763	9678	13326.79	22915.20	64725.23	75846.81	9294.07
	1990	13420	23400	66489	79131	9728	13420.00	23400.00	66489.00	79131.00	9728.00
	1991	12761	26578	66306	82931	11630	11045.24	25222.08	62923.30	78700.15	8691.08
	1992	12227	26588	67791	83742	10965	11650.28	25333.89	64593.43	79792.05	8993.61
	1993	10464	26742	68402	91321	10788	9798.50	25041.23	64051.69	85341.43	8820.22
	1994	9440	26560	65685	89848	9507	9228.21	25964.11	64211.32	87832.21	8753.06
	1995	10051	27098	67134	93990	9752	9772.03	26345.88	65270.67	89724.35	9078.88
	1996	10105	29916	69906	97852	10415	9244.17	27367.49	63950.79	89516.11	8789.34
	1997	10227	29425	67922	98766	9584	9153.20	27986.08	64600.52	93936.20	9081.49
	1998	9798	30216	71070	96636	9913	9348.27	28829.08	67807.87	92200.38	8942.94
	1999	8960	31398	70390	98194	9699	8677.75	30408.92	68172.62	95100.75	8822.69
	2000	8969	31448	70104	107093	9859	8969.00	31448.00	70104.00	107093.00	9859.00
	2001	8146	33306	75431	108617	9766	7847.53	32085.66	72667.19	104637.24	9203.15
	2002	5219	32706	72808	112664	8889	5219.00	32706.00	72808.00	112664.00	8889.00
Italy	1985	7807	20738	52021	1980	748	7807.00	20738.00	52021.00	1980.00	748.00
	1986	6123	22017	52463	2437	748	6123.00	22017.00	52463.00	2437.00	748.00
	1987	6833	24461	53987	49	748	6833.00	24461.00	53987.00	49.00	748.00
United Kingdom	1985	23839	42617	50576	15981	292	16701.46	37077.43	47334.72	14359.45	273.29
	1986	23771	43035	53202	15687	292	19080.60	39857.26	50107.57	14774.59	275.02
	1987	21793	44723	52561	14981	292	21793.00	44723.00	52561.00	14981.00	292.00
	1988	21368	43195	55637	16337	292	21368.00	43195.00	55637.00	16337.00	292.00
	1989	18787	40446	57770	17731	385	11873.39	40272.75	49799.27	16881.59	383.35
	1990	17806	41564	57208	16574	405	13274.07	40508.28	51718.83	16153.02	394.71
	1991	18471	44123	57774	17292	417	14288.87	40352.62	51929.43	15814.37	381.37
	1992	17665	44252	57397	18745	617	5726.89	35836.01	46481.05	15180.01	499.66
	1993	16879	45092	59021	22086	595	5819.22	37103.50	47532.24	15873.44	489.59
	1994	15007	45705	59538	21204	835	6449.21	36761.12	47887.18	17054.65	671.60
	1995	13177	47147	58642	21249	881	6100.27	38277.36	48720.74	17654.02	731.95
	1996	11754	52648	60534	22180	892	6243.72	39590.47	50022.86	18328.66	737.11
	1997	11568	50604	59895	23248	865	6354.16	41423.41	51115.31	19647.07	738.20
	1998	10346	51530	59963	25831	798	6518.45	43296.54	53035.16	20283.05	705.80
	1999	10199	50398	61323	24540	631	7082.37	45735.54	55649.84	20948.15	572.62

2000	7774	51862	60669	21942	565	7669.21	48555.42	58490.21	21646.23	557.38
2001	9011	52985	60624	23182	573	8034.95	49820.64	59891.52	22247.66	566.08
2002	7133	50297	60212	22661	585	7133.00	50297.00	60212.00	22661.00	585.00

B.1.2.3 Model 1: Europe: Efficiencies

	Year	Efficiency of Solid	Efficiency of Gas	Efficiency of Oil	Efficiency of Nuclear	Efficiency of Renew
Germany	1991	0.6420	0.9968	0.9968	0.9968	0.9654
	1992	1.0000	1.0000	1.0000	1.0000	1.0000
	1993	0.9755	0.9755	0.9695	0.9610	0.9755
	1994	1.0000	1.0000	1.0000	1.0000	1.0000
	1995	1.0000	1.0000	1.0000	1.0000	1.0000
	1996	0.9388	0.9788	0.9788	0.9788	0.9788
	1997	0.9415	0.9415	0.9299	0.9415	0.9415
	1998	0.9705	0.9705	0.9431	0.9705	0.9590
	1999	1.0000	1.0000	1.0000	1.0000	1.0000
	2000	0.9300	0.9960	0.9960	0.9630	0.9960
	2001	0.9941	0.9941	0.9769	0.9704	0.9941
	2002	1.0000	1.0000	1.0000	1.0000	1.0000
France	1985	0.8773	0.9313	0.8630	0.9313	0.6263
	1986	0.9130	0.9230	0.8755	0.9230	0.7410
	1987	0.9296	0.9296	0.8896	0.9296	0.7412
	1988	0.9901	0.9901	0.9430	0.9901	0.9001
	1989	0.9630	0.9881	0.9795	0.9881	0.9603
	1990	1.0000	1.0000	1.0000	1.0000	1.0000
	1991	0.8655	0.9490	0.9490	0.9490	0.7473
	1992	0.9528	0.9528	0.9528	0.9528	0.8202
	1993	0.9364	0.9364	0.9364	0.9345	0.8176
	1994	0.9776	0.9776	0.9776	0.9776	0.9207
	1995	0.9722	0.9722	0.9722	0.9546	0.9310
	1996	0.9148	0.9148	0.9148	0.9148	0.8439
	1997	0.8950	0.9511	0.9511	0.9511	0.9476
	1998	0.9541	0.9541	0.9541	0.9541	0.9021
	1999	0.9685	0.9685	0.9685	0.9685	0.9096
	2000	1.0000	1.0000	1.0000	1.0000	1.0000
	2001	0.9634	0.9634	0.9634	0.9634	0.9424
	2002	1.0000	1.0000	1.0000	1.0000	1.0000
Italy	1985	1.0000	1.0000	1.0000	1.0000	1.0000
	1986	1.0000	1.0000	1.0000	1.0000	1.0000
	1987	1.0000	1.0000	1.0000	1.0000	1.0000
United Kingdom	1985	0.7006	0.8700	0.9359	0.8985	0.9359
	1986	0.8027	0.9262	0.9418	0.9418	0.9418
	1987	1.0000	1.0000	1.0000	1.0000	1.0000
	1988	1.0000	1.0000	1.0000	1.0000	1.0000
	1989	0.6320	0.9957	0.8620	0.9521	0.9957
	1990	0.7455	0.9746	0.9040	0.9746	0.9746

1991	0.7736	0.9145	0.8988	0.9145	0.9145
1992	0.3242	0.8098	0.8098	0.8098	0.8098
1993	0.3448	0.8228	0.8053	0.7187	0.8228
1994	0.4297	0.8043	0.8043	0.8043	0.8043
1995	0.4629	0.8119	0.8308	0.8308	0.8308
1996	0.5312	0.7520	0.8264	0.8264	0.8264
1997	0.5493	0.8186	0.8534	0.8451	0.8534
1998	0.6300	0.8402	0.8845	0.7852	0.8845
1999	0.6944	0.9075	0.9075	0.8536	0.9075
2000	0.9865	0.9362	0.9641	0.9865	0.9865
2001	0.8917	0.9403	0.9879	0.9597	0.9879
2002	1.0000	1.0000	1.0000	1.0000	1.0000

B.2 Model 2

B.2.1 United States

B.2.1.1 Model 2: United States: Theta and Slacks

		Slack				
Year	**Theta**	**Coal**	**Gas**	**Oil**	**Nuclear**	**Renew**
1959	1	0	0	0	0	0
1960	1	0	0	0	0	0
1961	0.987116	0	0	0.080934	0	0
1962	1	0	0	0	0	0
1963	0.983865	0	0.001274	0.259357	0	0
1964	0.991347	0	0.273551	0.06948	0	0
1965	1	0	0	0	0	0
1966	1	0	0	0	0	0
1967	1	0	0	0	0	0
1968	1	0	0	0	0	0
1969	1	0	0	0	0	0
1970	0.986017	0	0.598706	0.42374	0	0
1971	1	0	0	0	0	0
1972	1	0	0	0	0	0
1973	0.976879	0	0	1.859248	0	0
1974	0.990897	0	0.80129	3.218911	0	0
1975	0.974007	0	1.766227	4.97149	0	0
1976	0.93925	0	0.542164	5.060046	0	0
1977	0.890228	0	0	6.410382	0	0
1978	0.978091	0	2.864601	10.24798	0	0
1979	0.935512	0	0	4.937813	0	0
1980	0.941477	0	0	2.045563	0	0
1981	0.926408	0	0.041988	0	0	0
1982	0.976461	0	1.279944	0.943871	0	0
1983	1	0	0	0	0	0
1984	0.992323	0.352544	0.058459	0	0	0
1985	0.969906	0.666361	0	0	0	0
1986	1	0	0	0	0	0
1987	0.948431	0.118988	0	0	0	0
1988	0.895453	0	0	0.037914	0.107713	0
1989	0.952366	0	0	0	0.34124	0
1990	0.954692	0.109207	0	0	0.58627	0
1991	0.956559	0.081437	0	0	0.913268	0
1992	0.933898	0	0.124374	0	0.19423	0
1993	0.939655	0	0	0	0.358649	0
1994	0.941745	0	0.299072	0	0	0
1995	0.989902	0	0.712143	0	0.289908	0
1996	1	0	0	0	0	0
1997	1	0	0	0	0	0
1998	0.983258	0	0.124736	0	0.029319	0
1999	1	0	0	0	0	0

