

Minimum Carbon Tax Level Needed to Prompt a Widespread Shift to Nuclear Power

By
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In Partial Fulfillment of the Requirements
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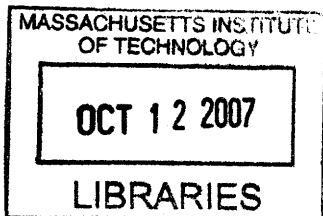
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1. Abstract

Carbon dioxide is suspected to be a major contributor to global warming. In the United States, nearly 70% of electricity is produced using coal or natural gas, both of which emit carbon dioxide into the environment. Nuclear power, which does not emit any carbon dioxide, produces 17% of the electricity consumed in the United States. In order to persuade utilities to switch from coal or natural gas to nuclear power and thus reduce carbon dioxide emissions, a carbon tax should be implemented. Depending on the cost of construction for new nuclear plants and the level of savings that will incentivize utilities to switch, the carbon tax needed to promote nuclear power will range between \$20/tC and \$200/tC. The full range of carbon tax scenarios are developed in this thesis, with the most likely carbon tax being \$110/tC. This cost assumes a \$1800/kw capital construction cost and a 10% risk perception premium on the bus bar cost of power to address the financial and industry community's somewhat negative perception of nuclear investments. From a policy perspective, this carbon tax will be more effective in causing utilities to move to nuclear power than a cap and trade policy. From a utility standpoint, switching to nuclear power under a carbon tax is less expensive than implementing a program of carbon capture and sequestration.

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2. Introduction

A Pigovian tax is used to limit negative externalities in society. Commonly referred to as sin taxes, such taxes are used by all 50 states to raise revenue from the sale of alcohol and cigarettes. Pigovian taxes can also be applied to producers who release harmful byproducts into the environment. This type of tax is a pollution tax, and it has two purposes. First, it is intended to encourage producers to reduce their pollutions and second, it can raise money to help fight the effects of pollution.

This pollution tax is thought to be a better way of reducing pollutants than the more straightforward government regulation. With regulation, a polluter can release a certain set amount of pollutants into the environment at no cost to him, and he has no incentive to lower his emissions below the set regulation rate. With a tax, however, there is a charge on all emitted pollutants. Therefore, although regulation can lower pollutants to a government regulated set level, a pollution tax, if set at the proper level, will always give producers an incentive to keep reducing their pollution.

One type of pollution tax, the carbon tax, is especially relevant to the future of nuclear power. Release of carbon dioxide into the atmosphere is judged to be the main contributor to global warming. In 2005, over 2.5 billion metric tons of carbon dioxide were released during power generation in the United States [1]. As seen in Figure 1, this is almost 300 million metric tons higher than the carbon dioxide release in 1999, just six years earlier.

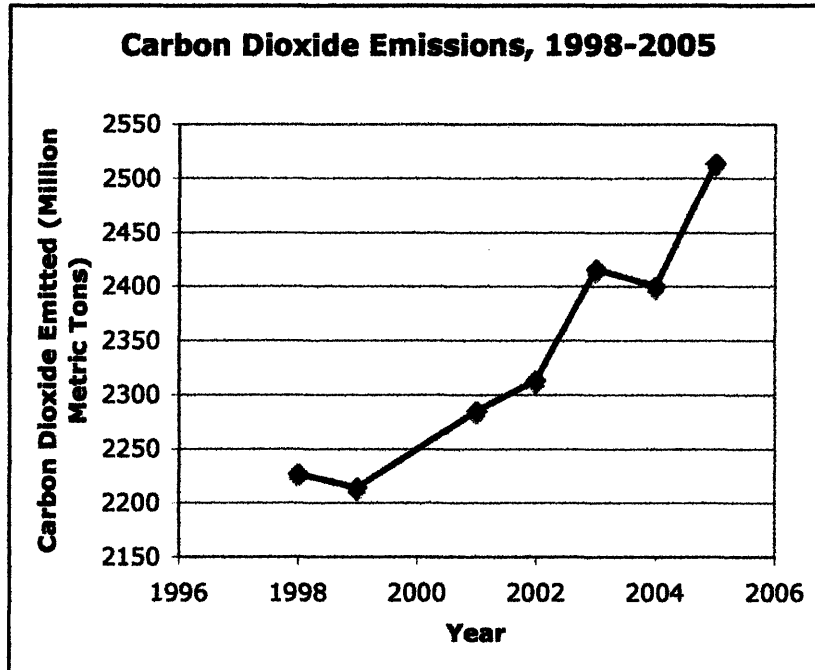


Figure 1. Carbon Dioxide Emissions in Million Metric Tons from 1998 to 2005 [1].

The damage done by CO₂ emissions to the atmosphere is being researched by many universities and organizations. Preliminary reports do not agree on an estimate of the marginal damage costs of these emissions. By combining 28 published studies, the marginal damage estimates had a mode of \$2/tC, a median of \$14/tC, and a mean of \$93/tC. The 95th percentile rose to \$350/tC [2]. This range aside, experts from Germany, the Netherlands, and the United States agree that the marginal damage costs are unlikely to exceed \$50/tC and argue that a carbon tax should be set accordingly [2]. Economic experts, however, argue that marginal damage costs are closer to \$85/tC [3], and they assert that the carbon tax must match this value. Regardless, while these prices would generate revenue from carbon dioxide emissions, research has not been done to determine if they are high enough to incentivize utilities to switch from fossil fuels to non-carbon dioxide emitting power generation.

While it is necessary to cut down on carbon dioxide emissions, there is no known way to convert coal, oil, and natural gases into energy without creating carbon dioxide. There are, however, a few options to reduce carbon dioxide emissions from current plants. First, research could develop new technologies to increase the efficiency of new or current coal and oil plants. Second, a higher reliance on natural gas would help to reduce carbon dioxide release, as natural gas emits less carbon dioxide than coal or oil plants. While both of these solutions would somewhat reduce emissions, neither would be able to completely reduce carbon dioxide pollution [4]. A third method involves capturing carbon dioxide and permanently storing it. At this time, capture and sequestration is not economically feasible, as it is predicted to cost up to an additional 5 cents/kwhr [5], which would almost double the current costs of coal and natural gas.

There are also alternative ways to generate power that do not release any carbon dioxide into the atmosphere. One of these is nuclear power. Through analyzing costs of coal, natural gas, and nuclear energy production, the minimum level of carbon tax needed to incentivize power production companies to switch to nuclear power can be calculated. By either shutting down existing coal and natural gas plants and replacing them with new nuclear plants, or by simply building new nuclear plants instead of coal and natural gas plants, a carbon tax will promote nuclear power and reduce carbon dioxide emissions.

3. U.S. Energy Generation Sources and Carbon Emissions

In 2005, United States energy consumption was 100.6 quadrillion Btu [6], making the United States the largest energy consumer in the world.

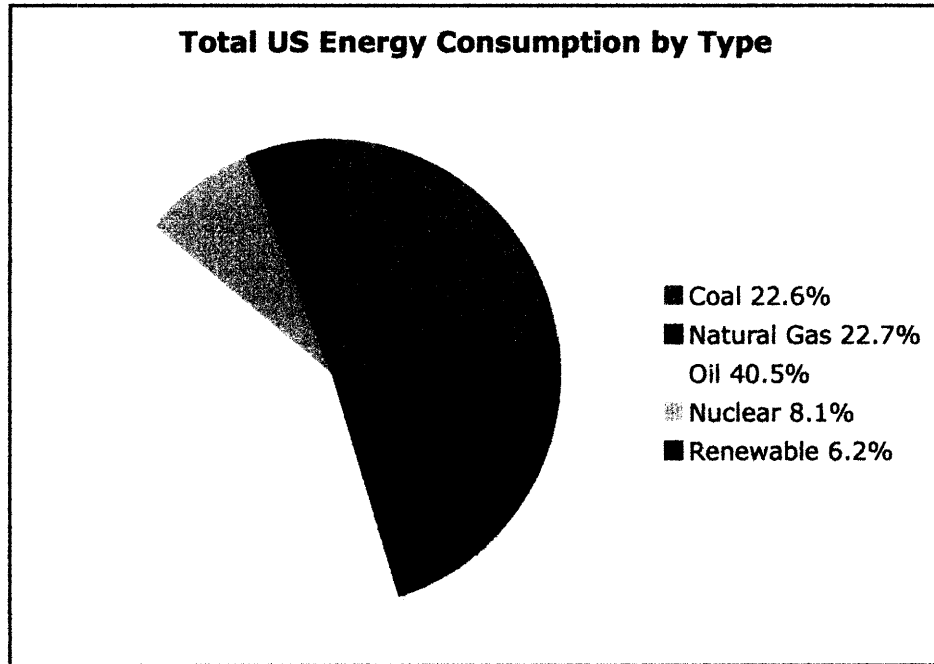


Figure 2. Proportions of Energy Sources Consumed in the United States [6].

