A STUDY ON THE IMPACT OF NUCLEAR POWER PLANT CONSTRUCTION RELATIVE TO DECOMMISSIONING FOSSIL FUEL POWER PLANTS IN ORDER TO REDUCE CARBON DIOXIDE EMISSIONS USING A MODIFIED NORDHAUS VENSIM DICE MODEL

A Thesis
Presented in Partial Fulfillment of the Requirements for the
Degree of Master of Science
with a
Major in Nuclear Engineering
in the
College of Graduate Studies
University of Idaho

by
Jason Lee Colpetzer

May, 2014

Major Professor: Akira Tokuhiro, Ph.D.

Authorization to Submit Thesis

This thesis of Jason Colpetzer, submitted for the degree of Master of Science with a Major in Nuclear Engineering and titled "A Study on the Impact of Nuclear Power Plant Construction Relative to Decommissioning Fossil Fuel Power Plants in Order to Reduce Carbon Dioxide Emissions Using a Modified Nordhaus Vensim DICE Model," has been reviewed in final form. Permission, as indicated by the signatures and dates given below, is now granted to submit final copies to the College of Graduate Studies for approval.

Major Professor: ______________________ Date: ______________
Akira Tokuhiro

Committee Members: ______________________ Date: ______________
Supathorn Phongikaroon

______________________ Date: ______________
David Solan

______________________ Date: ______________
Vivek Utgikar

Department Administrator: ______________________ Date: ______________
Lee Ostrom

Discipline's College Dean: ______________________ Date: ______________
Larry Stauffer

Final Approval and Acceptance

Dean of the College of Graduate Studies ______________________ Date: ______________
Jie Chen

Abstract

The current levels of CO_2 emissions and high levels accumulating in the atmosphere have climate scientists concerned. The Dynamic Integrated Climate Economy Model (DICE) is a model that has been used to simulate climate change and evaluate factors addressing global warming. The purpose of this study is to recreate DICE using Vensim and modify it to evaluate the use of nuclear power plants (NPPs) as a means to counter global temperature increases and the associated cost of damages. The amount of greenhouse gas emissions from a NPP are about 6% per Megawatt as that from a Fossil Fuel Power Plant (FFPP). A model was developed to simulate construction of NPPs with subsequent decommissioning of FFPPs with an equivalent power output. The results produced show that some minor benefit is achievable if all of the more than 10,000 FFPPs currently in operation in the U.S. are replaced with NPPs.

Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

The concern for climate change due to human activities is an important issue that requires serious attention. The onset of more frequent and increasingly more devastating weather events in recent history; for example the melting of polar ice caps at alarming rates, and rising of the world seas, presents a convincing reason for concern. These drastic and destructive events are only expected to become increasingly more devastating with time if no action is taken to limit or prevent climate change. Entire species, human health, and world economies are all at risk if climate change continues [EPA]. Some scientists suggest the current trend of climate change could eventually lead to catastrophic events that would devastate the entire world [Schneider, 2004].

The emission of greenhouse gases into the atmosphere from human activities including the burning of fossil fuels for energy production are the key factors that scientists believe are leading to climate change. The largest greenhouse gas of concern is carbon dioxide (CO_2). Data shows that the amount of CO_2 emissions and levels in the atmosphere have risen at a dramatic rate since the beginning of the industrial revolution and continue to grow as energy demand continues to grow [Nordhaus, 1993]. Some climate scientists believe that the safe upper limit of CO_2 in the atmosphere should be 350 parts per million (ppm). Current levels are well above this approaching 400 ppm [Hansen, et al., 2008].

One potential solution to reduce the amount of CO_2 emissions is nuclear power. Nuclear power plants (NPP) produce a significantly reduced amount of CO_2 than that from fossil fuel power plants (FFPP). In fact, nuclear power plants produce approximately 6% of the CO_2 emissions per Megawatt (MW) as that from a fossil fuel power plant. A number of climate scientists are now advocating nuclear power as vital to addressing climate change [WNN, 2013]. Fossil fuel power plants produce electricity through the burning of fossil fuels and in turn generate enormous amounts of CO_2 emissions. Currently nuclear power is responsible for approximately 20% of the power production in the U.S. [Nuclear Power in the USA]. The remainder is from fossil fuel power plants.

In order to evaluate what effect nuclear power would have on climate change, this goal of this study is to propose replacing FFPPs with NPPs. As FFPPs are replaced with NPPs, the amount of emissions will be greatly reduced and this reduction can be determined. The next step is to analyze how these reductions in emissions will affect climate change. A model has been developed which is used to simulate climate change based on available economic and environmental data. This model is the Dynamic Integrated Climate Economy model or DICE. DICE was developed at Yale University by Professor William D. Nordhaus [Newbold, 2010]. With the use of numerous publications and the assistance from other climate scientists, Dr. Nordhaus developed DICE to predict climate change, as well as to evaluate what effect certain actions to control CO_2 emissions will have on climate change. The DICE model "integrate[s] in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allow[s] a weighing of the costs and benefits of taking steps to slow greenhouse warming"[Newbold, 2010].

The DICE model has been replicated by Tom Fiddaman of the Massachusetts Institute of Technology (MIT) for Ventana Systems Incorporated Vensim simulation software. Vensim software is used for developing, analyzing, and packaging dynamic feedback models [Vensim]. To utilize the DICE model, it had to be recreated with Vensim. The DICE model that was recreated in Vensim allowed for simulating climate change, but did not allow for analysis of constructing NPPs in order to replace FFPPs. To allow for the research that has been proposed for this study, a modification to the DICE model in Vensim was necessary. The Vensim software allows for the ability to add variables in order to perform the function needed, that is, to determine the reduction of CO_2 emissions as FFPPs are replaced with NPPs.