2000	0.97843	0.211892	1.321069	0	0.168401	0
2001	1	0	0	0	0	0
2002	1	0	0	0	0	0
2003	1	0	0	0	0	0

B.2.1.2 Model 2: United States: Actual and Optimal Consumption

	Actual					Optimal				
Year	Coal	Gas	Oil	Nuclear	Renew	Coal	Gas	Oil	Nuclear	Renew
1959	9.510	11.717	19.323	0.002	2.901	9.510	11.717	19.323	0.002	2.901
1960	9.832	12.385	19.919	0.006	2.929	9.832	12.385	19.919	0.006	2.929
1961	9.615	12.926	20.216	0.020	2.953	9.491	12.759	19.875	0.020	2.953
1962	9.900	13.731	21.049	0.026	3.119	9.900	13.731	21.049	0.026	3.119
1963	10.406	14.403	21.701	0.038	3.098	10.238	14.169	21.092	0.037	3.098
1964	10.954	15.288	22.301	0.040	3.228	10.859	14.882	22.039	0.040	3.228
1965	11.563	15.769	23.246	0.043	3.398	11.563	15.769	23.246	0.043	3.398
1966	12.118	16.995	24.401	0.064	3.435	12.118	16.995	24.401	0.064	3.435
1967	11.899	17.945	25.284	0.088	3.694	11.899	17.945	25.284	0.088	3.694
1968	12.314	19.210	26.979	0.142	3.778	12.314	19.210	26.979	0.142	3.778
1969	12.346	20.678	28.338	0.154	4.102	12.346	20.678	28.338	0.154	4.102
1970	12.207	21.795	29.521	0.239	4.076	12.036	20.892	28.684	0.236	4.076
1971	11.565	22.469	30.561	0.413	4.268	11.565	22.469	30.561	0.413	4.268
1972	12.051	22.698	32.947	0.584	4.398	12.051	22.698	32.947	0.584	4.398
1973	12.964	22.512	34.840	0.910	4.433	12.664	21.991	32.175	0.889	4.433
1974	12.719	21.732	33.455	1.272	4.769	12.603	20.733	29.932	1.260	4.769
1975	12.677	19.948	32.731	1.900	4.723	12.347	17.663	26.909	1.851	4.723
1976	13.584	20.345	35.175	2.111	4.768	12.759	18.567	27.978	1.983	4.768
1977	13.937	19.931	37.122	2.702	4.249	12.407	17.743	26.637	2.405	4.249
1978	13.891	20.000	37.965	3.024	5.039	13.587	16.697	26.885	2.958	5.039
1979	15.103	20.666	37.123	2.776	5.166	14.129	19.333	29.791	2.597	5.166
1980	15.388	20.394	34.202	2.739	5.494	14.487	19.200	30.155	2.579	5.494
1981	15.892	19.928	31.931	3.008	5.471	14.722	18.419	29.581	2.787	5.471
1982	15.300	18.505	30.232	3.131	5.985	14.940	16.789	28.576	3.057	5.985
1983	15.878	17.357	30.054	3.203	6.488	15.878	17.357	30.054	3.203	6.488
1984	17.060	18.507	31.051	3.553	6.431	16.576	18.306	30.813	3.526	6.431
1985	17.465	17.834	30.922	4.076	6.033	16.273	17.297	29.991	3.953	6.033
1986	17.243	16.708	32.196	4.380	6.132	17.243	16.708	32.196	4.380	6.132
1987	18.017	17.744	32.865	4.754	5.687	16.969	16.829	31.170	4.509	5.687
1988	18.886	18.552	34.222	5.587	5.489	16.912	16.612	30.606	4.895	5.489
1989	19.100	19.712	34.211	5.602	6.294	18.190	18.773	32.581	4.994	6.294
1990	19.178	19.730	33.553	6.104	6.133	18.200	18.836	32.033	5.241	6.133
1991	19.002	20.149	32.845	6.422	6.158	18.095	19.274	31.418	5.230	6.158
1992	19.157	20.835	33.527	6.479	5.907	17.891	19.333	31.311	5.856	5.907
1993	19.862	21.351	33.841	6.410	6.156	18.663	20.063	31.799	5.665	6.156
1994	19.967	21.842	34.670	6.694	6.065	18.804	20.271	32.650	6.304	6.065
1995	20.150	22.784	34.553	7.075	6.669	19.947	21.842	34.204	6.714	6.669
1996	21.025	23.197	35.757	7.087	7.137	21.025	23.197	35.757	7.087	7.137
1997	21.491	23.329	36.266	6.597	7.075	21.491	23.329	36.266	6.597	7.075
1998	21.723	22.936	36.934	7.068	6.561	21.359	22.427	36.316	6.920	6.561
1999	21.681	23.010	37.960	7.610	6.599	21.681	23.010	37.960	7.610	6.599
2000	22.645	23.916	38.404	7.862	6.158	21.945	22.079	37.576	7.524	6.158

2001	21.981	22.906	38.333	8.033	5.286	21.981	22.906	38.333	8.033	5.286
2002	22.041	23.662	38.401	8.143	5.963	22.041	23.662	38.401	8.143	5.963
2003	22.758	22.507	39.074	7.973	6.150	22.758	22.507	39.074	7.973	6.150

B.2.1.3 Model 2: United States: Efficiencies

Year	Efficiency				
	Coal	Gas	Oil	Nuclear	Renew
1959	1	1	1	1	1
1960	1	1	1	1	1
1961	0.9871163	0.9871163	0.983112828	0.9871163	1
1962	1	1	1	1	1
1963	0.9838652	0.983776725	0.97191382	0.9838652	1
1964	0.9913474	0.973454235	0.988231836	0.9913474	1
1965	1	1	1	1	1
1966	1	1	1	1	1
1967	1	1	1	1	1
1968	1	1	1	1	1
1969	1	1	1	1	1
1970	0.986017	0.958547131	0.97166316	0.986017	1
1971	1	1	1	1	1
1972	1	1	1	1	1
1973	0.9768786	0.9768786	0.923513267	0.9768786	1
1974	0.9908973	0.954025848	0.89468115	0.9908973	1
1975	0.9740072	0.885465627	0.82211786	0.9740072	1
1976	0.9392499	0.912601382	0.795396425	0.9392499	1
1977	0.8902284	0.8902284	0.717544221	0.8902284	1
1978	0.978091	0.83486097	0.708158773	0.978091	1
1979	0.9355116	0.9355116	0.802499381	0.9355116	1
1980	0.9414768	0.9414768	0.881668514	0.9414768	1
1981	0.926408	0.92430103	0.926408	0.926408	1
1982	0.9764606	0.907293121	0.945239678	0.9764606	1
1983	1	1	1	1	1
1984	0.971658029	0.989164244	0.992323	0.992323	1
1985	0.93175152	0.9699056	0.9699056	0.9699056	1
1986	1	1	1	1	1
1987	0.941826682	0.9484309	0.9484309	0.9484309	1
1988	0.8954533	0.8954533	0.894345416	0.876174134	1
1989	0.9523662	0.9523662	0.9523662	0.891452294	1
1990	0.948997205	0.9546916	0.9546916	0.858644745	1
1991	0.952273709	0.9565594	0.9565594	0.814350166	1
1992	0.9338975	0.927928035	0.9338975	0.903919077	1
1993	0.9396547	0.9396547	0.9396547	0.883703187	1
1994	0.9417445	0.928051995	0.9417445	0.9417445	1
1995	0.9899023	0.958646019	0.9899023	0.94892589	1
1996	1	1	1	1	1
1997	1	1	1	1	1
1998	0.9832578	0.977819376	0.9832578	0.97910971	1
1999	1	1	1	1	1
2000	0.969072688	0.923191947	0.9784298	0.957010187	1
2001	1	1	1	1	1
2002	1	1	1	1	1