As seen in Figure 2, the main source of energy for the United States is oil. The United States imports most of its oil, as it produces just over 8 million barrels a day, while consuming roughly 20 million barrels per day [7, 8]. Oil, however, is mostly used in industrial and transportation sectors, and is only used to generate about 3% of United States electricity. It is therefore valuable to look instead at US electricity consumption to better understand the proportions between coal, natural gas, and nuclear. These proportions are shown in Figure 3.

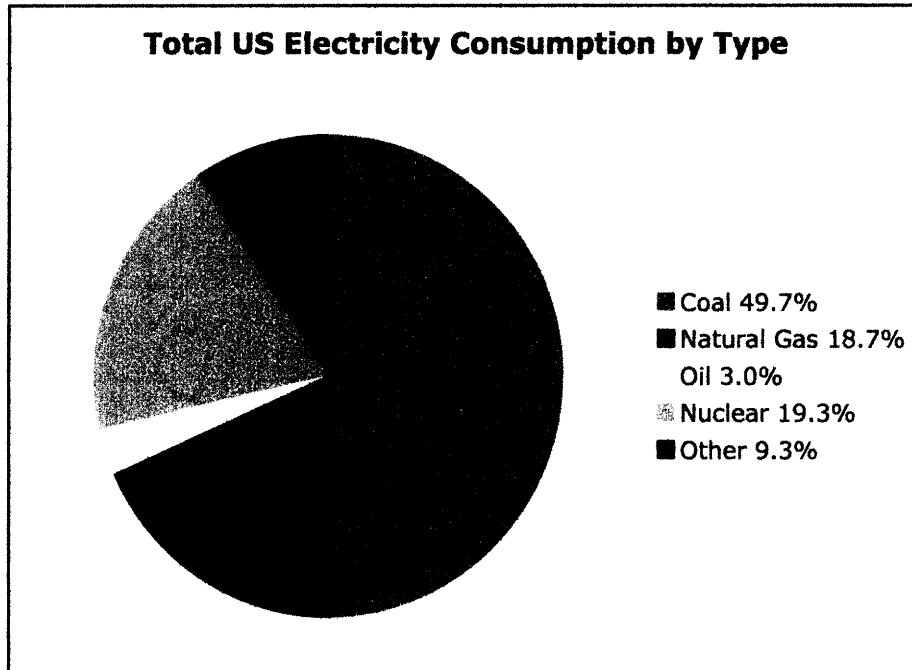


Figure 3. Proportions of Electricity Sources Consumed in the United States [9].

3.1 Coal

Coal is the most common source of electricity production, accounting for almost half of all electricity produced in the United States. In 2005, coal alone produced over 2 billion megawatt-hours [9]. Coal's popularity is due to its two important advantages. First, there is a plentiful supply of coal. The U.S. Geological Survey estimates the United States has a coal reserve as large as four trillion tons [10], which at current consumption levels would last for 200 years. Second, the cost of coal is relatively low, and because very little coal is imported, the price is not vulnerable to international relations, making the price of coal very stable.

But coal also has its disadvantages. First, coal is not renewable. The other disadvantage is the large amount of CO₂ that is released when coal is burned. Producing 2.5 billion

tons of carbon dioxide a year, coal-burning power plants are the largest source of carbon dioxide pollution in the United States [11]. For each kilowatt-hour of coal power, 2.095 pounds of carbon dioxide, or 0.571 pounds of pure carbon, are released into the environment [12].

3.2 Natural Gas

The next most common fossil fuel is natural gas, which accounts for nearly 20% of US electricity production. In 2005, natural gas produced over 750,000 megawatt-hours in the United States [9]. Natural gas has its advantages due largely to its ease of use, low capital cost, and short construction time to bring generation on-line. At the current rate of consumption, the U.S. Geological Survey estimates that there only is a 50-year supply of recoverable, undiscovered natural gas in the United States alone [13].

Natural gas also has disadvantages. Even though the supply is judged to be plentiful either in natural or liquefied form, natural gas prices experience large fluctuations [14]. Pipelines to transport natural gas are very expensive to build and maintain. Second, natural gas is flammable and strict precautions have to be taken during transport and use.

The last disadvantage to using natural gas for power production is often looked at as an advantage. Natural gas produces carbon dioxide when burned. But because it produces less carbon dioxide as coal, natural gas proponents describe the lower carbon dioxide output as an advantage. In reality, any amount of carbon dioxide released into the environment is a disadvantage. For each kilowatt-hour of natural gas energy, 1.314

pounds of carbon dioxide, or 0.358 pounds of pure carbon, are released into the environment [12].

3.3 Nuclear

Nearly 20% of US electricity produced comes from nuclear power plants. In 2005, nuclear energy plants generated slightly over 780,000 megawatt-hours [9]. The advantages and disadvantages of nuclear power are widely debated. In the 1970's, nuclear power reached a peak in popularity, before the partial meltdown at Three Mile Island reduced public support. There are, however, many advantages to nuclear power that cannot be easily dismissed. First, nuclear fuel is found around the world, with 17 countries, including the United States, Australia, and Canada, producing concentrated uranium oxides [15]. Second, nuclear power production does not release any carbon dioxide into the atmosphere. This is a unique advantage over coal and natural gas.

The disadvantages of nuclear power are more open to debate. Many people are afraid of nuclear power, because they think there is a high chance of a meltdown leading to radioactive emissions, which will harm the public. Second is the issue of the disposal of nuclear waste. Currently, in addition to on-site storage, the only solution in the United States to dealing with nuclear waste is the proposed nuclear waste repository at Yucca Mountain, Nevada, which is over 20 years behind schedule. For the future, new technologies are being developed to turn nuclear waste into nuclear fuel. Although the overall cost of nuclear today is higher than that of fossil fuels, if carbon sequestration is required, this will change.

3.4 The Effects of Carbon Dioxide

Greenhouse gases are a primary cause of global warming. Increasing levels of greenhouse gases, such as water vapor, methane, carbon dioxide, and nitrous oxide, are causing higher temperatures across the world.

When light energy comes from the sun to the Earth, it is able to pass through the atmosphere and bring heat to the Earth. Heat from the Earth, however, is a different wavelength than sunlight. When the heat from the Earth reaches the atmosphere, it is not able to pass through. Instead, it is absorbed by carbon dioxide, causing the carbon dioxide to move to an unstable, excited state. When the molecule becomes stable again, it releases the energy it has absorbed. Some of this energy goes into space, and some comes back to Earth. Essentially, carbon dioxide allows the heat from the sun in, but it doesn't let the Earth's heat out. It causes the atmosphere to work like a greenhouse [16].

Since the Industrial Revolution, the level of carbon dioxide in the atmosphere has been rising. The rise in the past 200 years is illustrated in Figure 4. Carbon release per year has gone from a negligible amount to almost 7000 million metric tons [17]. Increasing industrialization relies on fossil fuels, causing an increase in carbon dioxide levels.

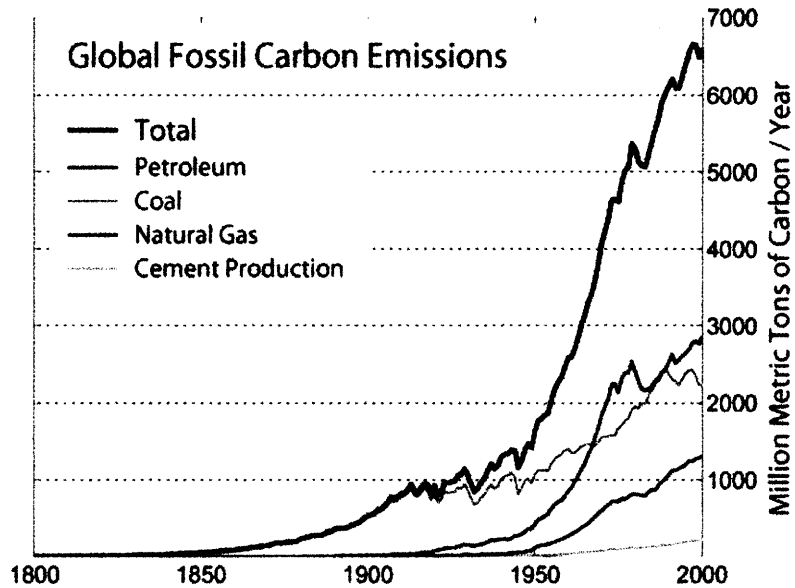


Figure 4. Level of Carbon Dioxide in the Atmosphere since 1800 [17].

