

# Viability of an Expanded United States Nuclear Power Program and its Effects on Energy Markets

By  
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Submitted to the Department of Nuclear Science and Engineering  
In Partial Fulfillment of the Requirements  
For the Degree of

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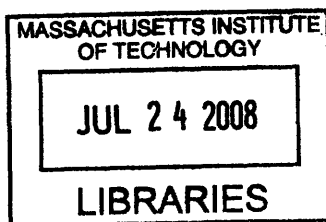
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## **1. Abstract**

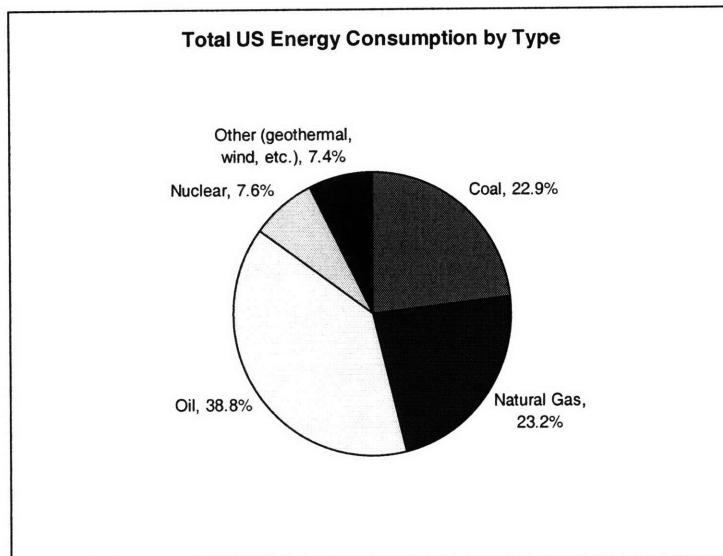
The four biggest energy sources in the United States are coal, crude oil, natural gas, and nuclear power. While coal and nuclear power are produced domestically, more than 70% of crude oil and 20% of natural gas is imported. This places an unhealthy dependence on foreign products for our economy. Just as importantly, all of these energy sources, with the exception of nuclear power, produce large amounts of polluting emissions in the form of greenhouse gases which are responsible for environmental degradation. For these two reasons, we explore possible government policies to shift the US energy economy towards domestically-produced, environmentally-clean alternative energy sources, the most prevalent of which is nuclear power. Different forms of government support for investment in nuclear power is discussed, such as investment tax credits and production tax credits. As an instrument of public policy to affect energy imports and environmental impact, the possibility of a carbon tax (on the order of \$150/tC) is considered. The effects of this carbon tax on the energy sector in the medium-term future (in the year 2020) are analyzed. Under the constraint of maintaining current natural gas demand the results show that there will be an increase in the use of nuclear power while lowering the dependence on crude oil and coal. To accomplish this, the use of natural gas is shifted from the power sector to the residential, commercial and industrial sectors due to the economic incentives to do so. From an environmental perspective, this carbon tax lowers emissions by a predicted 30% of its 2020 business-as-usual rates. Economically, the carbon tax lowers crude oil import levels by 20% and reduces the US balance of payments by over \$170 billion in the year 2020.

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## 2. Introduction to Major US Energy Sources

The United States is the world's largest energy consumer by far, accounting for 40% of the world's oil consumption and 25% of natural gas and coal in 2005 (Hodges, 2005). The US has dominated world energy consumptions since the early part of the century and so far, there have been no signs of a reversal. The US has been unable to domestically supply our growing energy needs and this has placed the economy in the untenable position of being dependent on imports to sustain it. Shown on Figure 1 are the major sources of energy in the United States.



**Figure 1: Relative Proportions of Energy Sources Used in the US (EIA, 2004)**

### 2.1 Crude Oil/Petroleum

In the US, oil is the chief source of energy in the industrial and transportation sectors, but accounts for only about 4% of our electricity generation needs. 40% of our oil imports

come from the OPEC (GC, 2006), a cartel of oil-producing countries that can set prices and quantities to be sold due to its market power (currently, OPEC supplies about two-thirds of the world's oil). The presence of such a powerful cartel combined with the ever-increasing world demand for a limited supply of oil, especially from recent industrial development in China and India, has resulted in a surging upward trend of oil prices. Oil prices as recently as few months ago went up to record levels, from \$30/bbl in Dec. 2003 to \$65/bbl in Dec. 2005. Crude oil prices in 2006 have reached levels in excess of \$ 70/bbl. with no signs of major price reductions due to high demand. This poses a threat to the continued development of the US economy as well as our national security.

## **2.2 Coal**

Coal-fired plants currently produce over 50% of the electricity in the US. It has been the fuel of choice for electric utilities due to its abundance and relative low cost. However, it is becoming less attractive because of its high pollution levels, contributing significantly to global warming through large-scale greenhouse gas emissions. Cost of coal-produced electricity will go up (from around 4.0cents/kWh to over 6.0cents/kWh) if regulations for tight CO<sub>2</sub> emission standards are established and/or carbon taxes are put in place (Portney, 2005). Alternatives to paying these taxes are either to shutdown non-compliant plants or using expensive new technologies such as carbon sequestration to capture emissions. Such government initiatives could be mandated in the future if environmental degradation continues at its current pace.

Coal liquefaction and gasification are technologies that have been researched and have had small-scale applications in the US in the past decade. These technologies can be used to produce liquid fuels for transportation with somewhat lower emissions. They have not yet been widely adopted due to high capital costs involved in setting up the processes. We will look at these technologies in Section 3 of this report to determine whether they can play a significant role in the future of our energy market.

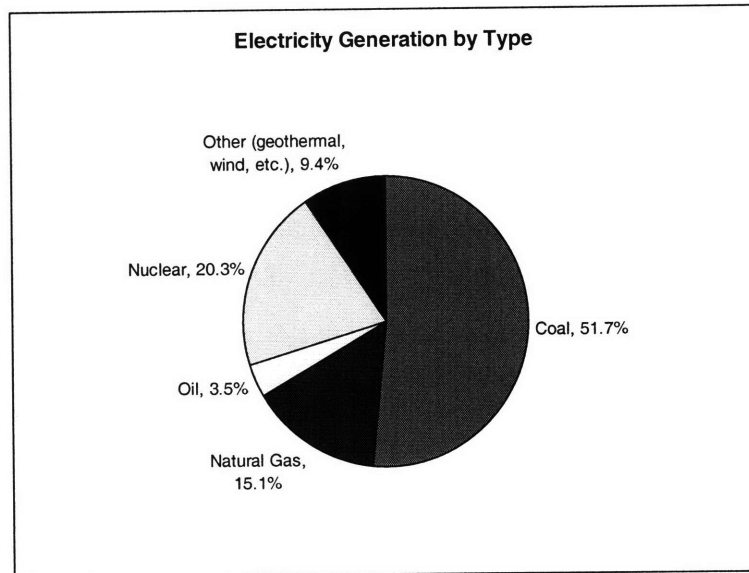
## **2.3 Natural Gas**

Natural gas accounts for about 15% of electricity generation in the US, and is also used for residential and commercial heating. In recent years, natural gas has also been used in the transportation sector as fuel for newer public transportation vehicles to reduce exhaust pollution coming from buses. Touted as a clean-burning gas because of its low carbon emissions compared to coal and oil, the US has natural gas reserves that can theoretically meet demand for the near term. While natural gas has had some recent price volatility, it is seen as a preferable option to crude oil due to the lack of dependence on foreign imports (less than 20% of our natural gas consumption is imported, mostly from Canada).

## **2.4 Nuclear Power**

Nuclear power in the United States is primarily used for electricity generation and currently accounts for about 20% of the total. Figure 2 summarizes the major sources of electricity production in the United States. In the 1970s, nuclear power was seen as the answer to all of the nation's energy problems, which resulted in the proposal of several new aggressive energy policies, such as the 1974 Project Independence Report which called for nuclear power to constitute the bulk of the nation's electricity generation model. Progress in the use of nuclear power has slowed down considerably since then, to the point that no new reactors have been built in the past 25 years. However, the time has come once again to look at nuclear power, and the US has been taking rather dramatic steps to revitalize nuclear energy in order to have utilities order new plants. The Nuclear Regulatory Commission has instituted new licensing regulations to remove regulatory uncertainty and speed up the licensing process. In 2005, the Energy Policy Act was passed that provided significant financial incentives for the first movers of new nuclear plant orders to reduce the investor risk and incentivize utilities through production tax

credits, loan guarantees and regulatory risk insurance to name a few of these Congressionally mandated incentives.



**Figure 2: Relative Proportions of Electricity Generation Sources Used in the US (EIA, 2004)**

The reason for the renewed interest in nuclear power is two-fold. First, global warming and the depletion of the ozone layer have led the impetus to reduce greenhouse gas emissions and become more environmentally conscious for the sake of future generations. Table 1 summarizes US carbon dioxide emissions from end uses of energy over time. The Energy Information Administration (EIA) of the US Department of Energy currently projects that, in the absence of carbon dioxide emissions standards, electricity's share of greenhouse emissions will be over 40% in 2020, of which 90% is due to coal-fired generation. (EIA-0573, 2004)