2003	1	1	1	1	1

B.2.1.4 Model 2: United States: Benchmark Years / Lambdas

Year	Is Efficient	Times Used as Benchmark	Benchmark Years
1959	yes	3	1959
1960	yes	1	1960
1961	no	0	1962 1959 1965 1967
1962	yes	4	1962
1963	no	0	1965 1962 1967
1964	no	0	1965 1962 1967
1965	yes	5	1965
1966	yes	1	1966
1967	yes	5	1967
1968	yes	2	1968
1969	yes	3	1969
1970	no	0	1969 1971 1968
1971	yes	11	1971
1972	yes	2	1972
1973	no	0	1972 1967 2003 1983
1974	no	0	1971 1983 1999
1975	no	0	1971 1983 1999
1976	no	0	1971 1983 1999
1977	no	0	1971 1999 1983 2003
1978	no	0	1983 1971 1999
1979	no	0	1971 1983 1999 2003
1980	no	0	1983 1971 1999 2003
1981	no	0	1983 1971 2003 1969
1982	no	0	1983 1971 1999
1983	yes	21	1983
1984	no	0	1983 1997 1965
1985	no	0	1983 2003 1986 1997
1986	yes	8	1986
1987	no	0	1986 2003 1959 1983
1988	no	0	1986 2003 1983
1989	no	0	1986 1997 1983 2003
1990	no	0	1997 1986 2003
1991	no	0	1997 1986 1983
1992	no	0	1999 1996 1983
1993	no	0	1997 1986 2003 1983
1994	no	0	1999 1996 1997 1983
1995	no	0	1996 1999 1983
1996	yes	4	1996
1997	yes	10	1997
1998	no	0	1997 2003 1999
1999	yes	13	1999
2000	no	0	2003 1997

2001	yes	1	2001
2002	yes	1	2002
2003	yes	14	2003

B.2.2 Europe

B.2.2.1 Model 2: Europe: Theta and Slacks

			Slack				
	Year	**Theta**	**Solid**	**Gas**	**Oil**	**Nuclear**	**Renew**
Germany	1991	0.9991206	19778.601	0	0	0	0
	1992	1	0	0	0	0	0
	1993	0.9738465	0	0	1407.409	0	0
	1994	1	0	0	0	0	0
	1995	1	0	0	0	0	0
	1996	0.9754186	1125.7718	0	0	0	0
	1997	0.9403638	0	0	3019.2872	0	0
	1998	0.9720153	0	0	3183.1002	0	0
	1999	1	0	0	0	0	0
	2000	0.9944439	1227.5059	0	0	1372.3116	0
	2001	0.9928769	0	0	2143.5809	1264.488	0
	2002	1	0	0	0	0	0
France	1985	1	0	0	0	0	0
	1986	0.9708336	0	0	412.24202	0	0
	1987	0.9978614	342.03928	0	3155.178	0	0
	1988	1	0	0	0	0	0
	1989	0.9974321	437.90167	0	601.00568	0	0
	1990	1	0	0	0	0	0
	1991	1	0	0	0	0	0
	1992	0.9989202	0	0	1175.8027	0	0
	1993	1	0	0	0	0	0
	1994	0.9984435	0	0	0	614.93434	0
	1995	0.9913712	0	0	0	3725.1558	0
	1996	0.9658512	0	534.85527	0	2117.128	0
	1997	0.9592646	385.89444	0	0	0	0
	1998	0.972629	0	0	0	0	0
	1999	0.9887874	0	286.36392	0	0	0
	2000	1	0	0	0	0	0
	2001	0.973391	0	0	0	0	0
	2002	1	0	0	0	0	0
Italy	1985	1	0	0	0	0	0
	1986	1	0	0	0	0	0
	1987	1	0	0	0	0	0
United Kingdom	1985	0.9052498	7070.8462	2351.1976	0	65.5103	0
	1986	0.9262147	3939.5218	0	0	0	0
	1987	1	0	0	0	0	0
	1988	1	0	0	0	0	0

1989	0.9938655	6991.5297	0	7753.0034	736.94992	0
1990	0.964941	4631.6114	0	3867.2225	0	0
1991	0.8829622	4549.9945	0	433.38199	0	0
1992	0.7970295	8426.6718	387.68602	0	0	0
1993	0.7751525	6005.2957	0	0	0	0
1994	0.7889931	5794.8494	318.63216	0	0	0
1995	0.8183582	4574.673	1979.8963	0	0	0
1996	0.8138548	3209.2497	4997.9609	0	0	0
1997	0.8409471	3296.2504	2503.5751	0	0	0
1998	0.8750328	2480.8115	2781.8586	0	2367.1268	0
1999	0.8999539	2408.6088	0	0	1196.1944	0
2000	0.9735678	0	2173.6654	435.06494	0	0
2001	0.9784539	1592.8655	2337.056	0	419.38547	0
2002	1	0	0	0	0	0

B.2.2.2 Model 2: Europe: Actual and Optimal Consumption

		Actual				**Optimal**			
	Year	**Solid**	**Gas**	**Oil**	**Nuclear**	**Solid**	**Gas**	**Oil**	**Nuclear**
Germany	1991	54190	45729	100842	36128	34363.74	45688.79	100753.32	36096.23
	1992	39115	45618	102551	39000	39115.00	45618.00	102551.00	39000.00
	1993	33307	47590	104539	37543	32435.91	44937.95	101804.94	36561.12
	1994	29032	48035	101429	36842	29032.00	48035.00	101429.00	36842.00
	1995	25373	52595	102194	37322	25373.00	52595.00	102194.00	37322.00
	1996	23776	59831	104061	38925	22065.78	58360.27	101503.03	37968.17
	1997	22421	54753	103091	41114	21083.90	48468.45	96943.04	38662.12
	1998	19619	54797	102269	38912	19069.97	50080.42	99407.03	37823.06
	1999	17635	54875	98969	43853	17635.00	54875.00	98969.00	43853.00
	2000	18111	58006	95805	43750	16782.87	57683.71	95272.70	42134.61
	2001	17523	56697	98561	44189	17398.18	54149.56	97858.94	42609.75
	2002	16334	56455	94084	42522	16334.00	56455.00	94084.00	42522.00
France	1985	16149	22703	64674	57273	16149.00	22703.00	64674.00	57273.00
	1986	14824	22991	65617	64593	14391.64	21908.19	63703.19	62709.05
	1987	14303	23327	66226	67239	13930.37	20121.93	66084.37	67095.20
	1988	13521	22514	65670	70182	13521.00	22514.00	65670.00	70182.00
	1989	13839	23192	66082	76763	13365.56	22531.44	65912.31	76565.88
	1990	13420	23400	66489	79131	13420.00	23400.00	66489.00	79131.00
	1991	12761	26578	66306	82931	12761.00	26578.00	66306.00	82931.00
	1992	12227	26588	67791	83742	12213.80	25383.49	67717.80	83651.58
	1993	10464	26742	68402	91321	10464.00	26742.00	68402.00	91321.00
	1994	9440	26560	65685	89848	9425.31	26518.66	65582.76	89093.22
	1995	10051	27098	67134	93990	9964.27	26864.18	66554.71	89453.82
	1996	10105	29916	69906	97852	9759.93	28894.40	66983.94	92393.34
	1997	10227	29425	67922	98766	9424.50	28226.36	65155.17	94742.73
	1998	9798	30216	71070	96636	9529.82	29388.96	69124.74	93990.98
	1999	8960	31398	70390	98194	8859.54	31045.95	69314.38	97092.99
	2000	8969	31448	70104	107093	8969.00	31448.00	70104.00	107093.00
	2001	8146	33306	75431	108617	7929.24	32419.76	73423.86	105726.81
	2002	5219	32706	72808	112664	5219.00	32706.00	72808.00	112664.00

Italy	1985	7807	20738	52021	1980	7807	20738	52021	1980
	1986	6123	22017	52463	2437	6123	22017	52463	2437
	1987	6833	24461	53987	49	6833	24461	53987	49
United Kingdom	1985	23839	42617	50576	15981	14509.40	38579.03	43432.72	14401.29
	1986	23771	43035	53202	15687	18077.53	39859.65	49276.47	14529.53
	1987	21793	44723	52561	14981	21793.00	44723.00	52561.00	14981.00
	1988	21368	43195	55637	16337	21368.00	43195.00	55637.00	16337.00
	1989	18787	40446	57770	17731	11680.22	32444.88	57415.61	16885.28
	1990	17806	41564	57208	16574	12550.13	36239.59	55202.34	15992.93
	1991	18471	44123	57774	17292	11759.20	38525.56	51012.26	15268.18
	1992	17665	44252	57397	18745	5652.85	35270.15	45359.42	14940.32
	1993	16879	45092	59021	22086	7078.50	34953.18	45750.28	17120.02
	1994	15007	45705	59538	21204	6045.57	36060.93	46656.44	16729.81
	1995	13177	47147	58642	21249	6208.83	38583.13	46010.27	17389.29
	1996	11754	52648	60534	22180	6356.80	42847.83	44267.93	18051.30
	1997	11568	50604	59895	23248	6431.83	42555.29	47864.95	19550.34
	1998	10346	51530	59963	25831	6572.28	45090.44	49687.73	20235.85
	1999	10199	50398	61323	24540	6770.02	45355.88	55187.87	20888.67
	2000	7774	51862	60669	21942	7568.52	50056.11	56891.72	21362.02
	2001	9011	52985	60624	23182	7223.98	51843.38	56980.73	22263.13
	2002	7133	50297	60212	22661	7133.00	50297.00	60212.00	22661.00