Carbon dioxide levels fluctuate seasonally, due to plant absorption and release, but the overall trend is clear. As of January 2007, carbon dioxide levels had reached 393ppm in the Earth’s atmosphere, up approximately 105ppm from pre-Industrial Revolution levels [18]. In the past 50 years, carbon dioxide concentration has risen over 50 parts per million. Even more recently, in the past 5 years alone, the average level of carbon dioxide has been rising about 2.25ppm per year, as seen in Figure 5.

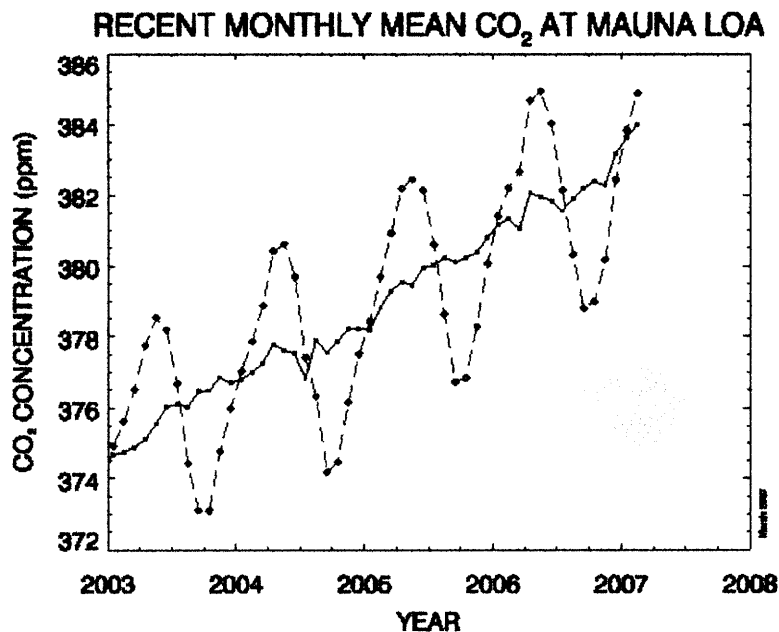


Figure 5. Carbon Dioxide Levels in the Atmosphere since 2003 [19].

Carbon dioxide levels are increasing at an alarming rate. Scientific evidence clearly shows the increase in carbon dioxide in the atmosphere to its highest levels ever recorded. Many believe that this increase in carbon dioxide levels is a primary cause of global warming. Whether this global warming is simply a cyclical event or whether it is caused by increased environmental greenhouse gas emissions is hotly debated in scientific and political circles. In any case, many advocate the reduction of carbon dioxide emissions. The Kyoto Protocol calls for such reductions and controls [20]. Unfortunately, many nations have not been successful in meeting these goals and global carbon dioxide levels continue to increase. In the United States, 98% of all carbon dioxide released into the atmosphere is the result of burning fossil fuels to make power [21]. A decreased dependence on fossil fuels will undoubtedly reduce carbon dioxide emissions.

4. Cost of Coal, Natural Gas, and Nuclear

To encourage a shift from fossil fuels to non-carbon dioxide emitting sources such as nuclear energy in the electricity generating sector, a carbon tax can be used. The magnitude of a carbon tax that will incentivize utilities to switch to nuclear power is dependent on the costs of coal, natural gas, and nuclear electricity.

4.1 Fuel Costs

Calculating the cost of fuel is the most difficult part in determining the cost of electricity, because of the large fluctuations in some fuel prices. As seen in Figure 6, the price of natural gas varies considerably, with last year's average at \$6.52/MMBtu, or \$0.022/kwhr.

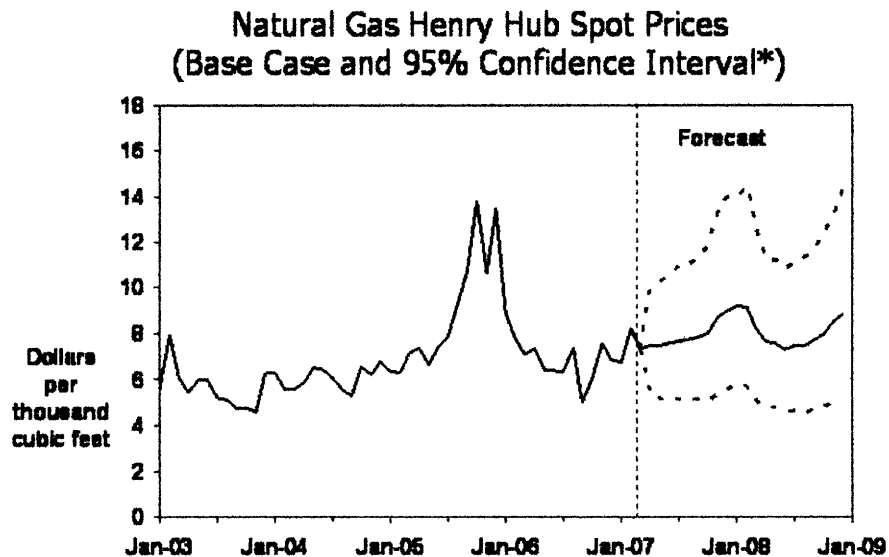


Figure 6. Natural Gas Fuel Cost from 2003 to 2009 [22].

The price of coal is much more stable, as shown in Figure 7. The fuel costs for a coal power plant was \$0.0176/kwhr in 2006 [23].

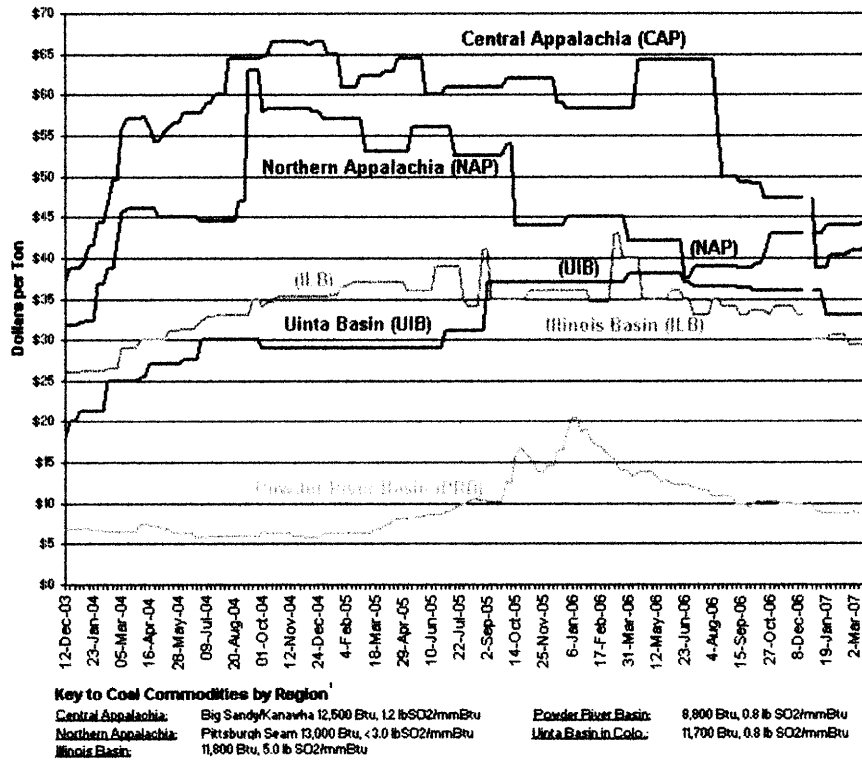


Figure 7. Average Weekly Coal Commodity Spot Prices from 2003 to 2007 [24].

Finally, the cost of uranium is steadily decreasing, as seen in Figure 8. The cost of uranium in 2006 was \$0.0045/kwhr [23].

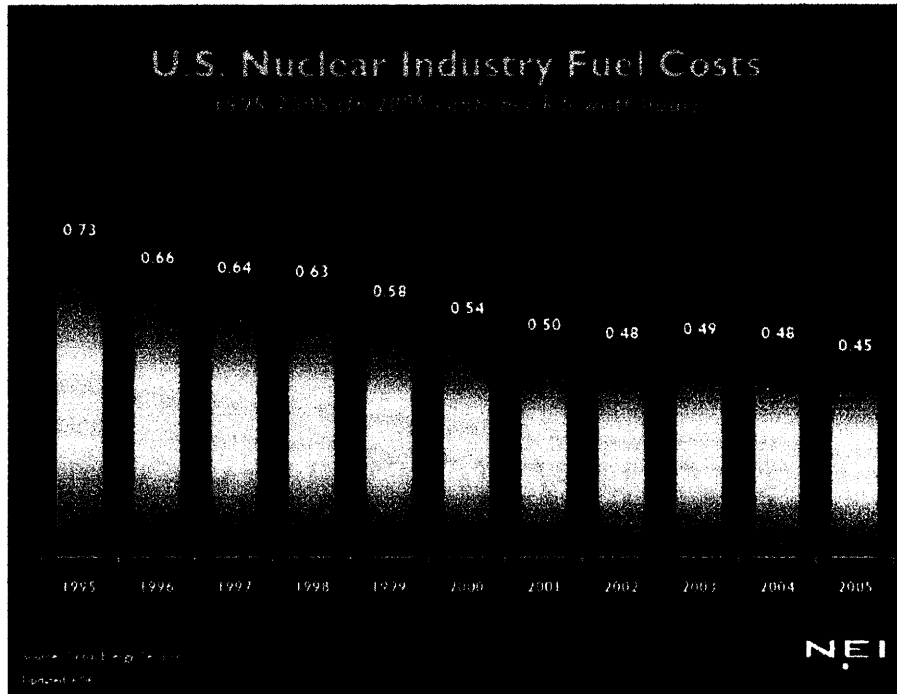


Figure 8. Decreasing Cost of Uranium, 1995-2005 [23].