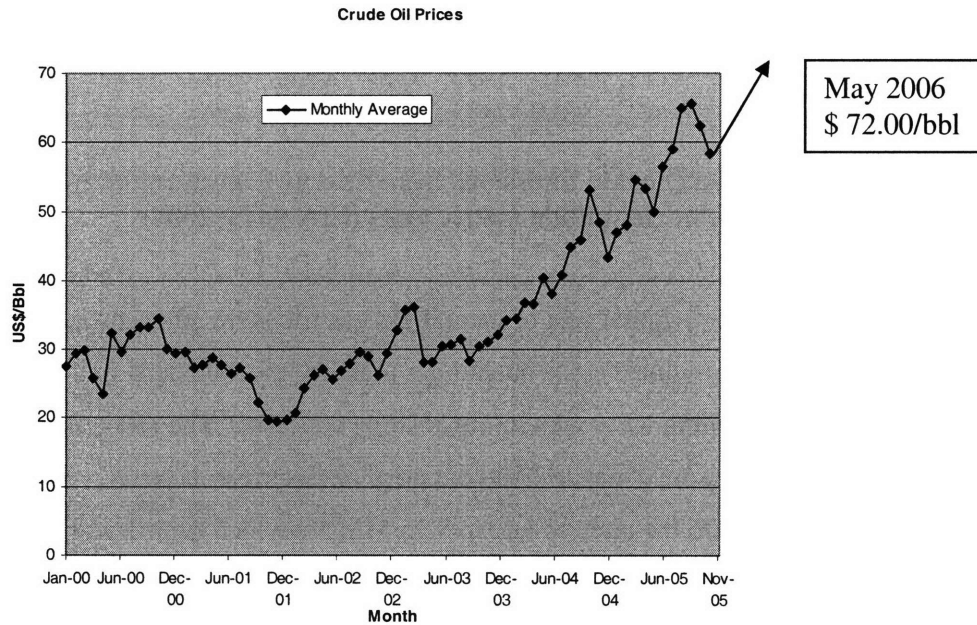
End-Use Sector	1990	1996	1997	1998	1999	2000	2001	2002	2003	P2004
Residential.....	953.7	1,090.2	1,082.0	1,088.5	1,110.9	1,171.8	1,168.3	1,190.4	1,213.2	1,212.0
Commercial.....	780.7	872.1	916.1	934.1	947.3	1,005.9	1,026.2	1,019.8	1,021.1	1,024.2
Industrial.....	1,692.2	1,788.8	1,804.4	1,791.2	1,779.1	1,780.3	1,698.4	1,671.0	1,685.6	1,730.2
Transportation.....	1,569.9	1,705.3	1,722.7	1,757.9	1,806.0	1,844.2	1,835.5	1,864.9	1,875.7	1,933.7
Total <sup>a</sup> .....	4,996.6	5,456.5	5,525.2	5,571.6	5,643.2	5,802.3	5,728.4	5,746.0	5,795.5	5,899.9
Electric Power.....	1,803.1	2,007.1	2,076.3	2,164.9	2,175.8	2,279.3	2,248.2	2,250.6	2,278.8	2,298.6

**Table 1: US Carbon Dioxide Emissions from Energy Consumption by End-Use Sector (in million metric tons) (EIA-0573, 2004)**

Due to the relatively low capital cost of natural gas electric generating stations, utilities have chosen to build combined cycle natural gas plants to meet demand in the last 10 years. They can be built quickly with minimal siting concerns. The problem with these plants is that while they are cheap to build the price of electricity is heavily dependent on the price of gas. In 2006 the price spiked to \$ 15/MMBtu which significantly affected the price of electricity cooling the interest of utilities on future natural gas expansion.

Even though the use of natural gas is cleaner than coal or oil, the burning of natural gas releases some greenhouse gases, mostly carbon dioxide. In this regard, nuclear power does not emit any greenhouse gases and thus does not contribute to this environmental degradation.

While oil is not a major fuel today for electric generating plants, it does affect the economy and overall electric demand. The recent spike in crude oil prices from under \$30 in 2000 to almost \$70 in mid-2005 (as shown in Figure 3) has raised concerns among the current administration of its effects on the US economy. Should prices continue to go up, it could lead to a stagnation of economic development and could even be a precursor to negative economic growth. As such, it is important to find alternative sources, such as nuclear power, that can help reduce our dependence on this foreign source of energy. If alternatives to oil, such as switching to natural gas or the development of gasification or liquefaction of coal technologies can be encouraged, this would reduce dependence on oil for our economy.



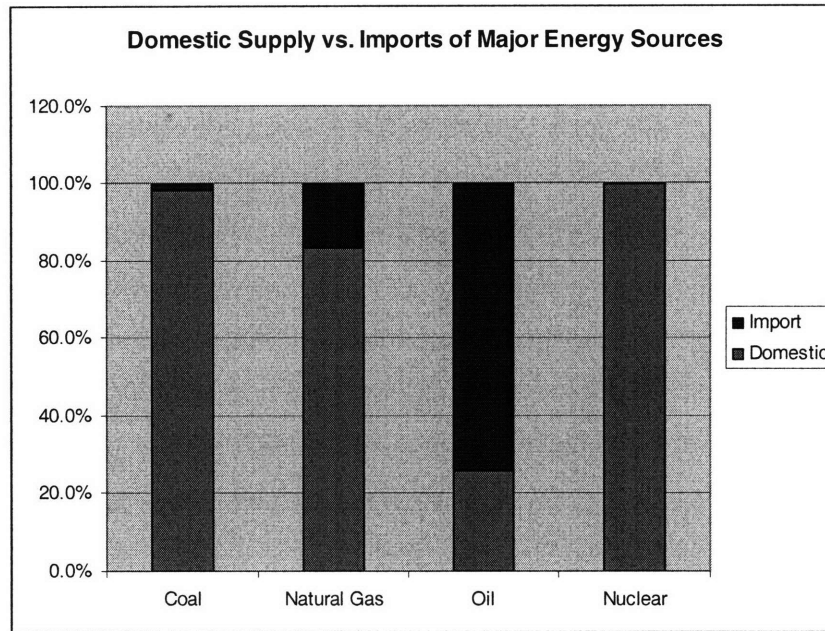
**Figure 3: Crude Oil Prices from 2000-2005**

### **3. State of Supply of US Energy**

#### ***3.1 Energy Economics***

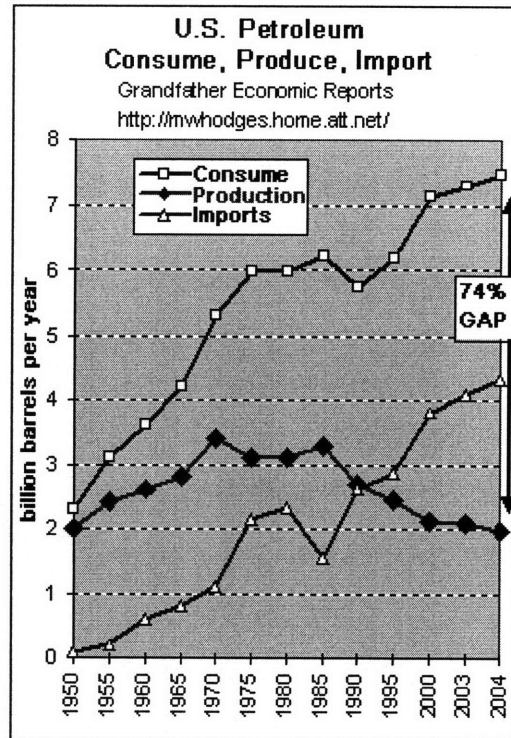
As we have already established from Figures 1 & 2, there are four major sources of energy in the United States: crude oil/petroleum, coal, natural gas, and nuclear power. From the US economy and national security perspective, we want to reduce our reliance on foreign energy sources as much as possible and become more self-reliant on our

domestic supply. Figure 4 summarizes the overall US current energy supply situation as it relates to domestic production and imports.



**Figure 4: Domestic Supply v. Imports of Major US Energy Sources (EIA, 2004)**

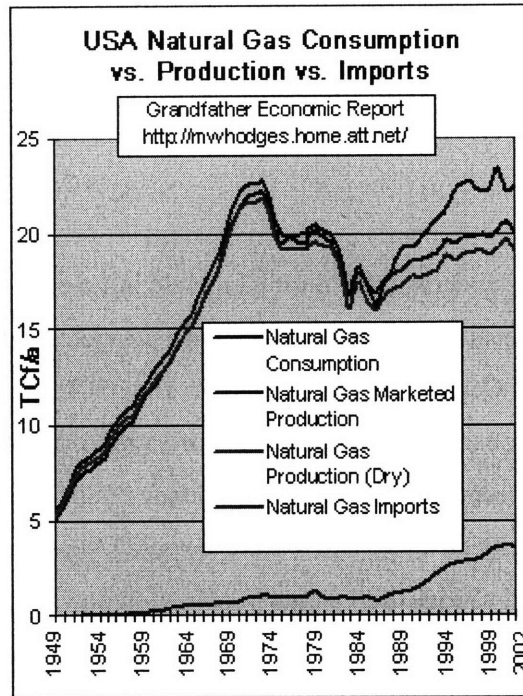
As it currently stands, the US has considerable deposits of crude oil, but it has not nearly been enough to meet the national demand, resulting in 74% of our crude oil being supplied by imports.



**Figure 5: US Petroleum Statistics (Hodges, 2005)**

More alarming is the fact that domestic production has been declining steadily, shown in Figure 5. As an example, current production in Alaska is 51% lower than in 1988. There has been a declining trend in the oil well productivity (i.e. the output per oil well) which has gone down 39% since the 1970s. If an aggressive new well drilling initiative does not take place, the shortfall in domestic supply will continue to increase further worsening our economic dependence on foreign sources of supply. New wells and new areas for oil development, such as those in Alaska, will be needed to make up for the less productive existing wells just to keep up with domestic production. Expanding US net oil production does not seem to be possible due to opposition from environmental groups in all areas - Alaska and off the US coast. If this is the case, a domestic supply shortfall is on the horizon, and the only path to lowering oil imports would be to shift our economy away from crude oil for energy.





**Figure 6: US Natural Gas Statistics (Hodges, 2005)**

The demand for natural gas has been steadily increasing as environmental awareness has increased in the community. However, the domestic supply has not been able to keep up with demand. This, in turn, has led to an increase in the import of natural gas, shown in Figure 6, which has tripled within the past 15 years, up to 16.7% of our total current natural gas demand. The supply of natural gas also seems to be somewhat saturated, not only due to the decline in domestic natural gas output, but also because importing presents several logistical difficulties, such as the limited number of terminals that can accept the Liquefied Natural Gas (LNG) tankers (Gold 2004) and the difficulties in siting gas pipelines from Canada and Mexico.

Coal is an abundant resource in the United States, able to supply all of the domestic demand. US coal production has been reaching record levels, increasing by 1.9 percent in 2005 to reach 1,133.3 million short tons. 92% of the domestic demand for coal has

been in the electricity sector, and its abundance and relatively cheap price make it a domestic energy resource for the United States. The major problem is burning the coal in an environmentally acceptable manner at a price that is competitive with other non-polluting alternatives.