B.2.2.3 Model 2: Europe: Efficiencies

	Year	Efficiency of Solid	Efficiency of Gas	Efficiency of Oil	Efficiency of Nuclear
Germany	1991	0.6341	0.9991	0.9991	0.9991
	1992	1.0000	1.0000	1.0000	1.0000
	1993	0.9738	0.9443	0.9738	0.9738
	1994	1.0000	1.0000	1.0000	1.0000
	1995	1.0000	1.0000	1.0000	1.0000
	1996	0.9281	0.9754	0.9754	0.9754
	1997	0.9404	0.8852	0.9404	0.9404
	1998	0.9720	0.9139	0.9720	0.9720
	1999	1.0000	1.0000	1.0000	1.0000
	2000	0.9267	0.9944	0.9944	0.9631
	2001	0.9929	0.9551	0.9929	0.9643
	2002	1.0000	1.0000	1.0000	1.0000
France	1985	1.0000	1.0000	1.0000	1.0000
	1986	0.9708	0.9529	0.9708	0.9708
	1987	0.9739	0.8626	0.9979	0.9979
	1988	1.0000	1.0000	1.0000	1.0000
	1989	0.9658	0.9715	0.9974	0.9974
	1990	1.0000	1.0000	1.0000	1.0000
	1991	1.0000	1.0000	1.0000	1.0000
	1992	0.9989	0.9547	0.9989	0.9989
	1993	1.0000	1.0000	1.0000	1.0000
	1994	0.9984	0.9984	0.9984	0.9916

	1995	0.9914	0.9914	0.9914	0.9517
	1996	0.9659	0.9659	0.9582	0.9442
	1997	0.9215	0.9593	0.9593	0.9593
	1998	0.9726	0.9726	0.9726	0.9726
	1999	0.9888	0.9888	0.9847	0.9888
	2000	1.0000	1.0000	1.0000	1.0000
	2001	0.9734	0.9734	0.9734	0.9734
	2002	1.0000	1.0000	1.0000	1.0000
Italy	1985	1.0000	1.0000	1.0000	1.0000
	1986	1.0000	1.0000	1.0000	1.0000
	1987	1.0000	1.0000	1.0000	1.0000
United Kingdom	1985	0.6086	0.9052	0.8588	0.9012
	1986	0.7605	0.9262	0.9262	0.9262
	1987	1.0000	1.0000	1.0000	1.0000
	1988	1.0000	1.0000	1.0000	1.0000
	1989	0.6217	0.8022	0.9939	0.9523
	1990	0.7048	0.8719	0.9649	0.9649
	1991	0.6366	0.8731	0.8830	0.8830
	1992	0.3200	0.7970	0.7903	0.7970
	1993	0.4194	0.7752	0.7752	0.7752
	1994	0.4029	0.7890	0.7836	0.7890
	1995	0.4712	0.8184	0.7846	0.8184
	1996	0.5408	0.8139	0.7313	0.8139
	1997	0.5560	0.8409	0.7991	0.8409
	1998	0.6352	0.8750	0.8286	0.7834
	1999	0.6638	0.9000	0.9000	0.8512
	2000	0.9736	0.9652	0.9377	0.9736
	2001	0.8017	0.9785	0.9399	0.9604
	2002	1.0000	1.0000	1.0000	1.0000

B.3 Model 3

B.3.1 United States

B.3.1.1 Model 3: United States: Beta, Actual and Optimal CO2 and GDP

Year	Beta	CO2 Actual	CO2 Optimal	Actual GDP	Optimal GDP
1959	0	2787.9	2787.9	2441.3	2441.3
1960	0	2889	2889	2501.8	2501.8
1961	0.0099	2910.1	2881.290301	2560	2585.343744
1962	0	3030.9	3030.9	2715.2	2715.2
1963	0.014077	3148.2	3103.883103	2834	2873.893935
1964	0.007336	3282.5	3249.501652	2998.6	3020.59743
1965	0	3426.6	3426.6	3191.1	3191.1
1966	0	3614.3	3614.3	3399.1	3399.1
1967	0	3708.8	3708.8	3484.6	3484.6
1968	0	3920.5	3920.5	3652.7	3652.7
1969	0	4090.4	4090.4	3765.4	3765.4
1970	0.009667	4212.9	4127.464933	3771.9	3808.361449
1971	0	4262.3	4262.3	3898.6	3898.6
1972	0	4487	4487	4105	4105
1973	0.020256	4685.7	4543.386145	4341.5	4429.441424
1974	0.047139	4521.3	4308.172248	4319.6	4523.219897
1975	0.08815	4389.1	4002.199079	4311.2	4691.234004
1976	0.102925	4654.8	4175.70471	4540.9	5008.272133
1977	0.12924	4793.8	4174.250726	4750.5	5364.453195
1978	0.110376	4843.5	4308.89336	5015	5568.536142
1979	0.098181	4904.7	4423.151159	5173.4	5681.330103
1980	0.087577	4735	4320.322432	5161.7	5613.746717
1981	0.07872	4615.6	4252.261353	5291.7	5708.261036
1982	0.075976	4373.4	4041.126999	5189.3	5583.561738
1983	0.039572	4338.5	4166.817312	5423.8	5638.430071
1984	0.044779	4581.3	4376.156258	5813.6	6073.924288
1985	0.042685	4569.9	4365.879046	6053.7	6312.099158
1986	0.001245	4580	4107.113088	6263.6	6271.397556
1987	0.038678	4738.6	4364.860418	6475.1	6725.54586
1988	0.096475	4955.5	4477.420615	6742.7	7393.198611
1989	0.08286	5034.8	4617.615969	6981.4	7559.879502
1990	0.092321	4988.6	4528.046462	7112.5	7769.134535
1991	0.100582	4941	4444.024338	7100.5	7814.682491
1992	0.093937	5042.7	4569.002377	7336.6	8025.780395
1993	0.079116	5128.6	4722.843631	7532.7	8128.660106
1994	0.071539	5204.7	4832.361487	7835.5	8396.043051
1995	0.070075	5255.8	4887.500341	8031.7	8594.520574
1996	0.064575	5443.7	5092.170895	8328.9	8866.742049
1997	0.019317	5510.9	5404.444843	8703.5	8871.62725
1998	0.015244	5552.5	5467.859911	9066.9	9205.112197
1999	0.013423	5630.5	5554.922362	9470.3	9597.41889

2000	0.009484	5798.6	5728.301111	9817	9910.103446
2001	0	5691.7	5691.7	9890.7	9890.7
2002	0	5729.3	5729.3	10074.8	10074.8

B.3.2 Europe [4]

B.3.2.1 Model 3: Europe: Beta, Actual and Optimal CO2 and GDP

	Year	Beta	CO2 Actual	CO2 Optimal	Actual GDP	Optimal GDP
Germany	1991	0	1196092.95	1196092.95	1785742	1785742
	1992	0	1145537.96	1145537.96	1825720	1825720
	1993	0.017395	1130742.22	1111073.298	1805888	1837300.88
	1994	0	1108406.72	1108406.72	1848266	1848266
	1995	0	1100701.24	1100701.24	1880207	1880207
	1996	0.014124	1119268.31	1103459.876	1894611	1921370.296
	1997	0.035986	1082107.81	1043166.862	1921019	1990149.174
	1998	0	1055999.65	1055999.65	1958596	1958596
	1999	0	1020004.99	1020004.99	1998679	1998679
	2000	0	1015897.18	1015897.18	2055775	2055775
	2001	0.000422	1027378.4	1026944.846	2072998	2073872.805
	2002	0	1016034.77	1016034.77	2074668	2074668
France	1990	0	564702.02	564702.02	1126972	1126972
	1991	0.052403	589181.36	558306.7838	1138197	1197841.368
	1992	0.038674	579050.76	556656.3772	1155177	1199852.662
	1993	0.049215	556217.73	528843.7525	1144928	1201275.059
	1994	0.02295	551730.13	532700.7372	1168583	1195402.33
	1995	0.028137	560060.85	544302.4179	1188101	1221530.598
	1996	0.073082	576299.7	534182.3924	1201205	1288991.824
	1997	0.048456	568413.55	540870.3893	1224081	1283395.314
	1998	0.037067	582538.26	560945.4891	1265715	1312630.878
	1999	0.021713	564299.35	552046.8311	1306384	1334749.255
	2000	0	558067.45	558067.45	1355936	1355936
	2001	0.007779	561654.32	557285.3234	1384351	1395119.59
	2002	0	553857.19	553857.19	1400755	1400755
United Kingdom	1990	0	742613.02	742613.02	797993.5	797993.5
	1991	0.031357	743596.24	720279.0696	787101.1	811782.4653
	1992	0.132667	720629.91	625025.9576	788637.4	893263.7157
	1993	0.184806	700748.14	571245.469	807027.4	956171.1478
	1994	0.17187	696348.78	576667.1759	842746.9	987589.9783
	1995	0.151755	686091.34	581973.3429	866786.5	998325.9453
	1996	0.153684	707759.01	598987.6328	891204.7	1028168.781
	1997	0.119937	684378.43	602296.0658	920412.1	1030803.658
	1998	0.097542	679374.09	613106.4466	948881	1041436.94
	1999	0.05227	647924.32	614057.251	975996.3	1027011.724

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[4] European GDP Measurements are in Millions of 1995 Euro.