4.2 Operation and Maintenance Costs

Operation and maintenance (O&M) costs for coal, oil, and nuclear power plants include cost of labor, materials and supplies (excluding fuel), contractor services, licensing fees, and other miscellaneous costs, including employee expenses and regulatory fees. Because O&M costs do not include fuel, they are much less susceptible to fluctuations in the market and international relations. The O&M cost for natural gas is \$0.0045/kwhr, for coal is \$0.0049/kwhr, and for nuclear is \$0.0127/kwhr [23].

4.3 Production Costs

Another commonly used cost to compare different power producing methods is the production cost. The production cost includes the total fuel and O&M costs. The production cost, then, for natural gas is \$0.0265/kwhr, for coal is \$0.0225/kwhr, and for

nuclear is \$0.0172/kwhr. Although the O&M cost for nuclear is much higher than that for natural gas and coal, the overall production cost of nuclear is much lower than the other two. As seen in Table 1, the production cost of nuclear power is O&M dominated, while the production costs of coal and natural gas are fuel dominated.

	Fuel	O&M
Natural Gas	83.0%	17.0%
Coal	78.2%	21.8%
Nuclear	26.2%	73.8%

Table 1. Percent of Production Cost due to Fuel and due to O&M for Natural Gas, Coal, and Nuclear.

Figure 9 shows total production costs for nuclear, coal, and natural gas in 2005. Prices are in cents/kwhr.

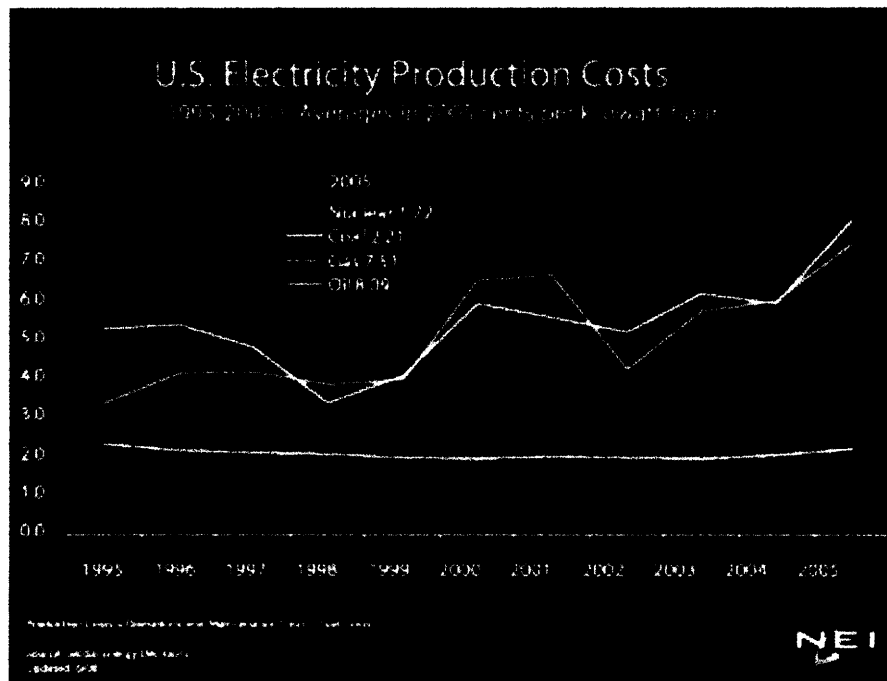


Figure 9. U.S. Electricity Production Costs [23].

4.4 Construction Costs

The cost of constructing a new power plant can vary greatly among the different generating options. The capital cost of natural gas plants is the lowest of the three being considered, with nuclear power being the highest. The cost of new nuclear plants is the most uncertain since none have been built in the United States in the last 25 years. Generally, a natural gas plant costs between \$400 and \$800 per kW, a pulverized coal plant costs between \$1000 and \$1500 per kW, and a nuclear plant costs between \$1200 and \$2000 per kW [23]. The cost of coal plants can easily become much higher than these estimates. The \$1000 to \$1500 per kW estimate is for pulverized coal plants, but if sequestration is included, costs will rise above \$2000 per kW [25].

4.5 Total Cost of Natural Gas and Coal Electricity

When the capital, O&M, and fuel costs are added together, the total cost of electricity (bus bar cost) for natural gas and coal plants is \$0.0051/kwhr¹ and \$0.042/kwhr, respectively [26], and the cost for nuclear plants is estimated to be between \$0.047 and \$0.067/kwhr.

5. Electricity Economics

The price of these generating options includes a risk premium, particularly in the capital cost calculation. This risk premium reflects the future viability of the plant in terms of

¹ The cost of coal electricity is taken from The Future of Nuclear Power. For natural gas, this report assumes a fuel cost of \$0.0012/kwhr, which is significantly lower than current cost estimates. The cost of natural gas electricity was found by modifying the report's estimate to account for the difference in fuel costs.

competing, operating, long term profit potential, and fuel supply interruptions. In determining the price of nuclear energy, the perceived risk of nuclear technology is considered. This perceived risk is included in the price of nuclear power through the risk premium as reflected in the cost of capital. The second economic factor is price elasticity of demand. A carbon tax changes the price of electricity, and it is important to understand the impact price changes have on consumer demand.

5.1 The Risk Premium and the Total Cost of Nuclear Electricity

A risk premium is the return of a company stock minus the risk-free rate. In other words, the risk premium is the difference between the expected value of an uncertain investment and the known value of a certain investment. For a natural gas or coal power plant, investors require a 12% return on equity. The required return for nuclear power is higher, mainly due to the concerns regarding construction costs (delays, new cost estimates, etc.) and operational risks. Because of this risk, the required return is 15%, making the risk premium for nuclear power 3% [27].

Because the cost of construction for nuclear power plants is uncertain (unlike the construction cost for natural gas and coal), the price of nuclear generated electricity varies, depending on the assumed construction cost. Table 2 shows the cost of nuclear energy, including risk premium, for varying levels of construction cost.

Construction Cost per kW	Overall Cost per kwhr
\$1200	\$0.047
\$1500	\$0.054
\$1800	\$0.062
\$2000	\$0.067 ²

Table 2. Cost of Nuclear Energy for Different Construction Costs [26, 28].

5.2 Price Elasticity of Demand

In order to assess the impact of an increase in price of electricity on the demand if carbon taxes are implemented, it is important to understand the price elasticity of demand. Should the price increase be high enough to reduce demand significantly, the chance of successful implementation of a carbon tax will be reduced. The price elasticity of demand indicates the relationship between the change in price and the change in quantity demanded of a commodity. It is defined by the following equation:

$$E_d = \left| \frac{\% \Delta \text{quantity demanded}}{\% \Delta \text{price}} \right| \quad (1)$$

Based on this value, goods are determined to be either elastic or inelastic. If E_d is greater than one, the good is said to be relatively elastic. Elastic goods are those for which many substitutes exist. If the price rises, people will stop purchasing the commodity, or switch to a substitute good. If E_d is less than one, the good is inelastic. Many things can cause a commodity to be considered inelastic. For example, addictions, small quantity goods, and necessities are all usually inelastic. If E_d is greater than one, a good is elastic. For a

² This cost of nuclear power with an assumed construction cost of \$2000/kW is taken from The Future of Nuclear Power. All other costs are taken from The Economic Future of Nuclear Power.

good with many substitutes, a price increase will cause people to switch to another good. Conversely, if there is a price decrease, the quantity demanded of the good will rise. This is important when considering a carbon tax. Taxes cause prices to rise, and if a good is elastic, the demand for that good will fall. In the case of a carbon tax, higher prices may reduce the demand for electricity, which would not be good for utilities but good for the environment, if it would reduce the emissions from fossil fuel plants.