Significant research has been underway for limiting the environmental impact of coal-fired plants in the form of greenhouse gases, and the most efficient coal technology so far is the Integrated Gasification Combined Cycle (IGCC). The IGCC technology modeled in EIA's Reference Case has an overnight capital cost of \$1388/kW with an efficiency of about 49%, as opposed to current coal-fired plant efficiency of 30-35% (EIA-S.1766, 2002). The levelized electricity cost using IGCC is 5.0 cents/kWh compared with an average of 4.0 cents/kWh of US coal-fired plants in operation now. (IEA, 2005) If the 60% target efficiency goal, set by the EIA's Annual Energy Outlook 2002 – Vision for 2010, can be reached for IGCC, carbon emissions would drop from 573 lbs/MWh (which is the current emissions rate) to 323 lbs/MWh.

Coal liquefaction is a process to convert coal into a liquid fuel like gasoline or diesel, and while several different methods to achieve this exist, the most popular one is the indirect synthesis of liquid hydrocarbons using the Fischer-Tropsch process. Commercialization of coal liquefaction in the United States could provide an alternative to use of crude oil in the transportation sector, and it is currently projected to cost over \$45/barrel to produce. (Miller, 2006) This makes the process competitive with current crude oil prices standing at \$70/barrel, but there are a number of significant impediments to deploying coal liquefaction technologies:

“first and foremost, the uncertainty and volatility of the world oil price; high capital investment for the plants; technical and economic risks associated with first-of-a-kind plants; environmental concerns associated with increased coal production and the coal to liquids industrial process; public attitude to increased coal use; siting and “not in my backyard” issues for new plants; and increasing the

supply of coal given a supply chain that is already stretched to capacity.” (Miller, 2006)

Nuclear power is another energy resource which can be supplied exclusively through domestic suppliers and can thus help the US economy become more self-sufficient. The demonstrated capability of nuclear energy to produce environmentally clean power is not questioned. It is a domestically available technology that uses uranium fuel which when integrated into the total cost of power, contributes less than 25% of the cost of power making it invulnerable to future price volatility. Performance of existing nuclear plants in the last 10 years has been exceptional achieving overall fleet average capacity factors (a measure of production efficiency) of over 90 %. This performance has provided the utility industry confidence needed to build new nuclear power plants.

### ***3.2 Energy and the Environment***

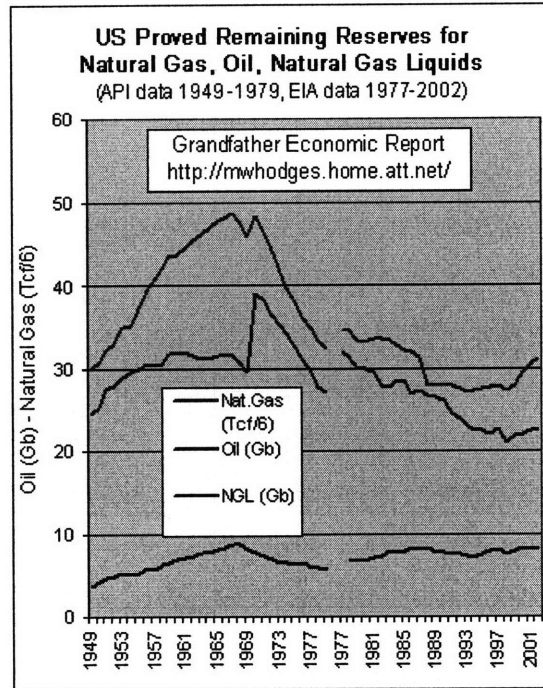
From the environmental standpoint, the two most harmful energy sources are coal and crude oil which are both responsible for large amounts of carbon dioxide emissions into the atmosphere that is leading to global warming. In order to control this, their use must be curtailed in favor of cleaner substitutes. The present options include:

- Increased efficiency in electricity generation and use
- Expanded use of renewable energy sources such as wind, solar, biomass, and geothermal
- Expanded use of natural gas, which has much lower emission levels
- Introduction and deployment of coal liquefaction/gasification technologies
- Capturing carbon dioxide emissions at fossil-fueled (especially coal) electric generating plants and permanently sequestering the carbon
- Increased use of nuclear power

### **3.3 Creating an Energy Plan**

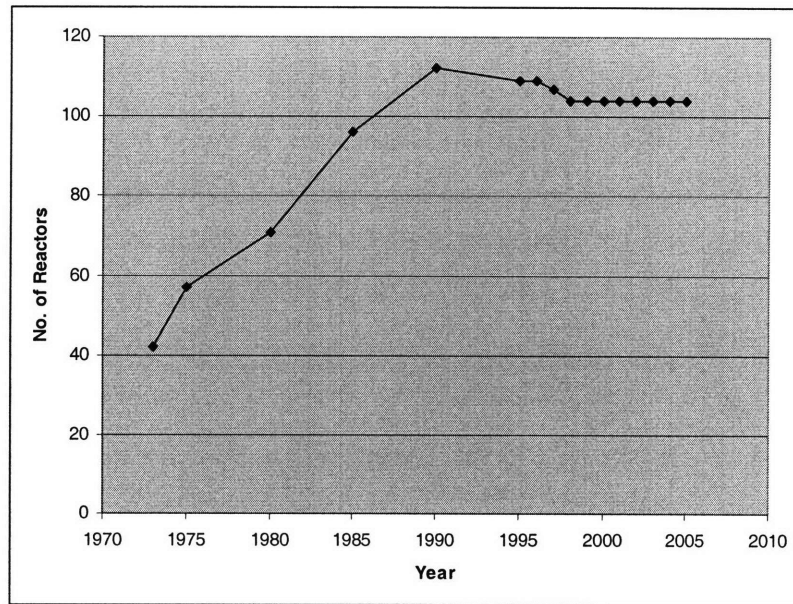
US needs in the energy sector sound simple enough, but the difficulty arises in attempting to form a coherent plan going forward that addresses both the environmental and US economy concerns. Everyone can agree that US reliance on crude oil must be reduced in the future. The use of coal is contentious due to environmental problems. Natural gas poses problems of future supply and price volatility making investment decisions difficult. The US has huge coal reserves that can easily sustain a larger part of the nation's energy needs, thus moving us away from energy imports. In particular, extracting fuel by coal liquefaction has raised the possibility of moving away from crude oil imports and using these liquid fuels instead. Coal is however the biggest environmental polluter of all the energy sources, and unless carbon sequestration can be perfected or other "clean coal" technologies implemented, the use of coal must also be reduced.

Natural gas is environmentally sound compared to crude oil and coal, and is considered by many as the future of the energy sector. But while the US has large reserves of natural gas (as shown in Figure 7), it cannot efficiently supply enough to meet the growing demand (Gerard, 2005), because of proven reserves decline and higher costs for accessing the more deeply-buried reserves. This will be exacerbated even more if natural gas is used as a substitute for crude oil and coal in the energy market. It will not reduce foreign reliance on meeting our energy needs, and will keep the US economy bound to the volatility of an international energy market. But even more importantly, not only does the North American natural gas reserves not have excess capacity to meet demand, but even if we wanted to increase our reliance on natural gas imports, it is not practical to make up our natural gas shortfall by shipping it from the Middle East due to shortage of Liquefied Natural Gas (LNG) storage facilities, LNG tankers, and energy losses during transportation.



**Figure 7: US Crude Oil and Natural Gas Reserves (Hodges, 2005)**

Nuclear power is an energy source that is both environment-friendly and can be expanded domestically. It is a clean source of energy emitting essentially no greenhouse gases, and as discussed earlier, it can be domestically produced with no need for interaction with the international markets to sustain it. Nuclear power appears to be the energy path of the future but as might have been obvious with the lack of growth in the nuclear power sector (shown in Figure 8), it has not been competitive due to its high capital cost, relatively low price of fossil fuels and investor risk perceptions. This may be changing with the increasing cost of oil and natural gas making nuclear an option that is being reconsidered by utilities. There are several problems with it that must first be addressed and solved with the combined efforts of the private market and the US government.



**Figure 8: Nuclear Industry Growth in the Past 30 Years**

#### **4. Problems with Nuclear Power**

A greater emphasis on nuclear power has the potential to solve many of the problems of the current energy crisis (environmental and economic), yet the transformation to a nuclear economy is not being aggressively pursued. This is because there are a number of critical problems to overcome before a large expansion of nuclear power can be successful:

- (i) **Cost:** New nuclear plants currently being offered to the market have relatively high capital costs. The MIT Future of Nuclear Energy Study estimates that these new plants will cost approximately \$2000/kwe overnight. (Deutch, 2003) Industry disputes this number citing costs in the \$1500/kwe level. Should the actual contract cost be in the range of

industry estimates, it is expected to be economic with other alternatives.. Even if the capital cost is reduced, long construction time is another significant barrier holding it back as compared to other current technologies.

- (ii) **Safety:** Modern reactor designs are designed to minimize risk of accidents. New nuclear plant designs have reduced the probability of significant reactor accidents by factors of 10 to 100 making them safer than the current fleet. This should assist in the licensing and public acceptance of new nuclear plants. In the wake of 9/11, there has also been growing concern regarding the security of nuclear facilities from terrorist attacks, which must also be addressed.
  
- (iii) **Waste:** Use of nuclear power produces radioactive waste that presents health and environmental risks and must be stored or disposed of safely. Geological disposal has been shown to be technologically feasible but its execution is yet to be demonstrated. The United States has selected Yucca Mountain in Nevada as its geological waste disposal site. License application for the construction and operation of this site will be filed in the next two years according to the Department of Energy. The repository is to open in the next 10 years. In the interim spent fuel from existing nuclear reactors is being stored at reactor sites in dry cask storage facilities or in existing spent fuel pools designed for this purpose.
  