The modified portion of the model incorporates the current amount of FFPPs including coal burning power plants (CPP), natural gas burning power plants (NGPP) and petroleum burning power plants (PPP) in operation in the U.S. The modified portion of the model allows for an input of a specific rate of NPP construction per year. After an annual construction rate is inputted to the model, the model will then eliminate an amount of fossil fuel power plants based on an equivalent amount of power produced from the newly constructed NPPs. The model will start by decommissioning the CPPs followed by the NGPPs and then the PPPs based on the amount of CO_2 emissions from highest to lowest [Sovacool, 2008].

Once this occurs the model is designed to calculate the reduction in CO_2 emissions as the difference from the operating FFPPs that are decommissioned and the NPPs that are used to replace them. The amount of CO_2 emissions that are eliminated are fed into the standard DICE model as a negative value into the CO_2 emissions variable that already exists on the DICE model. This reduction will ultimately change the final values for the climate change variables of the DICE model. These are the variables that will be evaluated for this study. Multiple simulations will be performed in order to evaluate a range of NPP rates.

The finalized model with the modified portion that feeds into the standard DICE model allows for the analysis of replacing FFPPs with NPPs and the resulting effect on climate change. The DICE model will simulate future values of CO_2 emissions, CO_2 in the atmosphere, atmospheric and ocean temperatures and the costs of the climate damages due to the associated climate change. This study will provide data that will help determine if increased NPP construction will be a feasible solution to climate change.

In order to more clearly illustrate how DICE is broken down and the work from this study is incorporated, Figure 1.1 details the key sections for this thesis work.

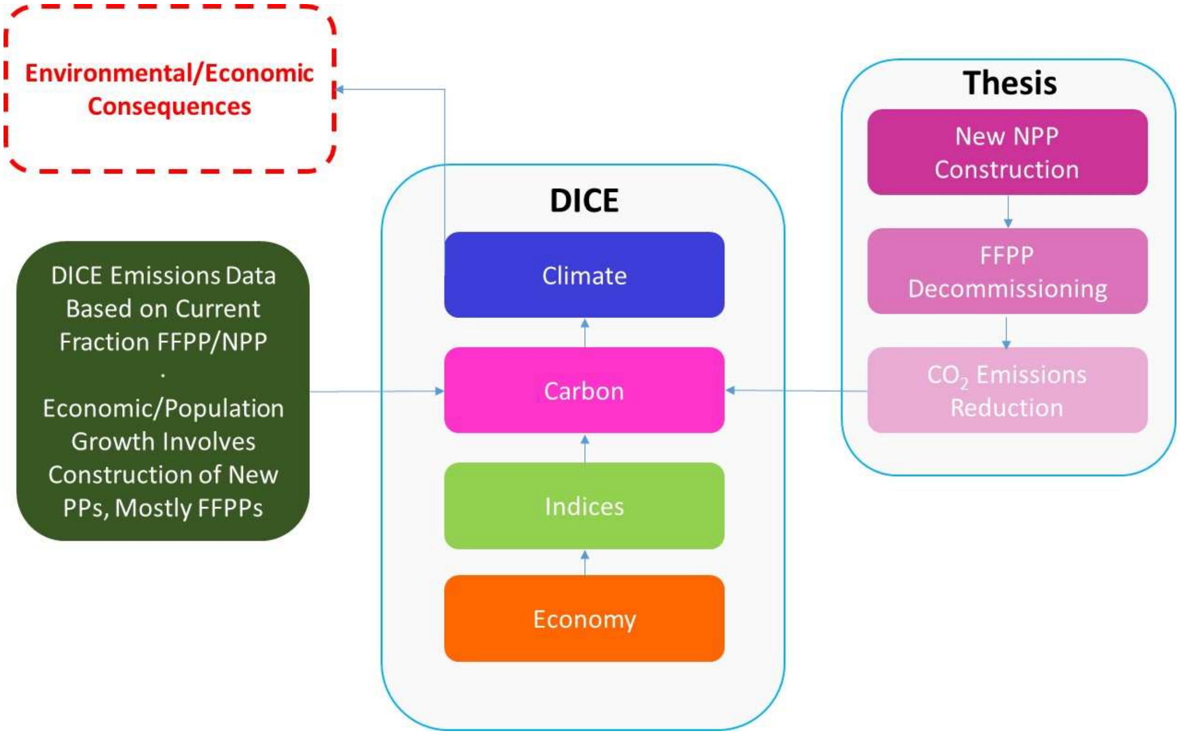


Figure 1.1. Schematic of DICE model and thesis work incorporated as part of this study.

Figure 1.1 highlights the keys features of this study. In the center is the breakdown of DICE. The economy and indices sections predict economic growth and determine the estimated amount of carbon emissions that will be produced as a result of the economic output. The carbon portion of the model evaluates the carbon emissions and how they will accumulate in the atmosphere. The climate variables will utilize the increased accumulation to predict variables such as ocean and atmospheric temperature increases and the resultant climate damages from these temperature increases. Of important note is that the DICE model uses current economic and other data to predict growth and the associated emissions. This data is based on the current fraction of FFPPs to NPPs and as growth occurs this fraction is maintained and is mostly FFPPs.

The right-hand portion of this model is a breakdown of the key factors of this thesis work. NPPs are constructed in order to replace FFPPs. The FFPPs that are replaced are decommissioned and in turn there is an overall reduction in CO_2 emissions due to the significant different in emissions from NPPs compared to FFPPs. This reduction in emissions is calculated as a negative value and is directly fed into the CO_2 emissions variable of the DICE model. The emissions variable continually shows an increase in emissions based on the predicted economic growth. The thesis portion of this model will continually reduce the total emissions quantity as the FFPPs are simulated to be replaced by NPPs.