Table 3 shows the price elasticity of demand for electricity in the short run and in the long run, in both the residential and commercial sectors. The short run shows the affects of a price increase on a day-to-day or week-to-week basis, while the long run looks at price increases that last for years.

	Short Run	Long Run
Residential Sector	0.23	0.31
Commercial Sector	0.24	0.25

Table 3. Price Elasticity of Demand for Electricity [29].

In both sectors, and in both the short and long run, electricity is inelastic. Most likely, this is because electricity is an essential commodity. This information is important, because when considering the effects of the carbon tax, the change in price will have very little effect on the quantity demanded. Electricity is inelastic, so it is not necessary to evaluate changes in demand when increasing the price.

6. Calculating the Carbon Tax

On simply an economic level, a utility will switch to nuclear power if it is less expensive than the alternatives. In calculating the carbon tax, the first step is to find the tax that will make the cost of nuclear equal to the cost of coal or natural gas.

6.1 Carbon Tax to Equate Nuclear with Coal and Nuclear with Natural Gas

The carbon tax to equate the cost of nuclear electricity and coal energy is first calculated in dollars per kilowatt-hour, using the following equation:

$$\text{cost of nuclear} = \text{cost of fossil alternative} + \text{cost of carbon tax} \quad (2)$$

where the cost of coal is \$0.042/kwhr, the cost of natural gas is \$0.051/kwhr, and the cost of nuclear varies based on assumed construction cost.

The carbon tax is then converted to dollars per metric ton of carbon by dividing by the carbon output rate of using coal to produce electricity, as seen in the following formula:

$$\frac{\text{tax [dollars/kwhr]}}{\text{carbon output rate [metric ton/kwhr]}} \quad (3)$$

where the carbon output rate is 0.571lbs/kwhr, or 2.59×10^{-4} t/kwhr, for coal and 0.358lbs/kwhr, or 1.62×10^{-4} t/kwhr, for natural gas [12].

For the varying costs of nuclear energy, the carbon taxes needed to equate the price of nuclear with coal and nuclear with natural gas at current prices are listed in Table 4.

Construction Cost for Nuclear Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Carbon Tax to Equate Coal and Nuclear (\$/tC)	Carbon Tax to Equate Natural Gas and Nuclear (\$/tC) ³
1200	0.047	19.30	--
1500	0.054	46.33	18.47
1800	0.062	77.22	67.74
2000	0.067	96.52	98.53

Table 4. Carbon Tax to Equate Costs of Nuclear and Coal Energy and Carbon Tax to Equate Nuclear and Natural Gas Energy.

When the cost of construction of a nuclear power plant is \$1200/kW, the cost of nuclear energy is \$0.047/kwhr. This is less expensive than the cost of natural gas energy, which is \$0.051/kwhr. Therefore, no carbon tax is needed to make nuclear energy the cost effective option. The cost of natural gas generated electricity is also a highly variable parameter due to the fact that over 70% of the price of electricity is dependent on its price. Table 5 shows the carbon tax needed to equate nuclear at \$2000/kw capital construction cost at varying natural gas prices that have existed in the last 5 years. This table shows that the carbon tax policy needs to consider several important factors prior to its establishment, since the price of fossil fuels themselves may drive utilities to nuclear energy on their own. Although the price of coal is less volatile, it too has market fluctuations that need to be considered.

* At current natural gas price of \$0.051/kwhr.

Construction Cost for Nuclear Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Cost of Natural Gas Energy (\$/kwhr)	Carbon Tax to Equate Natural Gas and Nuclear (\$/tC)
2000	0.067	0.046	\$129.63
2000	0.067	0.051	\$98.53
2000	0.067	0.056	\$67.90
2000	0.067	0.067	--
2000	0.067	0.077	--

Table 5. Carbon Tax to Equate Costs of Nuclear and Natural Gas Energy for Varying Costs of Natural Gas.

When natural gas costs \$0.067/kwhr, the cost of natural gas and nuclear energy generation are equal. When the cost of natural gas rises past this cost, nuclear energy is less expensive than natural gas, without any carbon tax in place.

6.2 Overall Carbon Tax

To determine the level of carbon tax needed to switch from fossil fuels to nuclear, the tax must be set high enough to equate nuclear costs with the lowest fossil fuel cost. This will motivate utilities to switch to nuclear, instead of choosing the least expensive fossil fuel. As seen in Table 6, if the carbon tax which equates nuclear and natural gas energy is used, the cheapest method of electricity production is not always nuclear. At the first three costs of nuclear energy, slightly exceeding the calculated carbon tax will cause not a switch from natural gas to nuclear, but from natural gas to coal.

Construction Cost for Nuclear Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Carbon Tax to Equate Natural Gas and Nuclear (\$/tC) ⁴	Resultant Price of Energy (\$/kwhr)	Cheapest Source of Electricity
1200	0.047	--	0.042	Coal
1500	0.054	18.47	0.047	Coal
1800	0.062	67.74	0.060	Coal
2000	0.067	98.53	0.068	Nuclear/ Natural Gas

Table 6. Effects of the Carbon Tax that Equates Costs of Nuclear and Natural Gas Energy.

Conversely, the calculated carbon tax to equate the costs of nuclear electricity and coal electricity can cause a switch to natural gas, as seen in Table 7. Again, the carbon tax is highly variable, depending on the current price on natural gas.

Construction Cost for Nuclear Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Carbon Tax to Equate Coal and Nuclear (\$/tC)	Resultant Price of Natural Gas Energy (\$/kwhr)	Cheapest Source of Electricity
1200	0.047	19.30	0.054	Nuclear/Coal
1500	0.054	46.33	0.059	Nuclear/Coal
1800	0.062	77.22	0.064	Nuclear/Coal
2000	0.067	96.52	0.067	Nuclear/Coal/Natural Gas

Table 7. Effects of the Carbon Tax that Equates Costs of Nuclear and Coal Energy.

⁴ At current natural gas price of \$0.051/kwhr.

The minimum carbon tax must always be the higher of the two values. Therefore, the carbon tax that must be exceeded to incentivize a utility to switch to nuclear power is seen in Table 8. The important assumption in applying this carbon tax is that if nuclear power is less expensive, by even the smallest amount, a utility will switch from current methods to nuclear power. This assumption is not necessarily correct.

Cost of Nuclear Energy (\$/kwhr)	Cost of Carbon Tax to Make Nuclear Equal to the Least Expensive Method of Electricity Production (\$/tC)
0.047	19.30
0.054	46.33
0.062	77.22
0.067	98.53

Table 8. Carbon Tax that Must Be Exceeded in Order to Prompt a Switch to Nuclear Electricity.

7. Other Considerations in Calculating the Carbon Tax

It is likely that if the cost of nuclear electricity were equal to the cost of a utility's current method of electricity generation, the utility would not switch to nuclear. To decide how much cheaper nuclear must be in order to incentivize a utility to make the switch, the pros and cons of nuclear power, as seen from the utility's viewpoint, must be analyzed.

7.1 Advantages in Switching to Nuclear

- Long-Term Price Stability—As discussed earlier, nuclear energy not only has the lowest fuel cost, but also the most stable. This fuel stability gives utilities long-term price stability. Long-term price stability allows utilities to sell at a premium a guaranteed source of electricity at a determined price to consumers. Currently, in California, consumers are paying a premium for future electricity in order to shield themselves from possible price spikes in the energy market [30].
- Plant Lifetime—New technologies allow safe operation of nuclear power plants for up to 60 years [31], while most coal and natural gas plants are traditionally operated for 40 years.
- Fuel Supply—The current uranium supply is predicted to last at least 50 years with cost effective mining. By this time, breeder technologies can be implemented in order to minimize dependence on uranium mining. There is no technology, however, to breed coal or natural gas. The supply is limited. Nuclear energy will not be hampered by a limited fuel supply.
- Emission Controls—Generating nuclear energy does not release carbon dioxide into the atmosphere. This means implementing or raising a carbon tax will never affect the cost of nuclear energy. In addition, if a cap-and-trade system is implemented with credit being given to nuclear energy, utilities using nuclear energy will be able to raise revenue by selling carbon dioxide allowances [32].

7.2 Disadvantages in Switching to Nuclear

- Licensing and Regulatory Uncertainties—A nuclear plant applying for a license in 2008 would not be able to begin construction until 2011 and would not begin operating until 2016 [33]. This means that utilities must consider nuclear energy close to ten years before they plan to implement nuclear reactors. In addition, some plant improvements, such as digital upgrades, can result in technical and regulatory delays and uncertainties.
- Initial Capital Cost—The initial capital cost of a nuclear power plant is much higher than that of natural gas or coal. A nuclear power plant costs between \$1200 and \$2000 per kW, while a coal power plant costs between \$1000 and \$1500, and a natural gas plant costs only \$400 to \$800. This high initial capital cost forces a utility to borrow large amounts of money and cause the company to acquire substantial debts, affecting its credit rating and ability to borrow funds.
- Public Opinion—In a 2005 survey, a record-high 70% of Americans supported nuclear energy. But conversely, 24% of Americans still do not support nuclear power [34]. A utility concerned with its public profile may see this disapproval rate as too high to go forth with building nuclear power plants. Local and state political reaction may cause substantial project delays. The issue of the disposal of nuclear waste also affects public support for increasing dependence on nuclear energy as a future source of electricity.
- Wall Street Reaction—Public opinion can also influence the value of a utility's stock. Because Wall Street's reaction determines so much of a company's worth, a utility must seriously consider how building nuclear plants will affect its stock.