- (iv) **Proliferation:** For US expansion of the nuclear industry, there are no proliferation concerns. However, on an international level, some have judged that the current international safeguards regime is inadequate to meet the security challenges of the expanded nuclear deployment contemplated in a global growth scenario. (Deutch, 2003) Current

reprocessing technologies now used in Europe, Japan, and Russia involve separation and recycling of plutonium which some argue presents unwarranted proliferation risks. (Deutch, 2003)

- (v) **Public Perception:** Nuclear power has perceived adverse safety concerns, environmental and health effects, perceptions that have been heightened by the accidents at Three Mile Island in 1979 and Chernobyl in 1986. While the average US citizen is uninformed of the safety features of nuclear power plants and is more exposed to the possible adverse consequences of accidents associated with nuclear power by sensationalist media coverage, nuclear energy has surprising public support. Shown on Figure 9 is the most recent survey conducted by the Nuclear Energy Institute indicating dramatic increase in public support since the Chernobyl accident in the former Soviet Union. If nuclear expansion plans are to be realized, public education is necessary. The first new plants that will be built are going to be built on existing nuclear plant sites for which there is strong community support.



## Widening Gap Between Those Who Favor and Oppose Nuclear Energy—Annual Averages Until 2004

"OVERALL, DO YOU STRONGLY FAVOR, SOMEWHAT FAVOR, SOMEWHAT OPPOSE OR STRONGLY OPPOSE THE USE OF NUCLEAR ENERGY AS ONE OF THE WAYS TO PROVIDE ELECTRICITY IN THE UNITED STATES?"

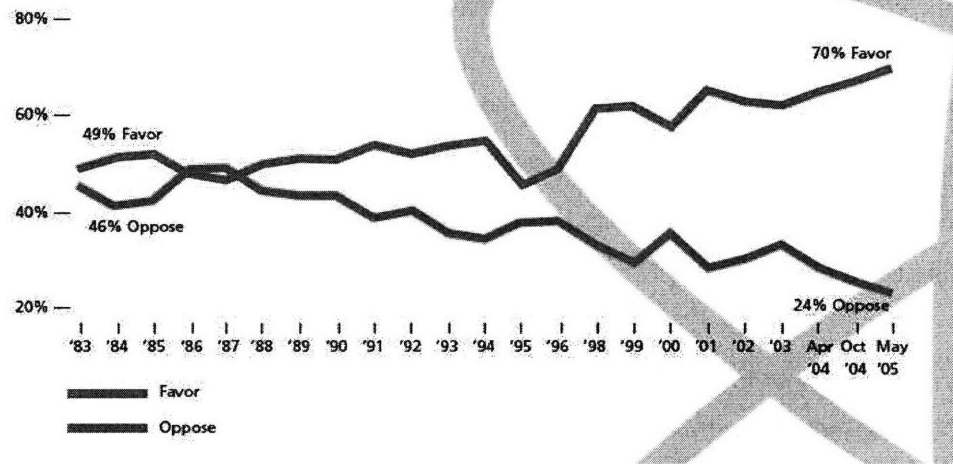


Figure 9: Nuclear Power Public Approval Rating (NEI, 2005)

## 5. Steps to Address Nuclear Power Challenges

### 5.1 Non-Economic Challenges

At present, nuclear power may not be economically competitive with other types of energy sources as discussed in the earlier section and will be validated with data later in this report. Unlike other energy technologies, it also requires significant government involvement due to safety, waste management and proliferation concerns. But given that natural gas supply cannot rise to meet a fast-growing demand, and that renewable energy sources, such as solar and geothermal, have limited potential in meeting the huge US

energy demand, the nuclear option must be retained and made competitive by overcoming the challenges discussed in Section 4. Several studies have been made and reports have been published regarding the most effective ways of addressing the non-economic challenges facing nuclear power, like The Future of Nuclear Power Study by John Deutch, the Organization for Economic Co-operation and Development's 2001 Nuclear Power and Climate Change study, and the WISE program's Nuclear Power Recommendations policy paper by Tyler Ellis. As such, this report will not attempt to analyze these in detail, but will rather list the options that are believed to be the best paths to solving these problems.

- (i) **Safety:** For the next 15 to 20 years existing reactors and current offerings by the industry will be needed to be deployed. These reactors have significant safety improvements but need to be demonstrated in operation. The development of a nuclear workforce is also necessary to meet the 46% attrition rate over the next five years and to allow near-term future expansion of nuclear power (Ellis, 2004). For the long term future in the 50 year time horizon to address a reprocessing and a closed fuel cycle, an issue of paramount importance that can help gain the public's trust in nuclear power, it is recommended that "the government, as part of its near-term R&D program, develop more fully the capabilities to analyze life-cycle health and safety impacts of fuel cycle facilities and focus reactor development on options that can achieve enhanced safety standards and are deployable within a couple of decades." (Deutch, 2003)
  
- (ii) **Waste:** The licensing and commissioning of Yucca Mountain in Nevada for disposal of radioactive waste would be a significant step to development of nuclear power (Energy Central, 2004). While Yucca Mountain is licensed, the government should establish central interim spent fuel storage facilities to

demonstrate that spent fuel can be safely transported in preparation for geological storage, which would be the Yucca Mountain site in Nevada.

- (iii) Proliferation: While not a factor in US deployment, the International Atomic Energy Agency (IAEA) should expand its safeguard functions, pay greater attention to proliferation risks at the front end of the fuel cycle from enrichment technologies, use a safety approach based on continuous materials protection and surveillance, include explicit analysis of proliferation risks in all R&D, and negotiate and implement international spent fuel storage over the next decade. (Deutch, 2003)
- (iv) Public Perception: The US public's views on nuclear power are critical to the expansion of the nuclear industry, and as such a widespread public education program is necessary.

## ***5.2 Economic Challenges***

Next, we will look at the steps needed to make nuclear power economically competitive with other energy sources used in the United States. Investors will choose to invest in nuclear related technologies only if they expect that the cost of producing electricity will be lower than the risk-adjusted cost of producing electricity using alternative means. The major barrier facing the building of new nuclear facilities is the fact that it has high construction/capital cost. Nuclear power plants have the advantage of low fuel and operating costs. What this means is that most of the investment for a nuclear power plant is paid up-front and is not tied to fluctuating unknown future fuel costs. . Thus, the investor has to take on significant risk in deciding to build a nuclear facility because the capital cost is a sunk cost and can face significant losses in the future if better or more cost-effective electricity production options become available. In a competitive deregulated market, it is not possible for the investor to pass on the risk to consumers in

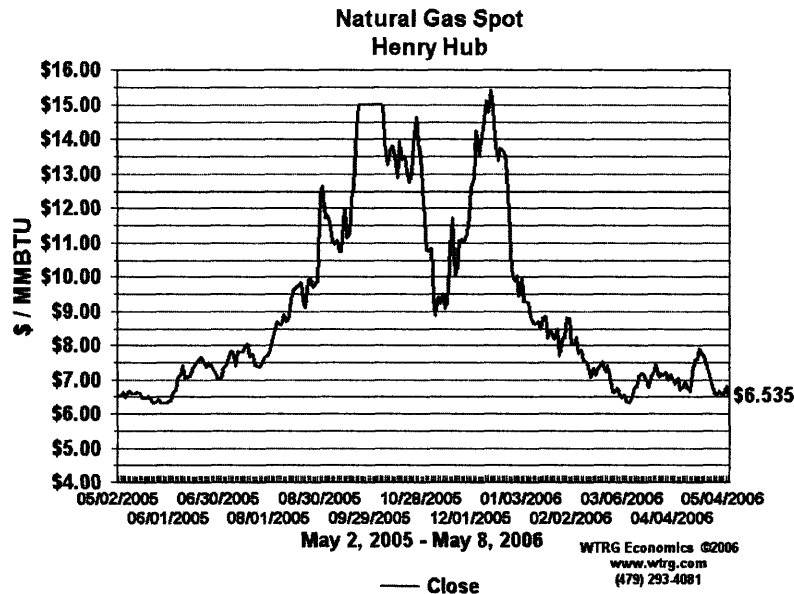
the form of higher prices, and thus he/she must bear the risk of uncertainties associated with obtaining permits, construction costs and operating performance.

Calculations presented in a recent IEA report “Projected Cost of Generating Electricity” using 40-year economic lifetime, 85% average load factor for base-load plants and 10% discount factor, shows levelized electricity generation costs for coal, gas and nuclear as shown in Table 2 (IEA, 2005). The study assumes the following costs: \$1200/kWh overnight construction cost for coal, \$500/kWh overnight construction cost and \$4.25/MMBtu fuel cost for natural gas, and \$1500/kWh overnight construction cost for nuclear.

Type of technology	Levelized Cost (cents/kWh)
Coal	4.0
Natural Gas	4.5
Nuclear	6.2

**Table 2: US Levelized Electricity Generation Cost for Different Technologies**

Until recently, nuclear technology was projected to cost significantly more than both coal-fired and natural gas plants. However, due to the increase in natural gas prices to above \$6/MMBtu (Figure 10), nuclear power is now comparable in cost to natural gas plants (which would now cost 5.8cents/kWh at a natural gas price of \$6/MMBtu), although it is not competitive with coal-fired plants, as shown in Table 2.



**Figure 10: Natural Gas Price Trend in the Past Year (WTRG)**

### 5.2.1 Direct Government Assistance for Nuclear Power

The United States government must take a series of steps to shift the energy sector away from coal and petroleum and towards alternative energy sources. Renewable energy sources are currently incapable of making up the void that will be left by coal and petroleum in the energy market, and thus nuclear power in the electricity generation sector must be a focal point. This can be done in two ways. First, investment in nuclear technology must directly be made more financially attractive and this can be done by government subsidies for “first-mover” construction costs. For nuclear power plants, the 1<sup>st</sup>-of-a-kind plant costs significantly more than the Nth-of-a-kind plant for a number of reasons. The first plant has higher costs - First of a Kind Engineering Costs (FOAKE), licensing costs, and also higher construction costs due to the lack of a learning curve for the new technology and uncertainty. As such, firms are less likely to be the first one building a power plant implementing new nuclear technology, preferring instead to

follow other firms and profit from easier licensing and less costly construction due to prior experience. Just as important, investment in nuclear power plants is capital-intensive and a long construction time means that profits are not realized until the plants become operational in 4 to 5 years. This leads to earnings per share dilution, i.e. more shares are issued by a company to raise capital but the profits are not realized until later, meaning that the share pays low or no dividends, making management less likely to invest for fear of shareholder backlash.