The ultimate results of this model allows for the evaluation of environmental and economic consequences as a result of increased CO_2 emissions. The thesis portion will alter the results based on the simulated reduction of CO_2 emissions from NPP construction and FFPP decommissioning. How large or small of an effect NPP construction can have on climate change will be studied.

The goal of this thesis is to determine if nuclear power is in fact the solution or part of the solution to combat climate change and global warming. Will using an aggressive NPP construction and FFPP decommissioning plan produce results worthy of the effort and cost.

Chapter 2. Global Warming/Climate Change

2.1 Climate Change

According to the Environmental Protection Agency's website, the definition of climate change is "a term that refers to major changes in temperature, rainfall, snow, or wind patterns lasting for decades or longer" [EPA]. Both human-made and natural factors contribute to climate change. Natural factors include changes in the Earth's orbit, the sun's intensity, the circulation of the ocean and atmosphere, and volcanic activity. The causes that will be examined in this report are the human factors which include burning fossil fuels, cutting down forests, and developing land for farms, cities and roads. All of these activities release greenhouse gases into the atmosphere [EPA].

Greenhouse Gases (GHGs) are gases in the atmosphere that absorb outgoing solar and infrared radiation. This is known as the greenhouse gas effect and can cause the global temperature to increase [NASA]. GHGs include Carbon Dioxide (CO_2), Methane (CH_4), Nitrous Oxide (N_2O), and Fluorinated Gases (CFCs, etc.). The GHG of interest for this report is CO_2 [NASA]. CO_2 can be formed both through natural and human activities. The focus of this report will be the production of CO_2 through human activities, specifically by the burning of fossil fuels.

Some amount of GHGs are required in order for life to exist on earth because they trap heat in the atmosphere maintaining the Earth's warm temperature. Human activities, including the burning of fossil fuels add more GHGs to the atmosphere than from natural causes alone. GHGs are currently at record-high levels in the atmosphere. GHGs have a residency of approximately 100 years in the atmosphere [Nordhaus, 2008]. The climate appears to have a lag of several decades behind the accumulation of GHGs in the atmosphere. This means the real effect of elevated levels of GHGs in the atmosphere will not be known until sometime in the future. The concern is that if we wait to see the true effect, it may be too late to reverse.

The Earth's climate has experienced many changes throughout history, however the current warming seen today cannot be explained by natural causes alone. Some scientists believe that doubling the amount of CO_2 in the atmosphere would increase the Earth's surface temperature from 1-5 degrees [Nordhaus, 2008]. The current consensus among more than 95% of climate experts is that humans are in fact contributing to global warming [Doran & Zimmerman, 2009].

A few theories do exist that suggest the correlation between CO_2 in the atmosphere and temperature has broken since man started adding CO_2 to the atmosphere. They contend that the earth's weakening magnetic field and solar activity are the causes of global warming rather than the increased amount CO_2 in the atmosphere [Blame You/ C(Lie)mate]. These skeptics are far outnumbered by the majority (>95%) of climate scientists that agree man is having an effect on global warming.

2.2 Concerns

The largest concern with climate change is the temperature increase. Concerns related to climate change range from economic and health effects to more devastating catastrophic effects including an ice age, melting of the polar ice caps, collapse of the thermohaline current, and extinction of entire species [Schneider, 2004]. Some scientists argue that if we do not act immediately it will be too late to reverse the effect of high quantities of GHGs in the atmosphere. Others disagree and believe more understanding is required to determine what actions, if any should be taken [Kolstad, 1994].

The health effects that could occur due to an increase in temperature include heat-related illnesses, respiratory problems due to an increase in fog, and the spread of disease and allergies. It is also predicted that climate change will increase the frequency and strength of storms, floods, droughts and fires [EPA]. An increase in these events will greatly increase the amount of injuries and deaths compared to our current climate.

A number of scientists also believe that climate change could have a detrimental effect on the Earth’s ecosystems. Species have adapted to climate change in order to survive. An increase in the rate climate change occurs could make it more difficult for the Earth’s species to survive. Increases in the oceans temperature and amount of carbon dioxide will affect habitats and food supplies. Climate change could also affect forests, habitats, the movement of invasive species and migration and life cycle events [EPA].

In addition to the health and ecosystem concerns are the potential economic costs related to climate change. The economic impact is unknown but could be of significant cost, especially to more impoverished regions. Sectors that could be affected by climate change that may have a detrimental effect on the economy include agriculture, forestry, energy systems, water systems, construction, fisheries, outdoor activities and tourism [Nordhaus, 1998]. All of the sectors would be affected differently based on the actual climate change in that specific region.

2.3 Mitigation

One of the largest areas for debate in regards to climate change and GHG emissions is what, if any, mitigating actions should be taken. Three main directions currently exist in this area. The first is the most drastic. This involves a significant reduction in GHG emissions, beginning immediately. GHG emissions could be reduced by developing clean technologies for the current industry and development of new clean power technologies. The cost involved with these actions would be significant. It would also be what is deemed irreversible costs [Kolstad, 1994]. Irreversible costs are costs that cannot be recuperated. Any capital spent on development of new technologies is essentially lost if at a future time it is determined that the clean technologies are unnecessary.

A second path is the use of taxes to curb production of GHGs by industry [Kolstad, 1994]. This cost is considered reversible. The income generated through these taxes could be used for any government program. This means that if after 100 years it is determined that the effect of GHG emissions on climate change is negligible, the capital collected from GHG taxes, assumed to be used for useful government programs would have benefited the general public. In the meantime, the taxes would aid in cutting down the amount of GHG emissions.