- Overall Risk Perception—In addition to the risk premium, utilities may be reluctant to switch to nuclear power simply because there is a perceived risk associated with it. Nuclear technology still seems unsafe and unpredictable to many people. The perception of risk affects all indicators noted above.

7.3 Advantage and Disadvantage Effects on the Carbon Tax

It is likely that for many utilities, the disadvantages of nuclear power outweigh the advantages, even if nuclear energy was equal to the costs of alternatives. To incentivize these utilities to shift towards nuclear, nuclear electricity must be a certain percentage less expensive than its fossil fuel counterparts. The next section will analyze the necessary carbon tax to bring nuclear power costs to a level that would be hard to ignore when choosing between nuclear power and fossil fuel alternatives particularly as it affects a utility's competitive position and the opinions of state regulatory authorities who attempt to keep the cost of electricity as low as possible for the consumer.

8. Recalculating the Carbon Tax

It is currently unknown exactly how much less expensive nuclear energy must be in order to incentivize utilities to switch from their current energy production method. In this section, the carbon tax is calculated to make nuclear energy 5%, 10% and 20% less expensive than the alternatives, to determine if the tax is credible and possible in the battle against carbon dioxide emissions.

8.1 Carbon Tax—5%, 10%, and 20%

The carbon tax to make the cost of nuclear energy less expensive than current methods is first calculated in dollars per kilowatt-hour, using the following equations for 5%, 10%, and 20%, respectively:

$$\text{cost of nuclear} = 0.95 * \text{cost of current method} + \text{cost of carbon tax} \quad (4)$$

$$\text{cost of nuclear} = 0.90 * \text{cost of current method} + \text{cost of carbon tax} \quad (5)$$

$$\text{cost of nuclear} = 0.80 * \text{cost of current method} + \text{cost of carbon tax} \quad (6)$$

Equation 3 is then used to convert the tax from dollars per kilowatt-hour to dollars per ton of carbon released.

8.1.1 Coal

The carbon tax levels to make the cost of nuclear energy 5% less than the cost of coal electricity are listed in Table 9.

Construction Cost for Nuclear Power Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Carbon Tax to Make Nuclear 5% Cheaper than Coal (\$/tC)	Carbon Tax to Make Nuclear 10% Cheaper than Coal (\$/tC)	Carbon Tax to Make Nuclear 20% Cheaper than Coal (\$/tC)
1200	0.047	28.86	39.47	64.67
1500	0.054	57.31	69.50	98.46
1800	0.062	89.81	103.82	137.07
2000	0.067	110.14	125.38	161.20

Table 9. Carbon Tax to Make Cost of Nuclear Energy 5%, 10%, and 20% Less than Cost of Coal Energy.

8.1.2 Natural Gas

The carbon tax levels to make the cost of nuclear energy 5%, 10%, and 20% less than the cost of natural gas energy are listed in Table 10.

Construction Cost of Nuclear Power Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Carbon Tax to Make Nuclear 5% Cheaper than Natural Gas (\$/tC)	Carbon Tax to Make Nuclear 10% Cheaper than Natural Gas (\$/tC)	Carbon Tax to Make Nuclear 20% Cheaper than Natural Gas (\$/tC)
1200	0.047	--	39.47	47.73
1500	0.054	35.98	69.50	101.61
1800	0.062	87.83	110.16	163.19
2000	0.067	120.25	144.38	201.68

Table 10. Carbon Tax to Make Cost of Nuclear Energy 5%, 10%, and 20% Less than Cost of Natural Gas Energy.

At the least expensive level, nuclear energy is already 5% less expensive than that of natural gas.

8.1.3 Overall Carbon Tax

The carbon taxes to make nuclear energy the cheapest method of electricity production by at least 5% are listed in Table 11.

Construction Cost of Nuclear Power Plant (\$/kW)	Cost of Nuclear Energy (\$/kwhr)	Cost of Carbon Tax to Make Nuclear 5% Cheaper than the Least Expensive Method of Electricity Production (\$/tC)	Cost of Carbon Tax to Make Nuclear 10% Cheaper than the Least Expensive Method of Electricity Production (\$/tC)	Cost of Carbon Tax to Make Nuclear 20% Cheaper than the Least Expensive Method of Electricity Production (\$/tC)
1200	0.047	28.86	39.47	64.67
1500	0.054	57.31	69.50	101.61
1800	0.062	89.82	110.16	163.19
2000	0.067	120.25	144.38	201.68

Table 11. Carbon Tax that Must Be Exceeded in Order to Prompt a Switch to Nuclear Electricity when the Requirement for Switching is a 5%, 10% or 20% Price Reduction.

If nuclear power plants can be constructed for \$1200 per kW, utilities will switch to nuclear, even if they require 20% savings to make that switch, at a carbon tax level of less than \$70 per ton of carbon emissions. This is less than the marginal damage cost average estimate of \$93/tC. If politicians see that estimate as an acceptable level for setting a carbon tax, even the most risk sensitive utilities will likely switch to nuclear power.

9. An Alternative for Utilities—Carbon Capture and Sequestration

If a carbon tax is implemented, there is a way that utilities can continue to use coal or natural gas and not be greatly affected by the tax. Utilities can use carbon sequestration to generate energy using coal or natural gas and reduce carbon dioxide emissions into the

environment by roughly 90% [35]. While the United States is researching carbon capture and sequestration, funding is currently not high enough to pursue a large-scale demonstration [25]. However, this may soon change, and private businesses are also looking into developing carbon capture technologies. If this alternative becomes viable in the near future, it may encourage utilities to turn dirty coal plants (that release carbon into the atmosphere) into clean coal plants (which use a carbon capture and sequestration system), instead of switching to nuclear power. To find the more cost effective option, the cost of carbon sequestration must be compared to the economic effects of a carbon tax.

9.1 Carbon Capture

Currently, the most common carbon capture technology for power plants is post-combustion carbon capture. Power plants use air-fired combustors, which produce a mixed flue gas of carbon dioxide and nitrogen. In coal plants, 10-12% of the flue gas is carbon dioxide, and in natural gas plants, 3-6% is carbon dioxide [36]. The carbon dioxide from this gas is then absorbed by amines [37].

Another method is pre-combustion carbon capture. Pre-combustion carbon capture has been commonly used in fertilizer and gaseous fuels. In this technique, fuel is turned into hydrogen (fuel gas) and carbon monoxide. The carbon monoxide is then made into carbon dioxide using shift conversion processes, which gives a 25-40% carbon dioxide stream and a hydrogen stream [37]. The carbon dioxide is then separated out using solvent scrubbing.

The third method of carbon capture is oxy-fuel combustion. This method removes the nitrogen from the air, raising the flue gas carbon dioxide concentration to over 80% [37]. Gas purification can raise this even higher. This technology has not yet been applied to power plants, but it is still being developed. These three methods, and industrial processes that have not yet been fully developed are shown in Figure 10.