The current US administration has taken a step in the right direction by making the licensing process much shorter and easier with the introduction of early site permits and combined construction and operating licenses. The Energy Policy Act of 2005 provides significant incentives as well which are awaiting final implementation regulations to see how effective they are to stimulate new nuclear plant investment. Some additional initiatives suggested by Ellis are: (Ellis, 2004)

- Partial initial plant financing through government grants or low-interest loans so that companies rely less on issuing debt/equity, e.g. instead of a 50/50 debt/equity ratio, firms can do 40/60 with some of the capital coming from government-guaranteed loans.
- Investment tax credit which allows companies to continually recover partial costs during the period of construction, thus reducing earnings per share dilution and making investment more attractive.
- Production tax credit for nuclear plant electricity generation similar to the one offered for renewable energy sources, which is typically on the order of 1.7 cents/kWh electricity produced from the plant. This will allow companies to hedge market risk once the plant is complete, and is especially important for nuclear technology since a large part of the plant cost is sunk during construction.

- Accelerating depreciation so that companies can recover costs for the plant earlier by paying lower corporate taxes each year, i.e. reduce its liability.

Many of these initiatives are contained in the Energy Policy Act which shows how far the Congress and the administration have come to support new nuclear plants. These include:

- Extension of the Price-Anderson Nuclear Industries Indemnities Act through 2025, which indemnifies the nuclear industry against liability claims arising from nuclear incidents while still ensuring compensation coverage for the general public
- Authorization of cost-overrun support of up to \$2 billion total for up to six new nuclear power plants, thus mitigating the cost uncertainty of 1<sup>st</sup>-of-a-kind plants
- Authorization of loan guarantees for “innovative technologies”, including nuclear, that avoid greenhouse gas emissions
- Authorization of a production tax credit of up to \$125 million per year, comparable with the existing renewable energy PTCs
- Authorization of \$1.25 billion for the Department of Energy to build a nuclear reactor to generate both electricity and hydrogen, and
- Updated tax treatment of decommissioning funds

## 5.2.2 Indirect Government Assistance for Nuclear Power

The second way to encourage investment in nuclear power as an alternative source is an indirect method – making the environmentally-impactful technologies less attractive.

While there are multiple types of undesirable emissions, the most important one is carbon dioxide as shown in Figure 11, and which will be our focus.

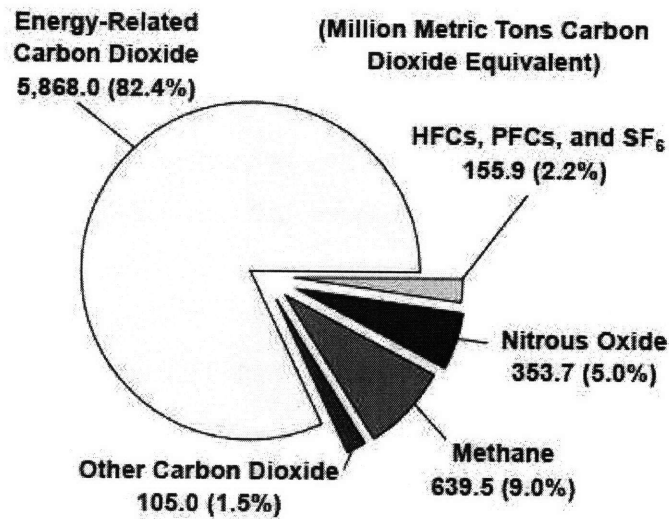


Figure 11: US Greenhouse Gas Emissions (EIA-0573, 2005)

Instituting a carbon tax to internalize the environmental cost of carbon dioxide emissions would increase the cost of using those sources of energy. Table 3 shows carbon dioxide emission rates for current technology electric power stations. (EPA, 2000)

Source	Output Rate (pounds of CO <sub>2</sub> /kWh)
Coal	2.10
Petroleum	1.95
Natural Gas	1.31

Table 3: Carbon Dioxide Emission Rates



The increase in levelized electricity cost as a function of the carbon tax can be calculated using the following equation, where 3/11 is the ratio of carbon in carbon dioxide:

$$\Delta LC = T_{carbon} * (3/11) * OutputRate$$

Using this, Table 4 shows the new levelized costs for coal given different levels of carbon tax.

Carbon Tax (\$/tC)	Coal Levelized Cost (cents/MWh)
50	5.3
100	6.6
150	7.9
200	9.2

**Table 4: Coal Levelized Cost as a Function of Carbon Tax**

The true social cost of carbon emissions should be equal to the cost of carbon sequestration, i.e. the cost of capturing the carbon dioxide released when these fuels are burned. This is estimated to be between \$100/tC to \$200/tC (Deutch, 2003), and a good approximation of the correct tax to be levied would be around \$150/tC. It is to be noted that even a carbon tax at the lower limit of \$100/tC makes nuclear power competitive with coal-fired plants, and will lead to a shift to nuclear power for electricity generation purposes and away from coal.

## **6. Energy Market Effects of a Carbon Tax**

The carbon tax would be levied on all energy sectors, although the implementation would be different. Implementation in the commercial, industrial and electricity sectors would

be quite straightforward as the amount of fuel used and/or emissions released can be measured. In the residential and transportation sectors, implementation of a carbon tax would be trickier, given the sheer number of units that has to be tracked. The simplest method for this would be to add the carbon tax to petroleum or natural gas at the retail level so that it can be paid as consumers by the fuel.

Legislation such as a carbon tax will not change the makeup of the energy sector overnight, especially given that nuclear power plants – the technology we’ve identified as the most cost-effective after a carbon tax – have a minimum of four- to five-year construction period, with a 10-year overall planning and construction timeline. To make this analysis tractable and instructive, we chose to examine the near to medium term, selecting the US energy landscape in the year 2020 to judge the impacts of a carbon tax on energy demand and supply.

### **6.1 Assumptions of Carbon Tax Model**

Table 5 shows 2004 energy consumption data gathered from the Energy Information Agency (EIA) website.

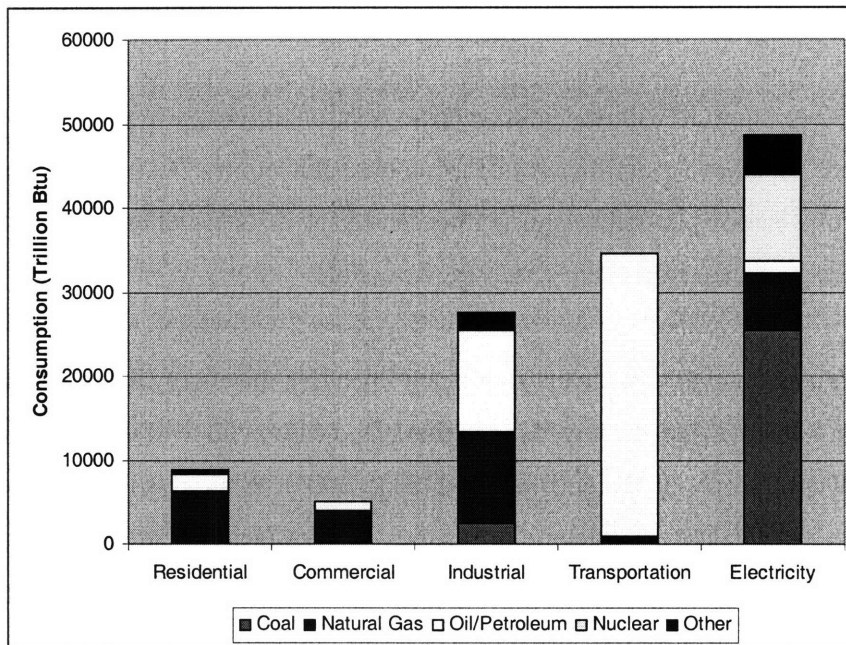
	Consumption by Sector (Trillion Btu)				
	Residential	Commercial	Industrial	Transportation	Electricity
Coal	11	87	2025	0	20268
Natural Gas	5032	3093	8665	705	5486
Oil/Petroleum	1572	787	9572	27004	1195
Nuclear	0	0	0	0	8232
Primary Total	7022	4072	22076	27709	38850

**Table 5: US Energy Consumption by Sector in 2004 (EIA)**

Table 6 shows the predicted energy distribution by sector assuming a blanket 1.5% annual consumption growth rate (a business-as-usual model) over the next 15 years, while Figure 12 gives a graphical representation of it. The consumption for residential, commercial, industrial and transportation are its primary totals, which does not include electricity used as energy in these sectors. This is done to allow us to look at electricity generation independently of energy consumption by other sectors.

	Consumption by Sector (Trillion Btu)				
	Residential	Commercial	Industrial	Transportation	Electricity
Coal	13.75	108.75	2531.25	0	25335
Natural Gas	6290	3866.25	10831.25	881.25	6857.5
Oil/Petroleum	1965	983.75	11965	33755	1493.75
Nuclear	0	0	0	0	10290
Primary Total	8777.5	5090	27595	34636.25	48562.5

**Table 6: Predicted Business-as-usual US Energy Consumption by Sector in 2020**



**Figure 12: Predicted Business-as-usual US Energy Consumption by Sector in 2020**

We begin our analysis of the effects of a carbon tax by noting which technologies have become more expensive (i.e. coal and petroleum, and to a lesser extent, natural gas), and which alternatives in each of the sectors have now become more competitive (i.e. nuclear power in the electricity generation sector). Four important assumptions that have been made are:

1. In the medium-term future, i.e. by 2020, we can expand the use of nuclear power by up to 200 new 1000MW plants to fill supply voids left behind by less competitive technologies, which will be driven out of the market. This is an extremely aggressive target by 2020 but shall be used in our analysis to show potential benefits should the tax be implemented.
2. As per our analysis in section 2, use of natural gas will be capped at present levels since the supply cannot be expanded due its inability to be transported efficiently over long distances, and increased reliance on imports of natural gas should demand increase, since domestic supply has no excess capacity.
3. Carbon sequestration will remain a secondary option as it is presently and will be assumed to not have a significant impact on our calculations. As such, the main effects of a carbon tax will be shifting in each sector in its use of energy sources and greater efficiency in energy use where possible.
4. Coal liquefaction will not have a significant impact in the energy industry. In addition to the barriers discussed in Section 3.1, a carbon tax will increase the cost of production by about 10 cents/barrel. (NETL, 2003) While this is still competitive with current crude oil prices, heavy investment in this technology comes with significant risk due to future crude oil price volatility and inherent cost uncertainty involved with building 1<sup>st</sup>-of-a-kind plants.