The third path is to continue to develop our scientific understanding of GHG accumulation in the atmosphere and climate change. This would allow time to determine what actions should be taken to combat climate change. It may be determined that there is no actual concern and no action is needed. Some scientists argue that this approach is too slow and by the time action is considered warranted, it would be too late [Kolstad, 1994].

The current administration under President Obama has tasked the EPA, under the Climate Action Plan, with establishing guidelines for CO_2 pollution for the United States existing power plants [2013 Proposed Standards]. In addition the EPA has developed standards for new power plants to cut carbon pollution. Some proponents argue that if the standards become too aggressive, electricity rates will increase resulting in the loss of jobs. The EPA is evaluating all sides of the argument in order to identify these standards.

An international committee has been formed under the United Nations in order to create emission reduction targets named the Kyoto Protocol [Kyoto, 2012]. The U.S. has chosen not to ratify the Kyoto Protocol because it does not require developing nations to make emissions reductions and it would cause economic harm to the U.S. To date, 191 countries across the world have ratified the Kyoto Protocol.

The current presidential administration is in line with the majority stance of climate scientists and believes that humans are having some effect on climate change. President Barack Obama has proposed a reduction of GHG emissions from the U.S. of 20% of 2005 levels by 2020 and 83% by 2050 [DOE, 2009]. The 83% reduction is even more aggressive than that proposed in this study and incorporates a more broad approach including vehicle emissions.

Chapter 3. Greenhouse Gas Emissions

3.1 Summary of Greenhouse Gas Emissions

Natural causes of GHGs include volcanic activity, circulation of the ocean, and solar radiation intensity among others. Human activities including deforestation, urban growth, and burning of fossil fuels. Since the start of the Industrial Revolution, the production of greenhouse gases through human activities has increased greatly. Life on earth relies on some quantity of GHGs in the atmosphere. Without GHGs, the earth would not maintain enough of the sun’s energy and the earth would be too cold to sustain life. The concern reviewed in this paper is whether there is now, or will soon be too much GHGs in the atmosphere which will increase the earth’s temperature and bring about climate change that may have negative consequences for life on earth. Here, the biggest concern of GHGs is CO_2. CO_2 is produced in large quantities during energy production and accounts for approximately 38% of the greenhouse gas effect [EPA]. Burning of fossil fuels such as natural gas and coal produces 33.4 billion tons of CO_2 a year.

CO_2 emissions have risen rapidly over the past few decades. The current atmospheric concentration of CO_2 of 380 ppm as of 2005 is much greater than the range seen over the past 650,000 years [Nordhaus, 2008]. Historically the range has been estimated to be between 180 and 300 ppm. According to CO2Now.org which tracks annual CO_2 levels, the upper safety limit for atmospheric CO_2 is 350 ppm. Atmospheric CO_2 levels have remained above 350 ppm since 1988. Based on current industrial growth, the atmospheric concentration of CO_2 is expected to continue to increase. In fact the amount of CO_2 in the atmosphere is accelerating from decade to decade. The amount of CO_2 in the atmosphere increases by approximately 2.0 ppm/yr.

CO2Now.org reports the CO_2 level in the atmosphere for the month of August 2013 is 395.15 ppm [CO2Now]. Figure 3.1 shows CO2Now.org's atmospheric CO_2 from 1959 to the present time. The data was gathered from by the National Oceanic and Atmospheric Administration (NOAA) at the Mauna Loa Observatory (MLO) on the island of Hawaii. The MLO was chosen as a site for atmospheric monitoring because it is located far from any other continent and provides a good average for the Pacific. The MLO is high enough that it is above the inversion layer and not affected by local effects.

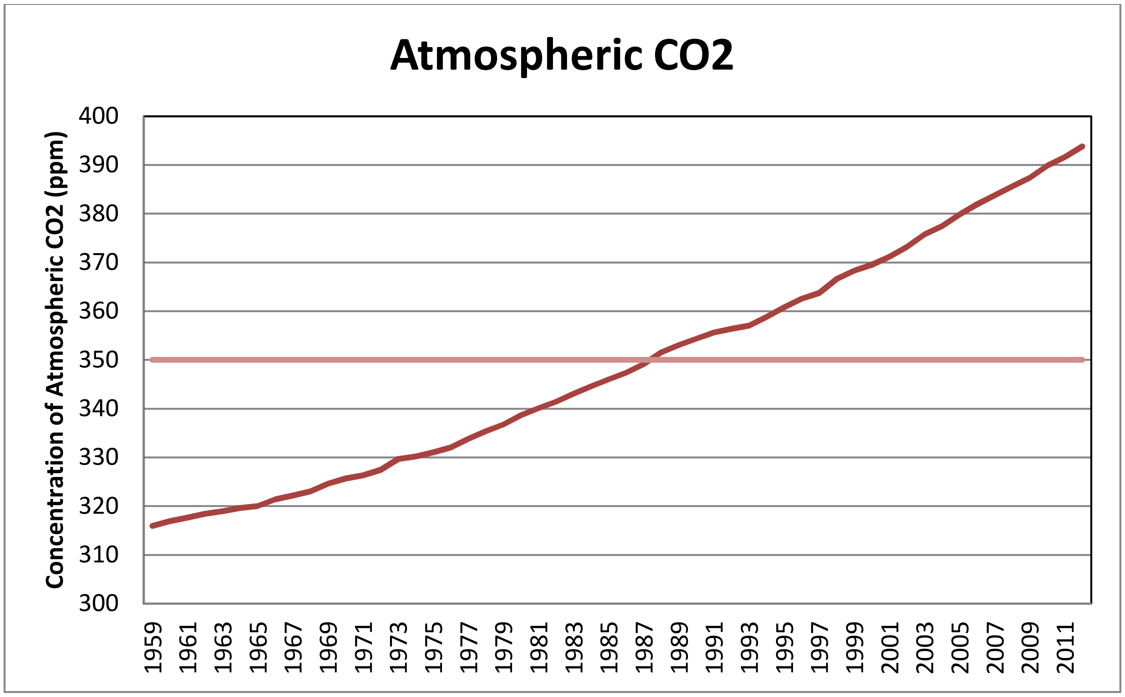


Figure 3.1 Atmospheric CO_2 versus time.