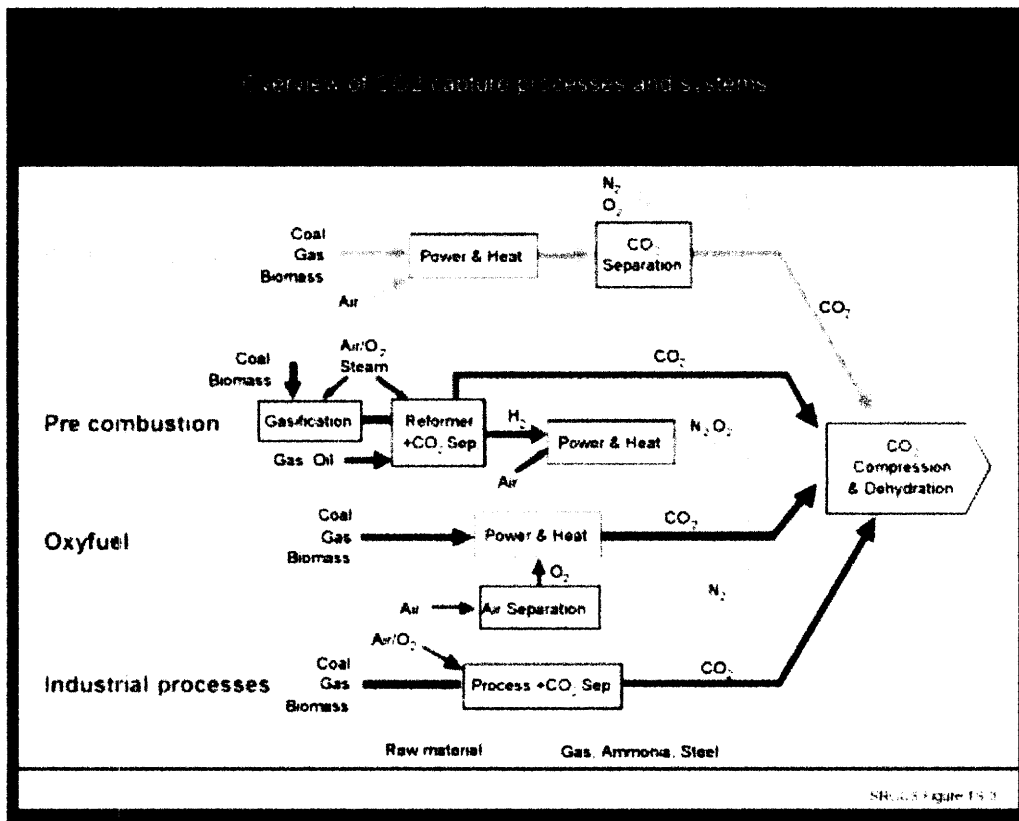


Figure 10. Carbon Dioxide Capture Processes [38].

9.2 Carbon Transport

After the carbon dioxide is removed from the stream, it must be transported to a storage site. The most common and most cost effective form of transport is by pipeline, but

when pipelines are not available, transport is done by ship [39]. Both of these methods are currently in use for carbon dioxide transport.

9.3 Carbon Storage

Carbon dioxide is transported to one of three types of storage sites—geological storage, ocean storage, or mineral storage. Each one works in a different way and each has its own type of leakage risk.

9.3.1 Geological Storage

Geological storage, or geo-sequestration, is the process of injecting carbon dioxide into geological formations, deep beneath the Earth's crust. It relies on naturally occurring geology, such as impermeable caprock, to keep the carbon dioxide from leaking up to the surface.

There are several possible geological storage sites. First, injecting carbon dioxide into oil and gas reserves can help increase oil recovery. This is a popular choice, because some of the storage cost is recovered through the revenue of additional oil sales. This option, however, may not be capable of handling large volumes of carbon dioxide. Next, saline formations are an attractive choice because of their high volume storage capability. They are also fairly common, so transport costs can be minimized. The main drawback to saline formations is the lack of research on using them for carbon dioxide storage, including probability of leakage. Finally, carbon dioxide can be injected into unminable coal beds, where it will be absorbed by the coal. This is not always possible, because not

all coal beds are permeable by injection. But this technique does cause methane gas to be released, and the sales of this gas can help pay for carbon dioxide storage. Research done by the International Panel on Climate Change suggests that these geological storage methods will trap 99% of injected carbon dioxide for over 1000 years [40]. All three of these techniques are illustrated in Figure 11.

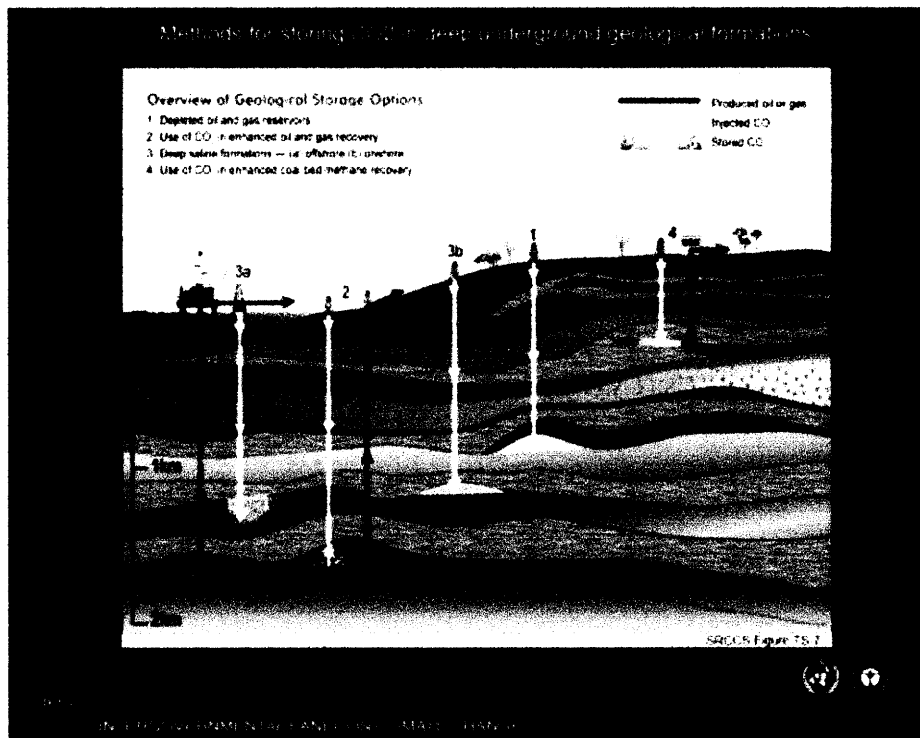


Figure 11. Geological Storage of Carbon Dioxide [38].

9.3.2 Ocean Storage

There are two ways that carbon dioxide can be stored in the ocean. The first, called dissolution, involves injecting carbon dioxide at depths of at least 1000 meters into the ocean. The carbon dioxide dissolves and circulates with the ocean water. The second method, called lake storage, injects carbon dioxide into the ocean at depths greater than

3000 meters. Below 3000 meters, carbon dioxide is denser than water, so it does not rise to the surface, but instead forms a “lake” at the bottom. Due to water circulation, both of these methods have negative effects. Although the level of carbon dioxide storage is determined by depth, the IPCC estimates that only 30-85% of the injected carbon dioxide will remain trapped after 500 years [41]. Figure 12 illustrates both methods of ocean storage.

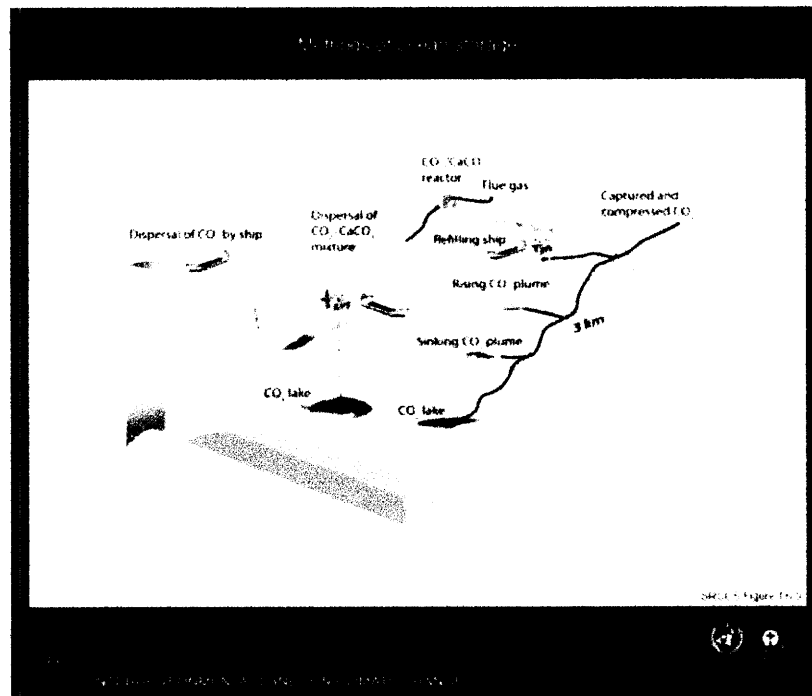


Figure 12. Ocean Storage of Carbon Dioxide [38].

9.3.3 Mineral Storage

Mineral storage injects carbon dioxide into stable minerals. Carbon dioxide reacts with metal oxides, forming stable carbonates. Although this process occurs naturally, it takes a very long time. In order to speed up the process and make it more manageable, the minerals must be pre-treated. Although this method uses the most energy of any type of

storage (up to 180% more power than a dirty coal plant [42]), there is thought to be no risk of carbon dioxide leakage to the environment.

9.4 Cost

The cost of carbon capture, with current technologies, will increase the cost of electricity by \$0.025 to \$0.04/kwhr [36]. This is roughly equivalent to a cost of \$150/tC. In addition, transport and storage will cost a minimum of \$10/tC [34], placing the total cost of capture and sequestration at a minimum of \$160/tC. This is more expensive for every calculated carbon tax, except the taxes to make nuclear energy 20% less expensive than the alternatives at the highest two possible nuclear plant construction costs.