## 6.2 Effects of Carbon Tax

The introduction of a carbon tax will lead to the following likely changes in each of our energy sectors.

### 6.2.1 Electricity Sector

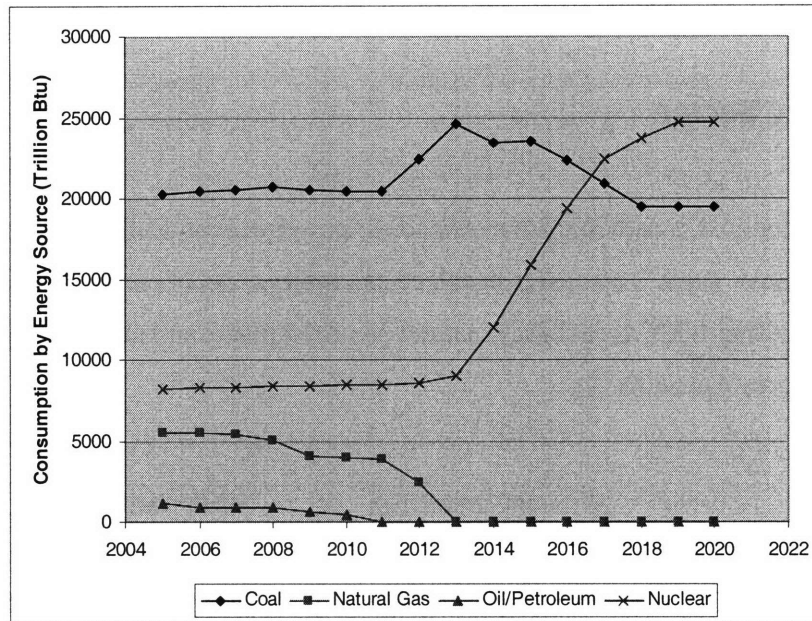
As discussed in Section 4, a carbon tax makes nuclear power economically competitive with coal-fired plants. Table 7 compares levelized electricity costs of normal coal-fired plants, coal plants using IGCC technology, natural gas-fired plants and nuclear power plants (calculations in Appendix A).

	Without Carbon Tax	With Carbon Tax
Normal coal-fired plant	4.0	7.9
IGCC plant	5.0	7.1
Natural Gas-fired plant	5.8	8.2
Nuclear power plant	6.2	6.2

**Table 7: Effect of a Carbon Tax on Levelized Electricity Generation Cost**

This will lead to a classic case of adverse selection, where coal-fired plants that can still efficiently produce electricity will choose to either pay the tax or invest in carbon sequestration technology, while the rest will shut down. The supply void will be taken up by nuclear technology and IGCC coal-fired plants. An important side-effect to note is that natural gas plants now become too expensive at 8.2cents/kWh, as does petroleum for electricity generation, compared to nuclear power and coal, and so both will be pushed out of this sector. Figure 13 shows what is expected to happen. Use of nuclear power goes up, while natural gas and petroleum go down to zero. Electricity produced from

coal stays at the same level, but it is now dominated by IGCC plants as opposed to the coal-fired plant technology used currently. Note that the spike in coal usage is due to increase in IGCC plants while some old coal plants still remained in operation until new nuclear power plant construction could be completed.



**Figure 13: Predicted Consumption Trend in the Electricity due to Carbon Tax**

### 6.2.2 Transportation Sector

Petroleum is the major energy source used in the transportation sector as fuel for cars, ships and airplanes. Natural gas has recently entered this sector as an alternative fuel for cleaner-air buses, but is still a fringe player in the market because it is not economically competitive with regular modes of transportation (Lazarony, 2003). The effects of a carbon tax on this market will not be a major shift in energy sources because there does not appear to be a suitable alternative to petroleum-operated transportation. However, an increase in the price of gasoline due to this carbon tax, will lead to lower consumption

and more efficient vehicles which in turn will lower the demand growth for petroleum in this sector.

### 6.2.3 Residential Sector

In the residential sector, energy is used primarily for heating purposes. Natural gas heating and oil heating are the primary technologies in this sector and they are currently considered competitive in cost, with the natural gas system's slightly higher cost being offset by its comparative environment-friendliness. However, with the new carbon tax, using oil as fuel for heating becomes more expensive than natural gas. The increase in heating oil price is 20% greater than the increase in natural gas price (Appendix B).

Table 8 shows the effects on prices of natural gas, oil and coal with a carbon tax.

	Price (\$/MMBtu)	Change in Price due to Carbon Tax (\$/MMBtu)	New Price (\$/MMBtu)
Coal	2.5	+3.05	5.55
Natural Gas	6.5	+2.10	8.60
Crude Oil	8.6	+2.55	11.15

**Table 8: Price Effects on Fuels due to Carbon Tax**

Table 8 assumes a very conservative crude oil price of \$50/bbl which is much lower than the May 2006 price of \$72/bbl. This is done to ensure our analysis is valid even if prices go down in the future. While coal prices are lower, it is not suitable for residential heating purposes because coal heating systems are generally outdated now and costs significantly more than natural gas or oil heating systems. (Gaiam, 2006) Rising crude oil prices have already made natural gas more palatable as fuel for the residential sector compared to heating oil, and a carbon tax just adds to this. The average US household using heating oil consumes more than 200MMBtu of heating oil annually, which means

that they can save more than \$500 per year on fuel costs by switching to natural gas. This surplus over the 20-year life of a heating system is sufficient to cover the cost of switching heating systems from oil to natural gas. (Gaiam, 2006) Assuming an average 20-year turnover rate and considering the infrastructure needed for switching heating systems (Gaiam, 2006), it can be expected that by 2020, an estimated 80-85% of high-end users (Northeast & Midwest in Figure 14) will switch from oil to natural gas, while low-end users (Southeast & West Coast, Figure 14) will find it cost-effective to stop using oil and switch to electricity-generated or solar heating instead.

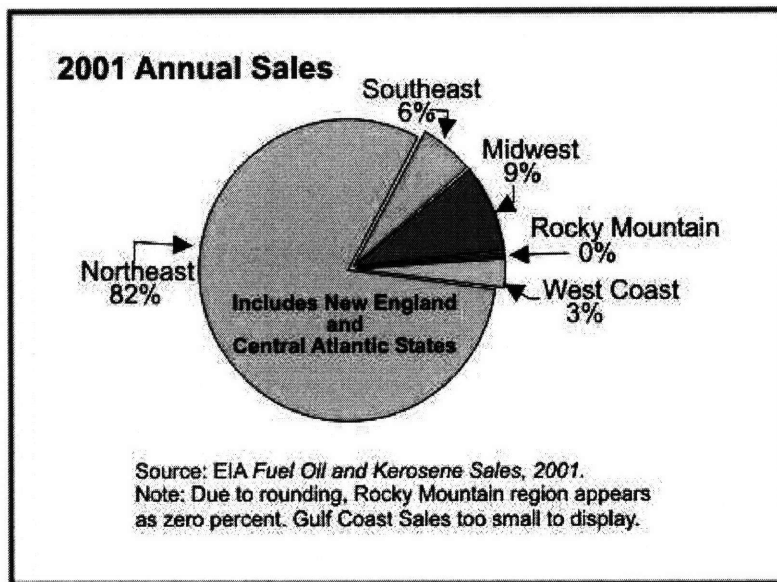


Figure 14: Residential Heating Oil Sales by Region (EIA)

## 6.2.4 Commercial Sector

In the commercial sector, similar to the residential sector, energy is used primarily for heating purposes. Natural gas and heating oil are once again the primary technologies available, although natural gas is more prevalent here, and has been becoming more popular over the past decade. The institution of the carbon tax can only serve to



accelerate this trend, given the significant fuel cost savings as indicated in Table 8. Thus by 2020, natural gas is expected to essentially be the sole source of energy in this sector.

### **6.2.5 Industrial Sector**

In this sector, primary energy (i.e. non-electrical energy) is used for a variety of different purposes and thus cannot be grouped as a whole. Natural gas and oil share this sector almost equally providing for about 85% of the total energy requirements together, with coal supplying about 10% of the energy. In the same vein as the commercial sector, natural gas has been gaining ground in this sector, although oil technology is still much cheaper for some industrial requirements. A carbon tax in this sector will lead a shift towards the use of natural gas. The market segment of crude oil-using technology where natural gas technology is competitive with oil technology is around 50%, and the market segment of coal-using technology where natural gas technology is cheaper is around 25%. (NAM, 2005) This is both due to the fact that natural gas might be incompatible with some of the technologies required in this sector, as well as the fact that natural gas supply is saturated and so total natural gas usage in the economy cannot go up. As a result of the fuel cost efficiency of natural gas, as shown in Table 8, it is expected that natural gas will capture the 50% of oil market share and 25% of coal market share. The higher fuel prices will also encourage coal and oil users to invest in more efficient technologies, up to 10-20% (NAM, 2005), thus reducing the predicted energy consumption in 2020.

### **6.3 US Energy Market Predictions**

As discussed in section 6.2 and shown on Table 8, the institution of a carbon tax combined with increasing crude oil prices has made natural gas as a fuel almost 25% cheaper than crude oil. Thus, given that capital costs of natural gas systems in a sector is

comparable to that of oil/petroleum systems and the switching costs are low enough that users will realize savings from lower fuel costs, the following changes are assumed to take place for this study given the economic imperative to find lowest operating costs. In order to more accurately predict fuel switching patterns, a more sophisticated economic analysis will be needed that assesses the prices at which consumers will switch fuels. While this is beyond the scope of this thesis, the assumptions made below can be readily adjusted to assess impacts. The model described here takes the predicted business-as-usual energy consumption model in 2020 from Table 6, and applies the following market effects and constraints, which are discussed extensively in the previous section:

- **Transportation sector:** Natural gas technology cost is much higher than petroleum technology cost in this sector. Thus, natural gas usage goes up marginally – by 15% – while more efficient vehicles and lower consumption reduce petroleum demand by 20%. (FuelEconomy.gov)
- **Residential sector:** Current natural gas users will stay with natural gas. However, due to the significant savings that can be realized by switching to natural gas (as shown in section 6.2.3) 80% of the high-end oil users (90% of demand) will switch to natural gas and 20% will stay with oil. The low-end oil users (10% of demand) will all switch to electricity generated heating systems.
- **Commercial sector:** Since natural gas technology is comparable in capital costs petroleum and cheaper than coal, the fuel cost savings will drive this sector towards using natural gas as the sole energy source, completely replacing both coal and petroleum sources.
- **Industrial sector:** 50% of coal and 25% of oil users will switch to natural gas, as discussed in section 6.2.5. For those remaining with coal and oil, a 10% consumption efficiency improvement will be seen.