If the amount of CO_2 in the atmosphere is doubled, calculations predict the global surface temperature could increase between 1 and 5°C [Nordhaus, 1993]. In addition to temperature increase, it is also expected that precipitation and evaporation will increase. This could lead to increases in extreme weather events which could have catastrophic consequences.

Key indicators of recent global warming due to the amount of CO_2 in the atmosphere include a decrease in arctic sea ice, an increase in sea level, an increase in global temperature and a decrease in land ice mass [NASA]. Additional evidence is provided by an increase in severe weather events since 1950. A decrease in low temperature events has also occurred since 1950.

3.2 Fossil Fuel Burning Power Plants

In the U.S., more than 94% of GHG emissions come from the combustion of fossil fuels [EPA Inventory, 2013]. Fossil fuels are formed by natural processes such as decomposition of dead organisms beneath the earth's surface. Fossil fuels are non-renewable resources because they take millions of years to form. Fossil fuels contain a large percentage of carbon and include coal, petroleum, and natural gas. Fossil fuels make up the majority of sources for energy production in the world, accounting for 86.4%. The primary sources are 36.0% petroleum, 27.4% coal and 23.0% natural gas. Nuclear power only accounts for 8.5% of the world's energy production [EIA International Energy Statistics].

Fossil fuel burning technologies typically produce between 600-1200 g CO_2/kWh_{el} [Lenzen, 2008]. Assuming an average of 900 g CO_2/kWh_{el}, this equates to 900,000 g per MWh_{el} or 900,000,000 g per GWh_{el} [Lenzen, 2008].

The burning of fossil fuels produces around 21.3 billion tones of CO_2 per year [EIA What are Greenhouse Gases]. It is estimated that natural processes can only absorb half this amount. This accumulation of CO_2 contributes to global warming which in turn causes the earth's surface temperature to rise.

3.3. Nuclear Power Plants

During its energy production stages, NPPs do not produce GHG emissions. However, Nuclear Power Plants are not a zero emission energy source. NPPs are indirectly involved in the production of GHGs during the upstream and downstream processes. The upstream and downstream processes of the nuclear fuel cycle includes, uranium mining, uranium milling, conversion to uranium hexafluoride, enrichment, fuel fabrication, reactor construction, reactor operation, decommissioning, fuel re-processing nuclear waste storage, and nuclear waste disposal and transportation.

The amount of GHGs produced in the development of NPPs is much less than that for FFPPs. It is estimated that for both Light Water Reactors (LWR) and Heavy Water Reactors (HWR) GHG emissions range from 10 to 130 g CO_2/kWh_{el}, with an average of 65 g CO_2/kWh_{el} [Lenzen, 2008]. These estimates include all upstream and downstream processes. So comparing with a FFPP, a NPP produces on average 835 g CO_2/kWh_{el} less. A NPP produces 7.2% the amount of GHGs as a FFPP.

The purpose of this paper is to examine the effect of new construction of NPPs to replace existing FFPPs on GHG emissions. As stated in the previous paragraph, a NPP produces significantly less GHGs than a FFPP. This paper will analyze what volume of NPP construction would be needed to reduce a sufficient amount of GHG emissions to have a measurable effect on climate change.

3.4. Green Energy Technologies

Much effort has been placed in developing green energy technologies over the past few decades. Examples of these technologies include hydrogen fuel cells, solar power, wind turbines and hydroelectricity. These technologies are similar to nuclear power in the sense that they produce very little GHGs during power generation. Many scientists debate what level of effort should be placed into developing these technologies. Some suggest that these technologies will reduce the amount of GHG emissions and should be the future of energy production. Most of these technologies are still in the developmental stages and have many years before a viable technology exists that can compete with the current energy industry technologies (i.e. NPPs, FFPPs).

For comparison purposes wind turbine and hydroelectricity produce between 15-25 g CO_2/kWh_{el} [Lenzen, 2008]. Solar photovoltaic and solar thermal power produce around 90 g CO_2/kWh_{el}. The Green technologies produce a comparable amount of GHGs to NPPs. However, it is unlikely you will hear NPPs discussed as a green or clean technology.

3.5. Reduction in GHGs through NPP Construction

The purpose of this report is to evaluate the effect of replacing FFPPs with the construction of NPPs. The analysis will consider hypothetically replacing an equivalent amount of power from FFPPs that will be decommissioned with newly constructed NPPs.

The modified DICE model used for this study allows for the use of any constant NPP production scenario. The model will construct an equal amount of NPPs each year the model is set to simulate. A large number of different production scenarios were used. This study analyzed the effect of various NPP construction rates between 0 and 1000 NPPs per year. It is assumed that most of these production scenarios are not realistic based on the current construction projects planned and the political climate surrounding nuclear power. This study does not consider NPPs planned or currently under construction in the U.S.