2000	0.00986	647682.2	633844.4895	1013666	1023660.848
2001	0.00366	656182.07	653780.378	1036999	1040794.52
2002	0	634831.72	634831.72	1055336	1055336

B.4 Model 4

B.4.1 United States

B.4.1.1 Model 4: United States: Theta, Actual and Optimal CO2

Year	Theta	CO2 Actual	CO2 Optimal
1959	1	2787.9	2787.9
1960	1	2889	2889
1961	0.971449	2910.1	2827.012862
1962	1	3030.9	3030.9
1963	0.966952	3148.2	3044.159546
1964	0.981594	3282.5	3222.080992
1965	1	3426.6	3426.6
1966	1	3614.3	3614.3
1967	1	3708.8	3708.8
1968	1	3920.5	3920.5
1969	1	4090.4	4090.4
1970	0.957755	4212.9	4034.926882
1971	1	4262.3	4262.3
1972	1	4487	4487
1973	0.910231	4685.7	4265.069865
1974	0.865529	4521.3	3913.317172
1975	0.784788	4389.1	3444.514328
1976	0.764643	4654.8	3559.259305
1977	0.712232	4793.8	3414.296323
1978	0.721979	4843.5	3496.905287
1979	0.779373	4904.7	3822.592715
1980	0.809545	4735	3833.197469
1981	0.824251	4615.6	3804.412916
1982	0.827103	4373.4	3617.252698
1983	0.881469	4338.5	3824.252389
1984	0.87836	4581.3	4024.028377
1985	0.865328	4569.9	3954.462884
1986	0.891046	4580	4080.989306
1987	0.840479	4738.6	3982.695685
1988	0.773769	4955.5	3834.413766
1989	0.793614	5034.8	3995.687264
1990	0.810791	4988.6	4044.709987
1991	0.81722	4941	4037.885996
1992	0.827364	5042.7	4172.15046
1993	0.835251	5128.6	4283.667766
1994	0.856123	5204.7	4455.863378
1995	0.869028	5255.8	4567.437362
1996	0.870079	5443.7	4736.447964
1997	0.947883	5510.9	5223.688976
1998	0.957995	5552.5	5319.266682
1999	0.961435	5630.5	5413.361457

2000	0.970614	5798.6	5628.20466
2001	1	5691.7	5691.7
2002	1	5729.3	5729.3

B.4.2 Europe

B.4.2.1 Model 4: Europe: Theta, Actual and Optimal CO2

	Year	Theta	CO2 Actual	CO2 Optimal
Germany	1991	1	1196092.95	1196092.95
	1992	1	1145537.96	1145537.96
	1993	0.949435	1130742.22	1073565.674
	1994	1	1108406.72	1108406.72
	1995	1	1100701.24	1100701.24
	1996	0.964811	1119268.31	1079881.818
	1997	0.905495	1082107.81	979843.536
	1998	1	1055999.65	1055999.65
	1999	1	1020004.99	1020004.99
	2000	1	1015897.18	1015897.18
	2001	0.998829	1027378.4	1026175.443
	2002	1	1016034.77	1016034.77
France	1990	1	564702.02	564702.02
	1991	0.812777	589181.36	478872.9993
	1992	0.860241	579050.76	498123.2627
	1993	0.818059	556217.73	455018.9756
	1994	0.898953	551730.13	495979.6762
	1995	0.885707	560060.85	496049.5912
	1996	0.824146	576299.7	474955.3231
	1997	0.851494	568413.55	484000.4431
	1998	0.873066	582538.26	508594.465
	1999	0.934559	564299.35	527371.2055
	2000	1	558067.45	558067.45
	2001	0.982213	561654.32	551664.1746
	2002	1	553857.19	553857.19
United Kingdom	1990	1	742613.02	742613.02
	1991	0.819318	743596.24	609241.9329
	1992	0.643202	720629.91	463510.8156
	1993	0.68002	700748.14	476522.6801
	1994	0.696024	696348.78	484675.6722
	1995	0.724624	686091.34	497158.0453
	1996	0.72341	707759.01	512000.2285
	1997	0.777618	684378.43	532185.1229
	1998	0.815932	679374.09	554323.1279
	1999	0.897723	647924.32	581656.7587
	2000	0.941168	647682.2	609577.696
	2001	0.970317	656182.07	636704.7489
	2002	1	634831.72	634831.72

C SAS Programs

C.1 Model 1

C.1.1 United States

```
data a;
input Year      RealGDP Coal    Gas     Oil     Nuclear Renew;
d=0;
drop year;
cards;
1959    2441.3  9.51    11.717  19.323  0.002   2.901
1960    2501.8  9.832   12.385  19.919  0.006   2.929
1961    2560    9.615   12.926  20.216  0.02    2.953
1962    2715.2  9.9     13.731  21.049  0.026   3.119
1963    2834    10.406  14.403  21.701  0.038   3.098
1964    2998.6  10.954  15.288  22.301  0.04    3.228
1965    3191.1  11.563  15.769  23.246  0.043   3.398
1966    3399.1  12.118  16.995  24.401  0.064   3.435
1967    3484.6  11.899  17.945  25.284  0.088   3.694
1968    3652.7  12.314  19.21   26.979  0.142   3.778
1969    3765.4  12.346  20.678  28.338  0.154   4.102
1970    3771.9  12.207  21.795  29.521  0.239   4.076
1971    3898.6  11.565  22.469  30.561  0.413   4.268
1972    4105    12.051  22.698  32.947  0.584   4.398
1973    4341.5  12.964  22.512  34.84   0.91    4.433
1974    4319.6  12.719  21.732  33.455  1.272   4.769
1975    4311.2  12.677  19.948  32.731  1.9     4.723
1976    4540.9  13.584  20.345  35.175  2.111   4.768
1977    4750.5  13.937  19.931  37.122  2.702   4.249
1978    5015    13.891  20      37.965  3.024   5.039
1979    5173.4  15.103  20.666  37.123  2.776   5.166
1980    5161.7  15.388  20.394  34.202  2.739   5.494
1981    5291.7  15.892  19.928  31.931  3.008   5.471
1982    5189.3  15.3    18.505  30.232  3.131   5.985
1983    5423.8  15.878  17.357  30.054  3.203   6.488
1984    5813.6  17.06   18.507  31.051  3.553   6.431
1985    6053.7  17.465  17.834  30.922  4.076   6.033
1986    6263.6  17.243  16.708  32.196  4.38    6.132
1987    6475.1  18.017  17.744  32.865  4.754   5.687
1988    6742.7  18.886  18.552  34.222  5.587   5.489
1989    6981.4  19.1    19.712  34.211  5.602   6.294
1990    7112.5  19.178  19.73   33.553  6.104   6.133
1991    7100.5  19.002  20.149  32.845  6.422   6.158
1992    7336.6  19.157  20.835  33.527  6.479   5.907
1993    7532.7  19.862  21.351  33.841  6.41    6.156
1994    7835.5  19.967  21.842  34.67   6.694   6.065
1995    8031.7  20.15   22.784  34.553  7.075   6.669
1996    8328.9  21.025  23.197  35.757  7.087   7.137
1997    8703.5  21.491  23.329  36.266  6.597   7.075
1998    9066.9  21.723  22.936  36.934  7.068   6.561
1999    9470.3  21.681  23.01   37.96   7.61    6.599
2000    9817    22.645  23.916  38.404  7.862   6.158
2001    9890.7  21.981  22.906  38.333  8.033   5.286
2002    10074.8 22.041  23.662  38.401  8.143   5.963
2003    10381.3 22.75   22.507  39.074  7.973   6.15
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT THETA _TYPE_ $ _RHS_;
CARDS;
0 >= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
1 MIN .
;
%MACRO A;
%DO I= 1 %TO 45;
DATA LAST;
MERGE NEW MORE;
IF _N_ =1 THEN _RHS_ = COL&I;
IF _N_ > 1 AND _N_ <= 6 THEN THETA = -COL&I;
*PROC PRINT;
```

```
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;

%A;
```