- Electricity sector: Total consumption will increase by 10% of oil usage in the residential sector. Natural gas and petroleum generation will completely shut down. Coal-fired plants using current technology will go down by 75%. Nuclear power in the sector will increase to fill the void created, or by 200 new power plants, whichever is lower. Any remaining demand void is met by new coal IGCC plants.

Given these changes and assumptions, the US market for energy in 2020 will look significantly different from the predicted business-as-usual market, as shown in Table 9.

	Consumption by Sector (Trillion Btu)				
	Residential	Commercial	Industrial	Transportation	Electricity
Coal	0	0	1139.1	0	19480
Natural Gas	7718.55	5090	15088.1	1000	0
Oil/Petroleum	353.7	0	8076.4	27004	0
Nuclear	0	0	0	0	24692
Primary Total	8581	5090	26571	28004	48759

**Table 9: Predicted US Energy Consumption by Sector in 2020 with a Carbon Tax**

While the consumption of natural gas remains about the same as predicted before and oil/petroleum consumption drops, nuclear power sees a huge boost from its earlier prediction since it does not incur any carbon tax and is therefore now more competitive than the other options. According to the calculations, 200 new nuclear power plants will have to be built by 2020 to meet demand. Consumption of coal remains at about the same level, but IGCC plants have taken the place of old coal-fired plants in the electricity sector.

## 6.4 Environmental Impact

In terms of the environmental effects of this carbon tax, Figure 15 shows the 2003 emissions levels, and Figure 16 compares 2020 predicted emissions levels with and without the institution of a carbon tax (calculations in Appendix D).

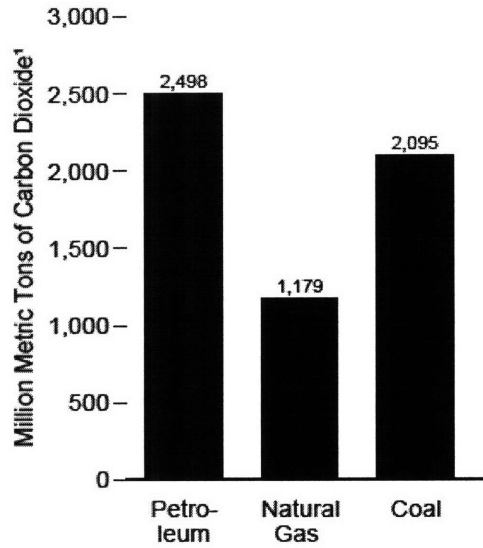


Figure 15: Emission Levels by Energy Source in 2003 (EIA)

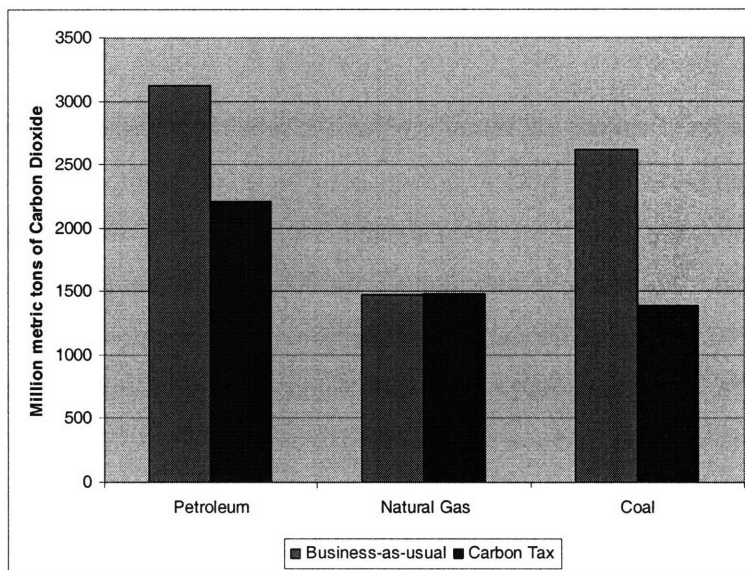


Figure 16: Predicted Emission Levels in 2020 by Energy Source in Two Scenarios

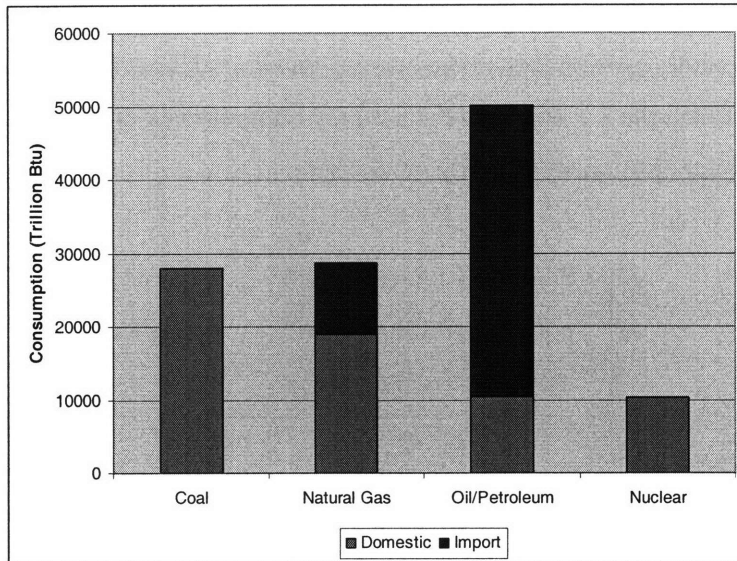
Carbon taxation does appear to have a significant impact on emissions levels, lowering carbon dioxide emissions by 30% from a business-as-usual model over the next 15 years, and it will serve to fulfill the US environmental policy requirements of leading our energy sector towards pollution-free energy production.

	Emissions Level – major polluters (million metric tons of carbon dioxide)	Percent Decrease in 2020 using Carbon Tax model
2003	5772.0	-12.1%
2020 (Predicted, Business-as-usual)	7214.9	-29.6%
2020 (Predicted, Carbon Tax)	5076.1	---

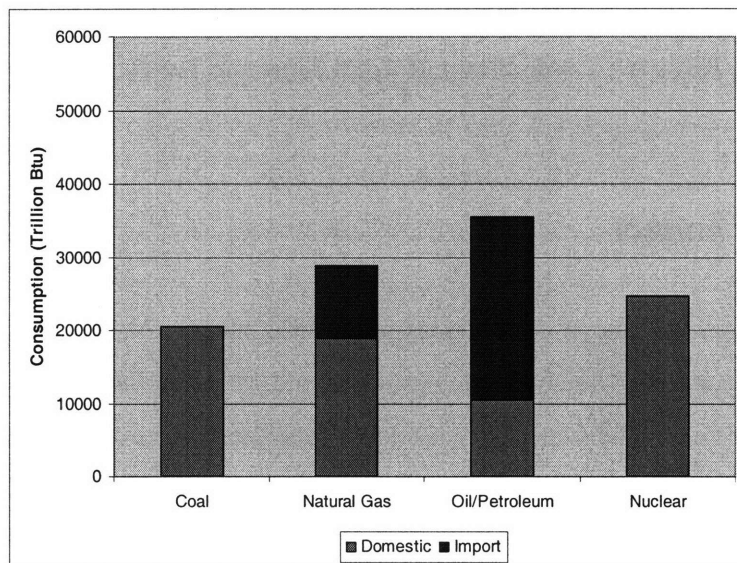
**Table 10: Comparison of Total Emission Levels**

### ***6.5 Economic Impact***

From an economic perspective, this carbon tax policy also has its advantages in international energy trading. As shown in Figures 17 and 18, while the import level of natural gas remains almost the same, there is a large decrease in the import of crude oil, from almost 80% of total consumption without a carbon tax to less than 60% with the tax.



**Figure 17: Predicted Energy Supply in 2020, Business-as-usual**



**Figure 18: Predicted Energy Supply in 2020 with a Carbon Tax**

This equates to a reduction of 2.54 billion barrels imported annually and a subsequent US reduction of over \$165 billion in costs for foreign oil, assuming current oil prices of \$65/barrel. A statistic that is not shown in the graphic is the surplus production of coal from the US coal mines that are not being used for domestic production. This surplus is

about 118.6 short tons of coal, which can be sold in the open market at a price of \$50 for an export increase of \$5.93 billion. (Appendix E) Thus, while the US economy is still dependent on foreign energy sources, it is much less so with a carbon tax which can provide over a \$170 billion annual trade relief to America's ever-growing trade deficit.

## **7.0 Conclusions**

Nuclear power has the potential to solve, or at the very least, mitigate a number of the potential problems facing the US energy industry. It is environmentally clean, and is domestically produced. With rising concern about greenhouse gas emissions and its effects on our environment, and the US's ever-increasing dependence on foreign imports to meet its energy needs, it is imperative for the US government to take steps to reverse these trends. While renewable energy has been more closely looked at, it is due to many public misconceptions of the dangers of nuclear power. Nuclear technology has a demonstrated capacity to produce clean energy and has a much better potential for expansion than renewable energy options. It needs government support to encourage industry to move forward to deployment.

It is recommended that the government encourage investment in nuclear power directly through more funding of R&D, faster certification processes, partial investment financing and tax credits. In addition, the government must immediately work to discourage growth of crude oil and coal energy by instituting carbon taxes, which has the potential to reduce emissions by 30% and create an international trade surplus of more than \$170 billion annually by the year 2020. The strategy identified will not increase reliance on foreign sources of energy, will cap natural gas production at current levels, will shift natural gas from electricity production to more useful applications in residential, commercial and industrial applications displacing oil and reducing oil imports. Clean coal technologies will be encouraged and nuclear energy significantly expanded due to its economic and true environmental value to contribute to the nation's energy mix.