Construction of a NPP is no insignificant task. Current construction rates of approximately 4.5 years and over $10 Billion per unit make an aggressive increase in NPP construction a huge challenge [EIA Economics]. The current political climate is not pro-nuclear. This is due to past nuclear accidents, starting with the Three Mile Accident in 1979, Chernobyl in 1986 and most recently the Fukushima nuclear accident. Some countries, including Germany and Japan, are reducing their fleet of NPPs in the wake of the Fukushima nuclear disaster.

Chapter 4. Nuclear Power

4.1. U.S. Nuclear Power

The U.S. is currently the largest producer of nuclear power with 104 nuclear power plants. This accounts for more than 30% of the world's total nuclear power generation [Nuclear Power in the USA]. The U.S. is the largest power producing and consuming nation in the world.

The 104 NPPs account for 20% of the U.S. domestic power generation. All of the operating power plants have been constructed prior to 1977 [Nuclear Power in the USA]. With an aging fleet of NPPs, the amount of NPPs is expected to start decreasing in the near future and without the construction of new plants, the fraction of power generation from NPPs will decrease. It is reported that 50-75 new NPPs will need to be added to the fleet to keep up with energy demands [Brinton, 2009]

Although there has been no new construction in decades, some of the NPPs have performed upgrades including Measurement Uncertainty Recapture (MUR), Stretch Power Uprate (SPU) and Extended Power Uprates (EPU). The uprates have the potential to increase power output of NPPs by 2-20% [U.S. NRC Power Uprates]. The upgrades are achieved through equipment upgrades, improved fuel performance and reduction of operating margin.

Future construction of NPPs in the U.S. is questionable. 27 new units have been proposed with a number of license applications pending. It is expected that 4-6 units may actually come online by the year 2020 [Nuclear Power in the USA]. It is still unclear whether the Fukushima nuclear disaster will have any effect on the future of nuclear power.

4.2. World Nuclear Power

Over 430 NPPs are operating across the world in more than 30 countries. This accounts for approximately 13.5% of the world’s electricity [Nuclear Power in the World Today]. France is the biggest advocate of nuclear power with over 75% of their power produced from NPPs. Currently 60 more NPPs are being contracted in 13 countries [Nuclear Power in the World Today]. This would be an increase of 17% of current output. An additional 150 NPPs are firmly planned which would be an increase of 46%.

The Fukushima nuclear disaster has had a major impact on nuclear power. In 2012 there was the sharpest decline of nuclear power generation since the industry began [Macalister, 2013]. None of the 48 operable nuclear power plants in Japan produced any power in 2012. Japan continues to struggle to bring these plants back online. Countries including Germany, Sweden, Italy, and Spain have all decided to phase out operation of any NPPs [Macalister, 2013].

On the other hand, countries like China, Russia, and India plan to increase NPP construction in order to accommodate their increased electricity demand. China even contends that nuclear power is a means to reduce their dependence on coal-fired power plants [Macalister, 2013].

4.3. NPP Construction

Although there are a number of NPPs under construction, a recent example used for analysis in this report is the Shin Kori 1 NPP in South Korea. This NPP began operation in December 2010. The total construction for this plant was approximately 1620 days or 54 months. This will be a factor when considering how many nuclear power plants can be constructed and how long they will take to come online. Power plant construction will be limited by construction time and resources. There currently are only five vendors of NPPs in the world. In order to determine the feasibility of NPP construction to mitigate GHG emissions, these factors will need to be considered.

Chapter 5. Dynamic Integrated Climate Model (DICE)

5.1. History of Model

One of the earliest forms of the model developed by Nordhaus in 1991 was a long-run steady-state model of the global economy that included estimates of both the costs of abating carbon dioxide emissions and the long-term future climate impacts from climate change [Newbold, 2010]. This model could be used to balance the benefits and costs of CO_2 emissions to help determine the optimal level of near-term controls. The result of the analysis was the effect on the global surface temperature. The global surface temperature was used because it acts as an indicator for all aspects of climate change.

The next version of the model presented in 1992 was a fully dynamic Ramsey-type optimal growth model that could determine the optimal time path of emission reductions and associated carbon taxes that emerged from it. Nordhaus released a book in 1994 that included a detailed description of the DICE model as well as a range of applications.

In addition to the DICE model. Nordhaus disaggregated the model into ten different groups of nations. This is called the Regional DICE model or RICE. This allows for further analysis using the DICE model to evaluate national level climate change policies and strategies. The RICE model was later updated to include only 8 regions. The most recent version released in 2010 includes a measure of the damages caused by sea level rise [Newbold, 2010].

A further update to the DICE model in 2008 allowed for a technology that could completely replace all fossil fuel powered plants. The supply of carbon based fuels is limited. So substitution of carbon based fuel with non-carbon based fuel will occur at some rate over time. This could be due to the exhaustion of carbon based fuels, development of new technologies that replace carbon or implementation of policies that limit GHG emissions. Any new non-carbon based technology would initially be very costly with costs slowly declining over time. The model developed for this study will not utilize this functionality, but rather uses a new portion of the model that was developed to simulate the replacement of fossil fuel burning power plants by the construction of nuclear power plants. The reason for not using this functionality is because the goal was to focus on NPP construction as the primary means of slowing climate change.

5.2. Description of Model

The DICE model views the economies of climate change from the standpoint of the Ramsey growth model, which is a neoclassical growth theory model [Nordhaus, 2008]. The neoclassical growth theory involves a steady growth rate that is driven by three factors; Labor, Capital and Technology. By varying the amount of labor and capital an equilibrium growth rate can be achieved. As new technologies are introduced, the labor and capital will again need to be adjusted in order to maintain growth equilibrium. Based on this approach, economies make investments in capital, education and technology. These investments allow for a reduction in consumption today, which allow for an increase in consumption in the future.