C.1.2 Europe

```
data a;
input Year     RealGDP Solid   Gas    Oil Nuclear    Renew;
d=0;
drop year;
cards;
11991   1785742.2      54190   45729  100842  36128   2855
11992   1825720 39115  45618   102551 39000   2679
11993   1805887.7      33307   47590  104539  37543   2704
11994   1848266.2      29032   48035  101429  36842   2731
11995   1880206.6      25373   52595  102194  37322   2731
11996   1894611.1      23776   59831  104061  38925   2777
11997   1921019.4      22421   54753  103091  41114   4152
11998   1958596.4      19619   54797  102269  38912   4437
11999   1998678.5      17635   54875  98969   43853   4388
12000   2055774.7      18111   58006  95805   43750   4785
12001   2072997.5      17523   56697  98561   44189   4950
12002   2074667.5      16334   56455  94084   42522   5109
21985   959802.6       16149   22703  64674   57273   9937
21986   982905.4       14824   22991  65617   64593   9590
21987   1007809.2      14303   23327  66226   67239   10118
21988   1054314.6      13521   22514  65670   70182   9373
21989   1098324.7      13839   23192  66082   76763   9678
21990   1126971.5      13420   23400  66489   79131   9728
21991   1138197.1      12761   26578  66306   82931   11630
21992   1155176.6      12227   26588  67791   83742   10965
21993   1144928 10464  26742   68402  91321   10788
21994   1168582.6      9440    26560  65685   89848   9507
21995   1188100.5      10051   27098  67134   93990   9752
21996   1201204.5      10105   29916  69906   97852   10415
21997   1224080.5      10227   29425  67922   98766   9584
21998   1265715.3      9798    30216  71070   96636   9913
21999   1306383.7      8960    31398  70390   98194   9699
22000   1355935.8      8969    31448  70104   107093  9859
22001   1384351.4      8146    33306  75431   108617  9766
22002   1400755.3      5219    32706  72808   112664  8889
31985   684135.4       7807    20738  52021   1980    748
31986   701415.8       6123    22017  52463   2437    748
31987   722352.3       6833    24461  53987   49      748
41985   679490.2       23839   42617  50576   15981   292
41986   706349.9       23771   43035  53202   15687   292
41987   738525.5       21793   44723  52561   14981   292
41988   775158.5       21368   43195  55637   16337   292
41989   791981  18787  40446   57770  17731   385
41990   797993.5       17806   41564  57208   16574   405
41991   787101.1       18471   44123  57774   17292   417
41992   788637.4       17665   44252  57397   18745   617
41993   807027.4       16879   45092  59021   22086   595
41994   842746.9       15007   45705  59538   21204   835
41995   866786.5       13177   47147  58642   21249   881
41996   891204.7       11754   52648  60534   22180   892
41997   920412.1       11568   50604  59895   23248   865
41998   948881  10346  51530   59963  25831   798
41999   975996.3       10199   50398  61323   24540   631
42000   1013666 7774   51862   60669  21942   565
42001   1036998.5      9011    52985  60624   23182   573
42002   1055336.4      7133    50297  60212   22661   585
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT THETA _TYPE_ $ _RHS_;
CARDS;
0 >= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
1 MIN .
;
%MACRO A;
%DO I= 1 %TO 51;
```

```
DATA LAST;
MERGE NEW MORE;
IF _N_ =1 THEN _RHS_ = COL&I;
IF _N_ > 1 AND _N_ <= 6 THEN THETA = -COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;

%A;
```

C.2 Model 2

C.2.1 United States

```
data a;
input Year      RealGDP Coal    Gas     Oil     Nuclear Renew;
d=0;
drop year;
cards;
1959    2441.3  9.51    11.717  19.323  0.002   2.901
1960    2501.8  9.832   12.385  19.919  0.006   2.929
1961    2560    9.615   12.926  20.216  0.02    2.953
1962    2715.2  9.9     13.731  21.049  0.026   3.119
1963    2834    10.406  14.403  21.701  0.038   3.098
1964    2998.6  10.954  15.288  22.301  0.04    3.228
1965    3191.1  11.563  15.769  23.246  0.043   3.398
1966    3399.1  12.118  16.995  24.401  0.064   3.435
1967    3484.6  11.899  17.945  25.284  0.088   3.694
1968    3652.7  12.314  19.21   26.979  0.142   3.778
1969    3765.4  12.346  20.678  28.338  0.154   4.102
1970    3771.9  12.207  21.795  29.521  0.239   4.076
1971    3898.6  11.565  22.469  30.561  0.413   4.268
1972    4105    12.051  22.698  32.947  0.584   4.398
1973    4341.5  12.964  22.512  34.84   0.91    4.433
1974    4319.6  12.719  21.732  33.455  1.272   4.769
1975    4311.2  12.677  19.948  32.731  1.9     4.723
1976    4540.9  13.584  20.345  35.175  2.111   4.768
1977    4750.5  13.937  19.931  37.122  2.702   4.249
1978    5015    13.891  20      37.965  3.024   5.039
1979    5173.4  15.103  20.666  37.123  2.776   5.166
1980    5161.7  15.388  20.394  34.202  2.739   5.494
1981    5291.7  15.892  19.928  31.931  3.008   5.471
1982    5189.3  15.3    18.505  30.232  3.131   5.985
1983    5423.8  15.878  17.357  30.054  3.203   6.488
1984    5813.6  17.06   18.507  31.051  3.553   6.431
1985    6053.7  17.465  17.834  30.922  4.076   6.033
1986    6263.6  17.243  16.708  32.196  4.38    6.132
1987    6475.1  18.017  17.744  32.865  4.754   5.687
1988    6742.7  18.886  18.552  34.222  5.587   5.489
1989    6981.4  19.1    19.712  34.211  5.602   6.294
1990    7112.5  19.178  19.73   33.553  6.104   6.133
1991    7100.5  19.002  20.149  32.845  6.422   6.158
1992    7336.6  19.157  20.835  33.527  6.479   5.907
1993    7532.7  19.862  21.351  33.841  6.41    6.156
1994    7835.5  19.967  21.842  34.67   6.694   6.065
1995    8031.7  20.15   22.784  34.553  7.075   6.669
1996    8328.9  21.025  23.197  35.757  7.087   7.137
1997    8703.5  21.491  23.329  36.266  6.597   7.075
1998    9066.9  21.723  22.936  36.934  7.068   6.561
1999    9470.3  21.681  23.01   37.96   7.61    6.599
2000    9817    22.645  23.916  38.404  7.862   6.158
2001    9890.7  21.981  22.906  38.333  8.033   5.286
2002    10074.8 22.041  23.662  38.401  8.143   5.963
2003    10381.3 22.75   22.507  39.074  7.973   6.15
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT THETA _TYPE_ $ _RHS_;
CARDS;
0 >= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 = 0
1 MIN .
```

```
;
%MACRO A;
%DO I= 1 %TO 45;
DATA LAST;
MERGE NEW MORE;
IF _N_ =1 THEN _RHS_ = COL&I;
IF _N_ > 1 AND _N_ <= 5 THEN THETA = -COL&I;
IF _N_ =6 THEN _RHS_ = COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;

%A;
```