## **Appendix**

### **A. Levelized Electricity Costs**

Carbon tax calculation equation in Section 5:

$$\Delta LC = T_{carbon} * (3/11) * OutputRate$$

Therefore, for each \$50/tC tax, the levelized electricity cost increase is

$$\Delta LC_{coal} = 1.3cents / kWh$$

$$\Delta LC_{NG} = 0.8cents / kWh$$

$$\Delta LC_{IGCC} = 0.7cents / kWh$$

Assuming a \$150/tC carbon tax, the new levelized electricity cost is

$$LC_{coal} = (4.0 + 3 * 1.3) = 7.9cents / kWh$$

$$LC_{NG} = (5.8 + 3 * 0.8) = 8.2cents / kWh$$

$$LC_{IGCC} = (5.0 + 3 * 0.7) = 7.1cents / kWh$$

### **B. Real Cost of Natural Gas and Petroleum as Fuels for Heating**

The data in Table A-1 was gathered from the EIA website and is used to calculate the unit emissions of natural gas and petroleum.



	Natural Gas	Petroleum	Coal
Total Consumption (Trillion Btu)	22981	40130	22391
Total CO2 Emissions (Million metric ton of CO2)	1179	2498	2095
Unit Emission (metric ton of CO2 per MMBtu)	0.05130	0.06225	0.09356

**Table A- 1: Emissions for Each Major Energy Source (EIA)**

The increase in price due to a \$150/tC carbon tax for each resource is

$$\Delta P_{NG} = \text{Emission} * (3/11) * T_C = 0.05130 * (3/11) * 150 = \$2.10 / \text{MMBtu}$$

$$\Delta P_{oil} = \text{Emission} * (3/11) * T_C = 0.06225 * (3/11) * 150 = \$2.55 / \text{MMBtu}$$

$$\Delta P_{coal} = \text{Emission} * (3/11) * T_C = 0.09356 * (3/11) * 150 = \$3.03 / \text{MMBtu}$$

### **C. Predicted Energy Consumption with the Institution of a Carbon Tax**

Table A-2 is a copy of Table 4 in the text and is used for ease of reference for the following calculations. The results are shown in Table A-3.

	Consumption by Sector (Trillion Btu)				
	Residential	Commercial	Industrial	Transportation	Electricity
Coal	13.75	108.75	2531.25	0	25335
Natural Gas	6290	3866.25	10831.25	881.25	6857.5
Oil/Petroleum	1965	983.75	11965	33755	1493.75
Nuclear	0	0	0	0	10290
Primary Total	8777.5	5090	27595	34636.25	48562.5

**Table A- 2: Predicted US Energy Consumption in 2020**

Transportation sector consumption:

$$Coal_{new} = Coal_{old} = 0$$

$$NaturalGas_{new} = NaturalGas_{old} * 1.15 = (881.25 * 1.15) \approx 1000$$

$$CrudeOil_{new} = CrudeOil_{old} * 0.80 = (33755 * 0.80) = 27004$$

$$Nuclear_{new} = Nuclear_{old} = 0$$

$$Total_{new} = NaturalGas_{new} + CrudeOil_{new} = (1000 + 27004) = 28004$$

Residential sector consumption:

$$Coal_{new} = Coal_{old} * 0.00 = 0$$

$$NaturalGas_{new} = NaturalGas_{old} + (CrudeOil_{old} * 0.90 * 0.80)$$

$$= 6290 + (1965 * 0.90 * 0.80) = 7718.55$$

$$CrudeOil_{new} = CrudeOil_{old} * 0.90 * 0.20 = (1965 * 0.90 * 0.20) = 353.7$$

$$Nuclear_{new} = Nuclear_{old} = 0$$

$$Total_{new} = Total_{old} - \Delta Oil to Electricity = 8777.5 - (1965 * 0.10) = 8581$$

Commercial sector consumption:

$$Coal_{new} = Coal_{old} * 0.00 = 0$$

$$NaturalGas_{new} = NaturalGas_{old} + CrudeOil_{old} + Coal_{old} + Other_{old} = Total_{new} = 5090$$

$$CrudeOil_{new} = CrudeOil_{old} * 0.00 = 0$$

$$Nuclear_{new} = Nuclear_{old} = 0$$

$$Total_{new} = Total_{old} = 5090$$

Industrial sector consumption:

$$Coal_{new} = Coal_{old} * 0.50 * 0.90 = (2531.25 * 0.50 * 0.90) = 1139.1$$

$$NaturalGas_{new} = NaturalGas_{old} + (Coal_{old} * 0.50) + (CrudeOil_{old} * 0.25) \\ = 10831.25 + (2531.25 * 0.50) + (11965 * 0.25) = 15088.1$$

$$CrudeOil_{new} = CrudeOil_{old} * 0.75 * 0.90 = (11965 * 0.75 * 0.90) = 8076.4$$

$$Nuclear_{new} = Nuclear_{old} = 0$$

$$Total_{new} = Total_{old} - (Coal_{old} * 0.50 * 0.10) - (CrudeOil_{old} * 0.75 * 0.10) \\ = 27595 - (2531.25 * 0.50 * 0.10) - (11965 * 0.75 * 0.10) = 26571$$

Electricity sector consumption (nuclear power conversion rate assumes 85% base-load efficiency):

$$Coal_{new} = Coal_{old} * 0.25 + IGCC = Coal_{old} * 0.25 + (Total_{new} - Nuclear_{new} \\ - Coal_{old} * 0.25 - Other) = Coal_{old} * 0.25 + (Total_{new} - Nuclear_{new} - Coal_{old} * 0.25 \\ - Total_{old} - Coal_{old} - NaturalGas_{old} - CrudeOil_{old} - Nuclear_{old}) = 19480$$

$$NaturalGas_{new} = NaturalGas_{old} * 0.00 = 0$$

$$CrudeOil_{new} = CrudeOil_{old} * 0.00 = 0$$

$$Nuclear_{new} = Nuclear_{old} + (200 plants) * (1000MW / plant) * (0.077734TBtu / MW) \\ = 24692$$

$$Total_{new} = Total_{old} + \Delta ResidentialOiltoElectricity = 48562.5 + (1965 * 0.10) = 48759$$

	Consumption by Sector (Trillion Btu)				
	Residential	Commercial	Industrial	Transportation	Electricity
Coal	0	0	1139.1	0	19480
Natural Gas	7718.55	5090	15088.1	1000	0
Oil/Petroleum	353.7	0	8076.4	27004	0
Nuclear	0	0	0	0	24692
Primary Total	8581	5090	26571	28004	48759

**Table A- 3: Predicted US Energy Consumption in 2020 with a Carbon Tax**

### **D. Environmental Effects of a Carbon Tax**

Table A-3 shows the revised predictions of energy consumption with a carbon tax. We will now quantify the effects of this revision on the pre-carbon tax emissions. Table A-4 shows the emission rates for each major energy source in the business-as-usual model, while table A-5 shows the emission rates for the carbon tax model. Total emissions by each energy source can be calculated by:

$$\text{Total Emissions} = (\text{Unit Emission}) * (\text{Total annual consumption})$$

This gives us the expected carbon dioxide emissions in 2020 without a carbon tax.

	Natural Gas	Petroleum	Coal
Total Consumption (Trillion Btu)	28726.25	50162.5	27988.75
Unit Emission (metric ton of CO2 per MMBtu)	0.05130	0.06225	0.09356
Total CO2 Emissions (Million metric ton of CO2)	1473.7	3122.6	2618.6

**Table A- 4: Predicted Emissions by Energy Source in 2020, Business-as-usual**

	Natural Gas	Petroleum	Coal (non-IGCC)	Coal (IGCC)
Total Consumption (Trillion Btu)	28896.6	35434.1	7473	13146
Unit Emission (metric ton of CO2 per MMBtu)	0.05130	0.06225	0.09356	0.0524
Total CO2 Emissions (Million metric ton of CO2)	1482.4	2205.8	699.1	688.8

**Table A- 5: Predicted Emissions by Energy Source in 2020, Carbon Tax**

### ***E. Economic Effects of a Carbon Tax***

Table A-3 shows the revised energy consumption predictions with a carbon tax in 2020. We will now quantify this to study its economic effects. As shown in Figure 4, the US is currently capable of supplying 26% of its annual crude oil demand ( $=0.26*40130=10433.8$  TBtu), and 82% of its annual natural gas demand ( $(0.82*22981=18844.4$  TBtu). US petroleum production had been steadily decreasing in the past couple of decades, but there have been some new oil drilling initiatives recently, so for our purposes we will assume that crude oil production remains constant in the US. It will be assumed that natural gas production will grow at the same rate as energy growth, i.e. 1.5% annually. All nuclear power is still produced domestically. Coal is produced domestically, and is assumed to stay at a constant rate of production in Table A-6, and match coal consumption in Table A-7.

	Total Consumption (Trillion Btu)	Domestic Production (Trillian Btu)	Imports (Trillian Btu)
Coal	20619.1	23080.5	0
Natural Gas	28896.6	18844.4	10052.2
Oil/Petroleum	35434.1	10433.8	25000.3
Nuclear	24692	24692	0

**Table A- 6: Predicted Energy Consumption and Supply in 2020 with a Carbon Tax**

	Total Consumption (Trillion Btu)	Domestic Production (Trillian Btu)	Imports (Trillian Btu)
Coal	27988.75	27988.75	0
Natural Gas	28726.25	18844.4	9881.85
Oil/Petroleum	50162.5	10433.8	39728.7
Nuclear	10290	10290	0

**Table A- 7: Predicted Energy Consumption and Supply in 2020, Business-as-usual**

Change in crude oil imports =  $(39728.7 - 25000.3) = 14728.4$  TBtu = 2.54 billion barrels

Amount saved in crude oil imports = 2.54 billion barrels \* \$65 = \$165 billion

Surplus of domestic coal production =  $(23080.5 - 20619.1) = 2461.4$  TBtu = 118.6 million short tons

Export profits from selling surplus = 118.6 million short tons \* \$50 = \$5.93 billion

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