The atmospheric concentration of CO_2 is considered as a form of “natural capital”. This natural capital has a negative impact on economic output due to its influence on the global average surface temperature. The amount of natural capital is increased by reductions of emissions. A reduction of emissions can occur due to policies which limit GHG emissions or replacing carbon based fuel with non-carbon based fuel. This includes NPPs which produce significantly less GHG emissions than FFPPs.

The DICE model is a global model that aggregates different countries into a single level of output, capital stock, technology, and emissions. Data from all major countries is used to estimate the global aggregate. Global economic output is determined using a Cobb-Douglas production function using physical capital, labor and energy as inputs [Newbold, 2010]. Energy production either comes from carbon based fuels such as coal or natural gas or from non-carbon based technologies. Non-carbon based technologies include solar, geothermal energy and nuclear power [Nordhaus, 2008].

Labor is a function of global population and grows over time. The total factor productivity also increases with time [Newbold, 2010]. Both increase exogenously. All regions start with an initial stock of labor and capital. Capital accumulation is determined by the individual consumption rates of each region [Nordhaus, 2008]. Consumption includes food, shelter, amenities and services.

The potential damages that occur due to climate change are divided into seven categories. These categories include agriculture, sea level rise, other market sectors, human health, nonmarket amenity impacts, human settlements and ecosystems, and catastrophes. Individual damage functions are used for each of these categories.

5.3. Application of Model

The DICE model was originally developed by visiting students at the University of Idaho from South Korea using the Nordhaus model version created by Tom Fiddaman of MIT [Fiddaman, 2007] with Vensim Simulation software. Vensim is a simulation program made by Ventana Systems. It is a “visual modeling tool that allows you to conceptualize, document, simulate, analyze and optimize models of dynamic systems” [Vensim User’s Guide, 2002]. The software provides a means of building models from casual loop or stock and flow diagrams. Figure 5.1 shows the DICE model trajectory.

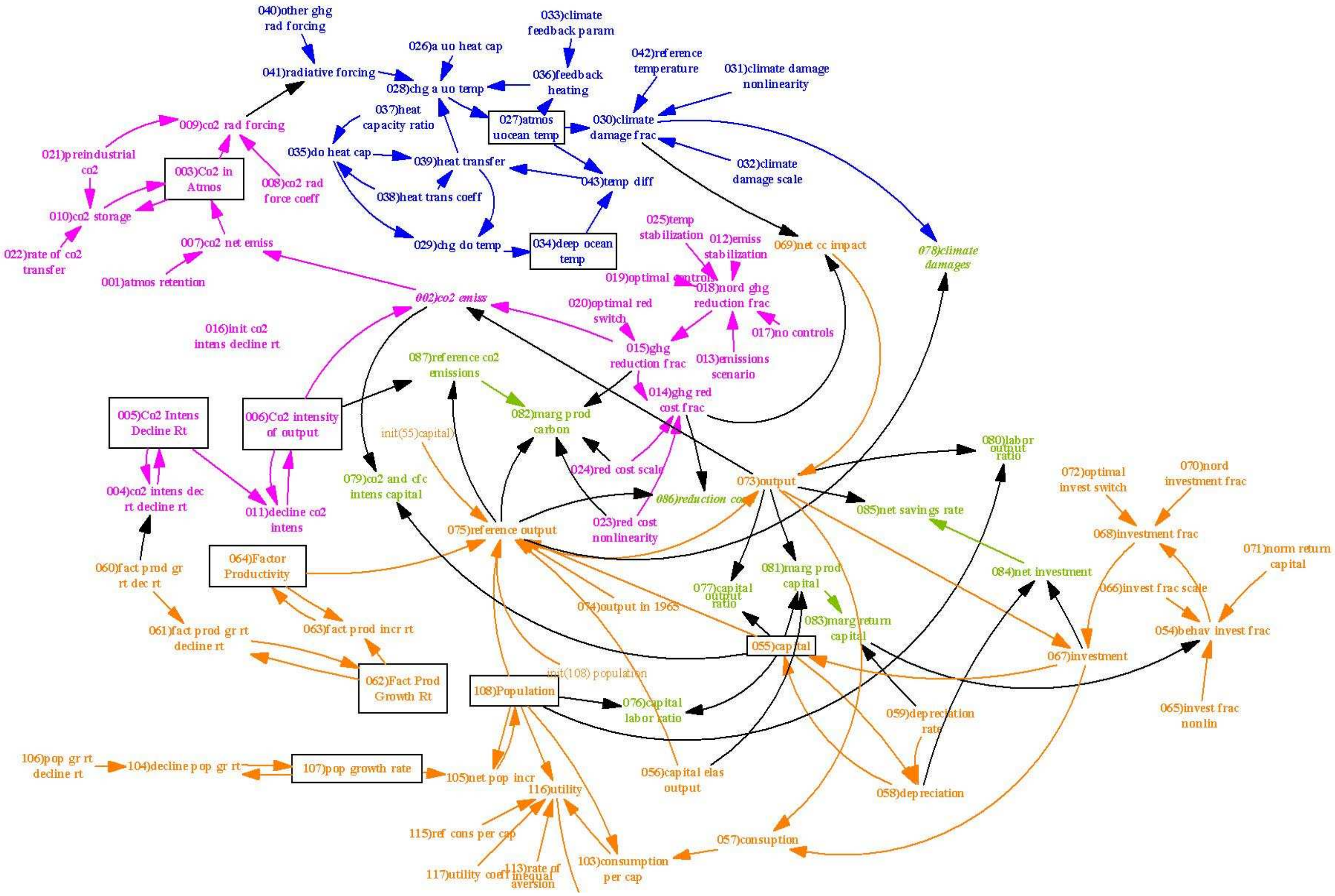


Figure 5.1. Vensim trajectory of the DICE model.