C.2.2 Europe

```
data a;
input Year     RealGDP Solid   Gas     Oil Nuclear    Renew;
d=0;
drop year;
cards;
11991   1785742.2      54190  45729   100842 36128   2855
11992   1825720 39115  45618  102551  39000  2679
11993   1805887.7      33307  47590   104539 37543   2704
11994   1848266.2      29032  48035   101429 36842   2731
11995   1880206.6      25373  52595   102194 37322   2731
11996   1894611.1      23776  59831   104061 38925   2777
11997   1921019.4      22421  54753   103091 41114   4152
11998   1958596.4      19619  54797   102269 38912   4437
11999   1998678.5      17635  54875   98969  43853   4388
12000   2055774.7      18111  58006   95805  43750   4785
12001   2072997.5      17523  56697   98561  44189   4950
12002   2074667.5      16334  56455   94084  42522   5109
21985   959802.6       16149  22703   64674  57273   9937
21986   982905.4       14824  22991   65617  64593   9590
21987   1007809.2      14303  23327   66226  67239   10118
21988   1054314.6      13521  22514   65670  70182   9373
21989   1098324.7      13839  23192   66082  76763   9678
21990   1126971.5      13420  23400   66489  79131   9728
21991   1138197.1      12761  26578   66306  82931   11630
21992   1155176.6      12227  26588   67791  83742   10965
21993   1144928 10464  26742  68402   91321  10788
21994   1168582.6      9440   26560   65685  89848   9507
21995   1188100.5      10051  27098   67134  93990   9752
21996   1201204.5      10105  29916   69906  97852   10415
21997   1224080.5      10227  29425   67922  98766   9584
21998   1265715.3      9798   30216   71070  96636   9913
21999   1306383.7      8960   31398   70390  98194   9699
22000   1355935.8      8969   31448   70104  107093  9859
22001   1384351.4      8146   33306   75431  108617  9766
22002   1400755.3      5219   32706   72808  112664  8889
31985   684135.4       7807   20738   52021  1980    748
31986   701415.8       6123   22017   52463  2437    748
31987   722352.3       6833   24461   53987  49      748
41985   679490.2       23839  42617   50576  15981   292
41986   706349.9       23771  43035   53202  15687   292
41987   738525.5       21793  44723   52561  14981   292
41988   775158.5       21368  43195   55637  16337   292
41989   791981  18787  40446  57770   17731  385
41990   797993.5       17806  41564   57208  16574   405
41991   787101.1       18471  44123   57774  17292   417
41992   788637.4       17665  44252   57397  18745   617
41993   807027.4       16879  45092   59021  22086   595
41994   842746.9       15007  45705   59538  21204   835
41995   866786.5       13177  47147   58642  21249   881
41996   891204.7       11754  52648   60534  22180   892
41997   920412.1       11568  50604   59895  23248   865
41998   948881  10346  51530  59963   25831  798
41999   975996.3       10199  50398   61323  24540   631
42000   1013666 7774   51862  60669   21942  565
42001   1036998.5      9011   52985   60624  23182   573
42002   1055336.4      7133   50297   60212  22661   585
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT THETA _TYPE_ $ _RHS_;
CARDS;
0 >= 0
```

```
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 = 0
1 MIN .
;
%MACRO A;
%DO I= 1 %TO 51;
DATA LAST;
MERGE NEW MORE;
IF _N_ =1 THEN _RHS_ = COL&I;
IF _N_ > 1 AND _N_ <= 5 THEN THETA = -COL&I;
IF _N_ =6 THEN _RHS_ = COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;
%A;
```

C.3 Model 3

C.3.1 United States

```
Title Directional Distance Function;
data a;
input Year     RealGDP CO2  Coal       Gas     Oil     Nuclear Renew;
d=0;
drop year;
cards;
1959    2441.3  2787.9  9.51    11.717  19.323  0.002   2.901
1960    2501.8  2889    9.832   12.385  19.919  0.006   2.929
1961    2560    2910.1  9.615   12.926  20.216  0.02    2.953
1962    2715.2  3030.9  9.9     13.731  21.049  0.026   3.119
1963    2834    3148.2  10.406  14.403  21.701  0.038   3.098
1964    2998.6  3282.5  10.954  15.288  22.301  0.04    3.228
1965    3191.1  3426.6  11.563  15.769  23.246  0.043   3.398
1966    3399.1  3614.3  12.118  16.995  24.401  0.064   3.435
1967    3484.6  3708.8  11.899  17.945  25.284  0.088   3.694
1968    3652.7  3920.5  12.314  19.21   26.979  0.142   3.778
1969    3765.4  4090.4  12.346  20.678  28.338  0.154   4.102
1970    3771.9  4212.9  12.207  21.795  29.521  0.239   4.076
1971    3898.6  4262.3  11.565  22.469  30.561  0.413   4.268
1972    4105    4487    12.051  22.698  32.947  0.584   4.398
1973    4341.5  4685.7  12.964  22.512  34.84   0.91    4.433
1974    4319.6  4521.3  12.719  21.732  33.455  1.272   4.769
1975    4311.2  4389.1  12.677  19.948  32.731  1.9     4.723
1976    4540.9  4654.8  13.584  20.345  35.175  2.111   4.768
1977    4750.5  4793.8  13.937  19.931  37.122  2.702   4.249
1978    5015    4843.5  13.891  20      37.965  3.024   5.039
1979    5173.4  4904.7  15.103  20.666  37.123  2.776   5.166
1980    5161.7  4735    15.388  20.394  34.202  2.739   5.494
1981    5291.7  4615.6  15.892  19.928  31.931  3.008   5.471
1982    5189.3  4373.4  15.3    18.505  30.232  3.131   5.985
1983    5423.8  4338.5  15.878  17.357  30.054  3.203   6.488
1984    5813.6  4581.3  17.06   18.507  31.051  3.553   6.431
1985    6053.7  4569.9  17.465  17.834  30.922  4.076   6.033
1986    6263.6  4580    17.243  16.708  32.196  4.38    6.132
1987    6475.1  4738.6  18.017  17.744  32.865  4.754   5.687
1988    6742.7  4955.5  18.886  18.552  34.222  5.587   5.489
1989    6981.4  5034.8  19.1    19.712  34.211  5.602   6.294
1990    7112.5  4988.6  19.178  19.73   33.553  6.104   6.133
1991    7100.5  4941    19.002  20.149  32.845  6.422   6.158
1992    7336.6  5042.7  19.157  20.835  33.527  6.479   5.907
1993    7532.7  5128.6  19.862  21.351  33.841  6.41    6.156
1994    7835.5  5204.7  19.967  21.842  34.67   6.694   6.065
1995    8031.7  5255.8  20.15   22.784  34.553  7.075   6.669
1996    8328.9  5443.7  21.025  23.197  35.757  7.087   7.137
1997    8703.5  5510.9  21.491  23.329  36.266  6.597   7.075
1998    9066.9  5552.5  21.723  22.936  36.934  7.068   6.561
1999    9470.3  5630.5  21.681  23.01   37.96   7.61    6.599
2000    9817    5798.6  22.645  23.916  38.404  7.862   6.158
2001    9890.7  5691.7  21.981  22.906  38.333  8.033   5.286
2002    10074.8 5729.3  22.041  23.662  38.401  8.143   5.963
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
```

```
INPUT Beta _TYPE_ $ _RHS_;
CARDS;
0 >= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
1 MAX .
;
%MACRO A;
%DO I= 1 %TO 44;
DATA LAST;
MERGE NEW MORE;
IF _N_ >=1 AND _N_ <=7 THEN _RHS_ = COL&I;
IF _N_ = 1 THEN BETA = -COL&I;
IF _N_ = 2 THEN BETA = COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;
%A;
```

C.3.2 Europe

```
Title Directional Distance Function Europe;
data a;
input Year      RealGDP GreenhouseGases         Coal    Gas     Oil     Nuclear Renew;
d=0;
drop year;
cards;
11991   1785742 1196092.95      54190   45729   100842  36128   2855
11992   1825720 1145537.96      39115   45618   102551  39000   2679
11993   1805888 1130742.22      33307   47590   104539  37543   2704
11994   1848266 1108406.72      29032   48035   101429  36842   2731
11995   1880207 1100701.24      25373   52595   102194  37322   2731
11996   1894611 1119268.31      23776   59831   104061  38925   2777
11997   1921019 1082107.81      22421   54753   103091  41114   4152
11998   1958596 1055999.65      19619   54797   102269  38912   4437
11999   1998679 1020004.99      17635   54875   98969   43853   4388
12000   2055775 1015897.18      18111   58006   95805   43750   4785
12001   2072998 1027378.4       17523   56697   98561   44189   4950
12002   2074668 1016034.77      16334   56455   94084   42522   5109
21990   1126972 564702.02       13420   23400   66489   79131   9728
21991   1138197 589181.36       12761   26578   66306   82931   11630
21992   1155177 579050.76       12227   26588   67791   83742   10965
21993   1144928 556217.73       10464   26742   68402   91321   10788
21994   1168583 551730.13       9440    26560   65685   89848   9507
21995   1188101 560060.85       10051   27098   67134   93990   9752
21996   1201205 576299.7        10105   29916   69906   97852   10415
21997   1224081 568413.55       10227   29425   67922   98766   9584
21998   1265715 582538.26       9798    30216   71070   96636   9913
21999   1306384 564299.35       8960    31398   70390   98194   9699
22000   1355936 558067.45       8969    31448   70104   107093  9859
22001   1384351 561654.32       8146    33306   75431   108617  9766
22002   1400755 553857.19       5219    32706   72808   112664  8889
41990   797993.5        742613.02       17806   41564   57208   16574   405
41991   787101.1        743596.24       18471   44123   57774   17292   417
41992   788637.4        720629.91       17665   44252   57397   18745   617
41993   807027.4        700748.14       16879   45092   59021   22086   595
41994   842746.9        696348.78       15007   45705   59538   21204   835
41995   866786.5        686091.34       13177   47147   58642   21249   881
41996   891204.7        707759.01       11754   52648   60534   22180   892
41997   920412.1        684378.43       11568   50604   59895   23248   865
41998   948881  679374.09       10346   51530   59963   25831   798
41999   975996.3        647924.32       10199   50398   61323   24540   631
42000   1013666 647682.2        7774    51862   60669   21942   565
42001   1036999 656182.07       9011    52985   60624   23182   573
42002   1055336 634831.72       7133    50297   60212   22661   585
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT Beta _TYPE_ $ _RHS_;
CARDS;
0 >= 0
0 <= 0
0 <= 0
0 <= 0
```

```
0 <= 0
0 <= 0
0 <= 0
1 MAX .
;
%MACRO A;
%DO I= 1 %TO 38;
DATA LAST;
MERGE NEW MORE;
IF _N_ >=1 AND _N_ <=7 THEN _RHS_ = COL&I;
IF _N_ = 1 THEN BETA = -COL&I;
IF _N_ = 2 THEN BETA = COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;
%A;
```