This conclusion, however, assumes that the carbon output rate for a dirty coal plant is the same as that for a clean coal plant. But because a clean coal plant requires much more energy than a dirty one, it creates more carbon, as seen in Figure 13. More carbon is created, so more must be captured, transported, and stored. In addition, a larger percentage of the energy produced is needed to run the plant. Overall, more carbon is generated, and total output power of the plant lower. The utility spends more money capturing carbon, and generates less revenue because it has less electricity to sell. With current technologies, in almost every scenario, nuclear energy is more cost effective than a clean coal energy.

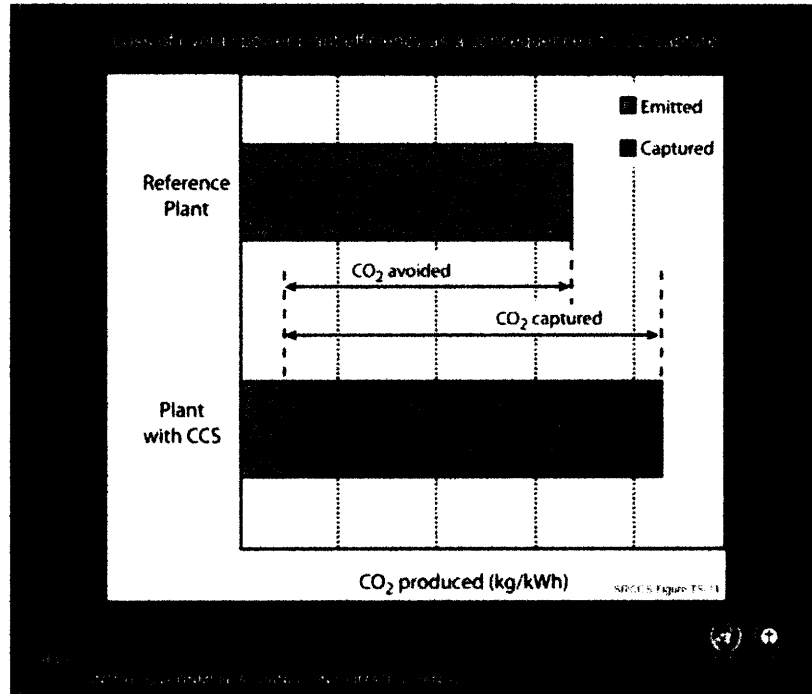


Figure 13. Carbon Dioxide Production for a Pulverized Coal Plant and a CCS Coal Plant.

10. An Alternative for Policy Makers—Cap and Trade

An alternate way to control power plant carbon dioxide emissions is emissions trading, also known as cap and trade. In this system, the government sets a limit, or cap, on the amount of carbon that can be released into the environment. The cap amount is then divided into allowances, or credits, which are distributed among utilities. These credits work much like vouchers, allowing utilities to emit a certain amount of carbon. Utilities can only emit as much carbon as they have credits. If a utility wishes to exceed its limit, it is forced to buy credits from other utilities that are not using all of their allowances. Buying another utility's credits is called a trade.

The idea of cap and trade is to lower carbon emissions. Over time, it is likely that policy makers would gradually lower the cap, by reducing the value of each credit. An alternative would be to retire a percentage of traded credits, meaning that the cap would be naturally lowered each time a trade was made.

The most obvious difference between a carbon tax and a cap and trade system is that under the carbon tax, a utility must pay to emit any amount of carbon, while under cap and trade, a utility is allowed a certain level of emissions with no penalty. If the utility exceeds this level, however, it is forced to buy credits from other utilities. This is of particular note to policy makers, because under a carbon tax, the government is collecting revenue, while under a cap and trade system, the benefactor is the utility that is selling its extra credits.

The idea of utilities profiting under cap and trade leads to the question of which policy will more encourage utilities to reduce their carbon dioxide emissions. Under a carbon tax, a utility must pay for any amount of carbon released. This motivates the utility to not emit any at all. Under a cap and trade system, a utility is allowed to emit a pre-set amount of carbon with no financial loss and possible financial gain if they switch to non-emitting sources and sell their credits. When a utility does not release its full allowance of carbon, it has credits to sell to other utilities. Eliminating emissions completely under a carbon tax prevents the utility from having to pay the tax; under a cap and trade system, it allows the company to generate extra revenue. While both systems will likely raise the cost of electricity, a carbon tax will allow for the revenue to go back to the public through

tax-shifting and environmental program benefits, while cap and trade will channel revenues to utility companies.

10.1 Current Cap and Trade Systems

Carbon dioxide cap and trade systems are in place in both the European Union and the United States.

10.1.1 European Union

The European Union currently has the largest carbon dioxide cap and trade system. In an effort to reduce carbon dioxide emissions as outlined by the Kyoto agreement, the program began in December 2002. The 25 member states are each allowed to set their own caps, and allocations for the 11,500 polluting installations are set based on historic emission rates [43]. Distributing allocations this way means that nuclear power is not given any credits [44]. While historic polluters can benefit from switching to nuclear, those who are already using nuclear energy are not able to generate revenue by selling their credits.

Allowing member states to set their own limits has been the object of much criticism. After some initial success, utilities realized that the market contained an excess of allowances, in relation to the amount of carbon being released. At the end of 2005, the system had a 2.4% excess of allowances. Because members are allowed to keep excess credits, this surplus will keep the cost of carbon emissions low until 2007 [45]. In *A Convenient Windfall: Global Warming's Big Cash Dividend*, environmentalist Peter

Barnes summed up many of the criticisms of the European Union's cap and trade, saying, "The undisputed results were windfall profits for the utilities, higher prices for everyone else, and zero public benefit" [46].

10.1.2 United States

The Regional Greenhouse Gas Initiative is the first carbon dioxide cap and trade program to be implemented in the United States. Connecticut, Delaware, Maine, New Hampshire, New Jersey, New York, and Vermont all voluntarily signed a Memorandum of Understanding on December 20, 2005 [47]. Unlike the European Union, the cap is regulated. Beginning in 2009, states must stabilize their carbon dioxide emissions level, by keeping it at the current level until 2015. In 2019, emissions must be reduced by 10% [48].

This program also differs from the European Union in the treatment of nuclear plants. All sources of electricity are assigned credits equally, including nuclear power [49]. This allows utilities using nuclear power to benefit from the cap and trade system, by selling credits and generating revenue.

10.2 Cost

The European Union cap and trade program started at about \$40/tC, but since realizing the surplus of credits, the price has fallen to \$12/tC [50]. This is lower than all calculated carbon taxes. Such a low price is unlikely to motivate utilities to switch to nuclear power or to reduce their carbon emissions by any method. A utility that switches to nuclear

power will be eligible to receive revenue from its allocated credits, under a system like the one in the United States. Depending on the cap and trade system and the number of credits given to each utility, this additional revenue may cause a utility to move to nuclear power, but until the exact system is known, these effects are unclear.

11.0 Conclusions

The increase in carbon dioxide in the environment is undeniably driven largely by the use of fossil fuels, a majority of which is from power production. Of the three main energy production methods in the United States, only nuclear power does not emit carbon dioxide into the environment. While only 17% of electricity produced in the United States is generated using nuclear power, a carbon tax or other carbon policy could incentivize utilities to shift to non-carbon dioxide emitting technologies.

Carbon taxes are an effective method of incentivizing utilities to switch to nuclear power from coal or natural gas. The level of the tax needed to move utilities to nuclear energy depends on capital costs of new plants and the “risk perception” premium as seen by utilities. Capital costs will dictate the overall cost of nuclear power, and the “risk perception” premium will determine how much lower the cost of nuclear generated electricity will have to be for utilities to consider switching to nuclear power. The full range of carbon tax scenarios are developed in this thesis, with the most likely carbon tax being \$110/tC. This cost assumes a \$1800/kW capital construction cost and a 10% risk perception premium on the bus bar cost of power to address the financial and the industry community’s somewhat negative perception of nuclear investments.

If a carbon tax is legislated, it is likely that it will be less costly than the cost of carbon capture and sequestration. The practicality and costs of carbon capture and sequestration are not sufficiently developed to make credible estimates of its value in reducing overall carbon emissions.

Legislatures may also choose to implement a cap and trade policy. While this method is currently in effect in the European Union, it is unlikely to create the needed incentives to move utilities to lower carbon emissions technologies. Instead, it will benefit utilities financially at the expense of the consumer, with little carbon dioxide reduction benefits in the near term unless the caps are significantly reduced. Therefore, a carbon tax is more beneficial to the environment, as it will more effectively cause utilities to switch from coal or natural gas to nuclear power.

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