C.4 Model 4

C.4.1 United States

```
Title CO2 minimization;
data a;
input Year     RealGDP CO2  Coal       Gas     Oil     Nuclear Renew;
d=0;
drop year;
cards;
1959    2441.3  2787.9  9.51    11.717  19.323  0.002   2.901
1960    2501.8  2889    9.832   12.385  19.919  0.006   2.929
1961    2560    2910.1  9.615   12.926  20.216  0.02    2.953
1962    2715.2  3030.9  9.9     13.731  21.049  0.026   3.119
1963    2834    3148.2  10.406  14.403  21.701  0.038   3.098
1964    2998.6  3282.5  10.954  15.288  22.301  0.04    3.228
1965    3191.1  3426.6  11.563  15.769  23.246  0.043   3.398
1966    3399.1  3614.3  12.118  16.995  24.401  0.064   3.435
1967    3484.6  3708.8  11.899  17.945  25.284  0.088   3.694
1968    3652.7  3920.5  12.314  19.21   26.979  0.142   3.778
1969    3765.4  4090.4  12.346  20.678  28.338  0.154   4.102
1970    3771.9  4212.9  12.207  21.795  29.521  0.239   4.076
1971    3898.6  4262.3  11.565  22.469  30.561  0.413   4.268
1972    4105    4487    12.051  22.698  32.947  0.584   4.398
1973    4341.5  4685.7  12.964  22.512  34.84   0.91    4.433
1974    4319.6  4521.3  12.719  21.732  33.455  1.272   4.769
1975    4311.2  4389.1  12.677  19.948  32.731  1.9     4.723
1976    4540.9  4654.8  13.584  20.345  35.175  2.111   4.768
1977    4750.5  4793.8  13.937  19.931  37.122  2.702   4.249
1978    5015    4843.5  13.891  20      37.965  3.024   5.039
1979    5173.4  4904.7  15.103  20.666  37.123  2.776   5.166
1980    5161.7  4735    15.388  20.394  34.202  2.739   5.494
1981    5291.7  4615.6  15.892  19.928  31.931  3.008   5.471
1982    5189.3  4373.4  15.3    18.505  30.232  3.131   5.985
1983    5423.8  4338.5  15.878  17.357  30.054  3.203   6.488
1984    5813.6  4581.3  17.06   18.507  31.051  3.553   6.431
1985    6053.7  4569.9  17.465  17.834  30.922  4.076   6.033
1986    6263.6  4580    17.243  16.708  32.196  4.38    6.132
1987    6475.1  4738.6  18.017  17.744  32.865  4.754   5.687
1988    6742.7  4955.5  18.886  18.552  34.222  5.587   5.489
1989    6981.4  5034.8  19.1    19.712  34.211  5.602   6.294
1990    7112.5  4988.6  19.178  19.73   33.553  6.104   6.133
1991    7100.5  4941    19.002  20.149  32.845  6.422   6.158
1992    7336.6  5042.7  19.157  20.835  33.527  6.479   5.907
1993    7532.7  5128.6  19.862  21.351  33.841  6.41    6.156
1994    7835.5  5204.7  19.967  21.842  34.67   6.694   6.065
1995    8031.7  5255.8  20.15   22.784  34.553  7.075   6.669
1996    8328.9  5443.7  21.025  23.197  35.757  7.087   7.137
1997    8703.5  5510.9  21.491  23.329  36.266  6.597   7.075
1998    9066.9  5552.5  21.723  22.936  36.934  7.068   6.561
1999    9470.3  5630.5  21.681  23.01   37.96   7.61    6.599
2000    9817    5798.6  22.645  23.916  38.404  7.862   6.158
2001    9890.7  5691.7  21.981  22.906  38.333  8.033   5.286
2002    10074.8 5729.3  22.041  23.662  38.401  8.143   5.963
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT theta _TYPE_ $ _RHS_;
CARDS;
```

```
0 >= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
1 MIN .
;
%MACRO A;
%DO I= 1 %TO 44;
DATA LAST;
MERGE NEW MORE;
IF _N_ =1  THEN _RHS_ = COL&I;
IF _N_ = 2 THEN THETA = -COL&I;
IF _N_ >= 3 AND THETA <= 7 THEN _RHS_ = COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;
%A;
```

C.4.2 Europe

```
Title Emissions Minimization for Europe;
data a;
input Year     RealGDP Greenhousegases Coal   Gas     Oil     Nuclear Renew;
d=0;
drop year;
cards;
11991   1785742 1196092.95     54190   45729  100842  36128  2855
11992   1825720 1145537.96     39115   45618  102551  39000  2679
11993   1805888 1130742.22     33307   47590  104539  37543  2704
11994   1848266 1108406.72     29032   48035  101429  36842  2731
11995   1880207 1100701.24     25373   52595  102194  37322  2731
11996   1894611 1119268.31     23776   59831  104061  38925  2777
11997   1921019 1082107.81     22421   54753  103091  41114  4152
11998   1958596 1055999.65     19619   54797  102269  38912  4437
11999   1998679 1020004.99     17635   54875  98969   43853  4388
12000   2055775 1015897.18     18111   58006  95805   43750  4785
12001   2072998 1027378.4      17523   56697  98561   44189  4950
12002   2074668 1016034.77     16334   56455  94084   42522  5109
21990   1126972 564702.02      13420   23400  66489   79131  9728
21991   1138197 589181.36      12761   26578  66306   82931  11630
21992   1155177 579050.76      12227   26588  67791   83742  10965
21993   1144928 556217.73      10464   26742  68402   91321  10788
21994   1168583 551730.13      9440    26560  65685   89848  9507
21995   1188101 560060.85      10051   27098  67134   93990  9752
21996   1201205 576299.7       10105   29916  69906   97852  10415
21997   1224081 568413.55      10227   29425  67922   98766  9584
21998   1265715 582538.26      9798    30216  71070   96636  9913
21999   1306384 564299.35      8960    31398  70390   98194  9699
22000   1355936 558067.45      8969    31448  70104   107093 9859
22001   1384351 561654.32      8146    33306  75431   108617 9766
22002   1400755 553857.19      5219    32706  72808   112664 8889
41990   797993.5       742613.02      17806  41564   57208  16574   405
41991   787101.1       743596.24      18471  44123   57774  17292   417
41992   788637.4       720629.91      17665  44252   57397  18745   617
41993   807027.4       700748.14      16879  45092   59021  22086   595
41994   842746.9       696348.78      15007  45705   59538  21204   835
41995   866786.5       686091.34      13177  47147   58642  21249   881
41996   891204.7       707759.01      11754  52648   60534  22180   892
41997   920412.1       684378.43      11568  50604   59895  23248   865
41998   948881  679374.09      10346   51530  59963   25831  798
41999   975996.3       647924.32      10199  50398   61323  24540   631
42000   1013666 647682.2       7774    51862  60669   21942  565
42001   1036999 656182.07      9011    52985  60624   23182  573
42002   1055336 634831.72      7133    50297  60212   22661  585
;
PROC TRANSPOSE OUT=NEW;
DATA MORE;
INPUT theta _TYPE_ $ _RHS_;
CARDS;
0 >= 0
0 <= 0
0 <= 0
0 <= 0
0 <= 0
```

```
0 <= 0
0 <= 0
1 MIN .
;
%MACRO A;
%DO I= 1 %TO 38;
DATA LAST;
MERGE NEW MORE;
IF _N_ =1  THEN _RHS_ = COL&I;
IF _N_ = 2 THEN THETA = -COL&I;
IF _N_ >= 3 AND THETA <= 7 THEN _RHS_ = COL&I;
*PROC PRINT;
PROC LP MAXIT1 = 9000 MAXIT2=9000 EPSILON = 1.0E-10;
RUN;
%END;
%MEND A;
%A;
```