The trajectory is divided into 5 sections. The blue section represents climate, the pink carbon, green is indices, the orange represents economy and the black is optimization. For the purposes of this research, variables from the climate and carbon sections will be changed to analyze multiple scenarios. The variables that will be analyzed as part of this study include CO_2 in the atmosphere, atmospheric and ocean temperature increase and climate damages, as these are the primary climate change variables that the DICE model will simulate.

The CO_2 in the atmosphere is calculated as a function of CO_2 emissions and the atmospheric retention of CO_2 in the atmosphere. A residence time of 120 years is used in the DICE model. The atmospheric and upper ocean temperature increase is calculated as a function of the surface warming from accumulation of CO_2 in the atmosphere. The deep ocean temperature changes as a function of the heat transfer between the upper ocean. The warmer the upper ocean, the warmer the deep ocean will become. The climate damages is calculated from the simulated reference annual economic output and designed to change as the temperature changes. Appendix A lists all of the variables of the DICE model and each of their uses and causes.

To model the effects of NPP construction as a means to reduce greenhouse gas emissions from power plants in the U.S., the DICE model was modified. The modified version includes a section that allows for the modeling of the construction of NPPs and subsequent decommissioning of fossil fuel burning power plants. This portion of the model uses a ratio of the power produced by a NPP compared to that of the FFPP to determine how many

FFPPs will be shut down if a NPP is built. Since the amount of GHGs produced by a NPP is much less than that of a FFPP, the GHG emissions will be reduced. Further increasing the NPP construction rate will continue to reduce emissions.

The modified DICE model can determine what the reduction of GHGs will be based on the different construction rates and then feed this reduction into the Nordhaus portion of the DICE model. The DICE model can then predict the total amount of CO_2 emissions after some period of time, the total amount of CO_2 in the atmosphere, atmospheric and ocean temperature increases and other factors. The model will be used to predict the benefit, if any, of using NPPs as a means to reduce CO_2 emissions to the atmosphere. The model will be described in further detail below.

The modified NPP construction portion of the model starts with the historic and current quantity of NPPs in the U.S. from 1965 until 2012. The present amount of operating NPPs in the US is 104. The model also assumes the lifetime of a NPP to be 60 years. The model will automatically decommission a NPP after 60 years from the year it was constructed. Based on the design of the model the amount of NPPs constructed will need to be maintained to meet the original power output, so after 60 years it can be inferred that when new NPPs start to be decommissioned, new NPPs will be constructed to replace them. This essentially means the NPP construction rate will double, after 60 years. This is not shown in the model, and will ultimately not have an effect on the results. The model then provides the ability to adjust the construction rate of NPPs from 2014 onward. The model will allow for a constant construction rate each year for the entire duration of the simulation. The model will also start to decommission these NPPs after 60 years as stated earlier. The amount of NPPs in operation will then become constant as the amount of NPPs constructed will eventually equal the amount decommissioned.

The next portion of the model will assume a specific amount of FFPPs will be replaced by NPPs based on the power ratio between the different types of power plants. Since coal burning power plants (CPPs) produce the largest amount of CO_2, these plants will be replaced first. The amount of CPPs decommissioned will be based on their average power compared to the average power of a NPP. Table 5.1 below shows the average power for the different power plants used for this study.

Table 5.1. Power output and CO_2 emissions for each type of power plant.

Plant	Operating Units	MWh/unit	ton CO2 emissions/unit	Annual Output of CO2 (tons)	ton CO_2/MWh	% of CPP
Coal Power Plant (CPP)	1396	1,300,000	1,360,000	1,898,560,000	1.05	100%
Petroleum Power Plant (PPP)	3779	24,896	19,000	71,801,000	0.78	74%
Natural Gas Power Plant (NGPP)	5529	189,522	84,000	464,436,000	0.44	42%
Nuclear Power Plant (NPP)	104	7,590,000	500,940	52,097,760	0.07	6%

The average power for coal burning power plants, natural gas power plants and petroleum power plants is calculated by taking the average power output for all of the plants in operation in the U.S. for 10 years from 2001 to 2010 [EIA Electric Power, 2013]. It should also be noted that for the newly constructed NPPs the same power capacity is used for the entire model and advances in power output are not considered. For CPPs, dividing the average power (MWh/unit) of a NPP by a CPP (#NPP/#CPP) gives you the amount of CPPs that will be shut down each time a NPP is built. The model will then calculate the amount of CO_2 emissions that will be eliminated by closing the CPPs due to new construction of NPPs. Table 5.1 also lists the amount of CO_2 produced by each type of power plant. A CPP will produce about 1.05 tons of Carbon per MWh, while a NPP will produce 0.07 tons per MWh. This equates to roughly 6% the emissions from a NPP compared to a CPP.

The model is designed to first replace CPPs, then NGPPs and finally PPPs. The NGPPs will not be replaced until all of the CPPs are replaced and the PPPs will not be replaced until the NGPPs have all been decommissioned. Varying the NPP construction rate will alter the rate at which the FFPPs are eliminated. If the NPP construction rate is large enough, all of the FFPPs will eventually be replaced. Once all of the FFPPs have been decommissioned, additional construction of NPPs will have no further effect on the model because the all of the power generated from FFPPs has been replaced with NPP generated power. Figure 5.2 shows the modified portion of the DICE model created for this study. The amount of CO_2 that is calculated to be reduced by closing the FFPPs is then fed into the standard DICE model CO_2 emission variable. Figure 5.3 is of the entire DICE model including the standard Nordhaus portion and the modified portion.

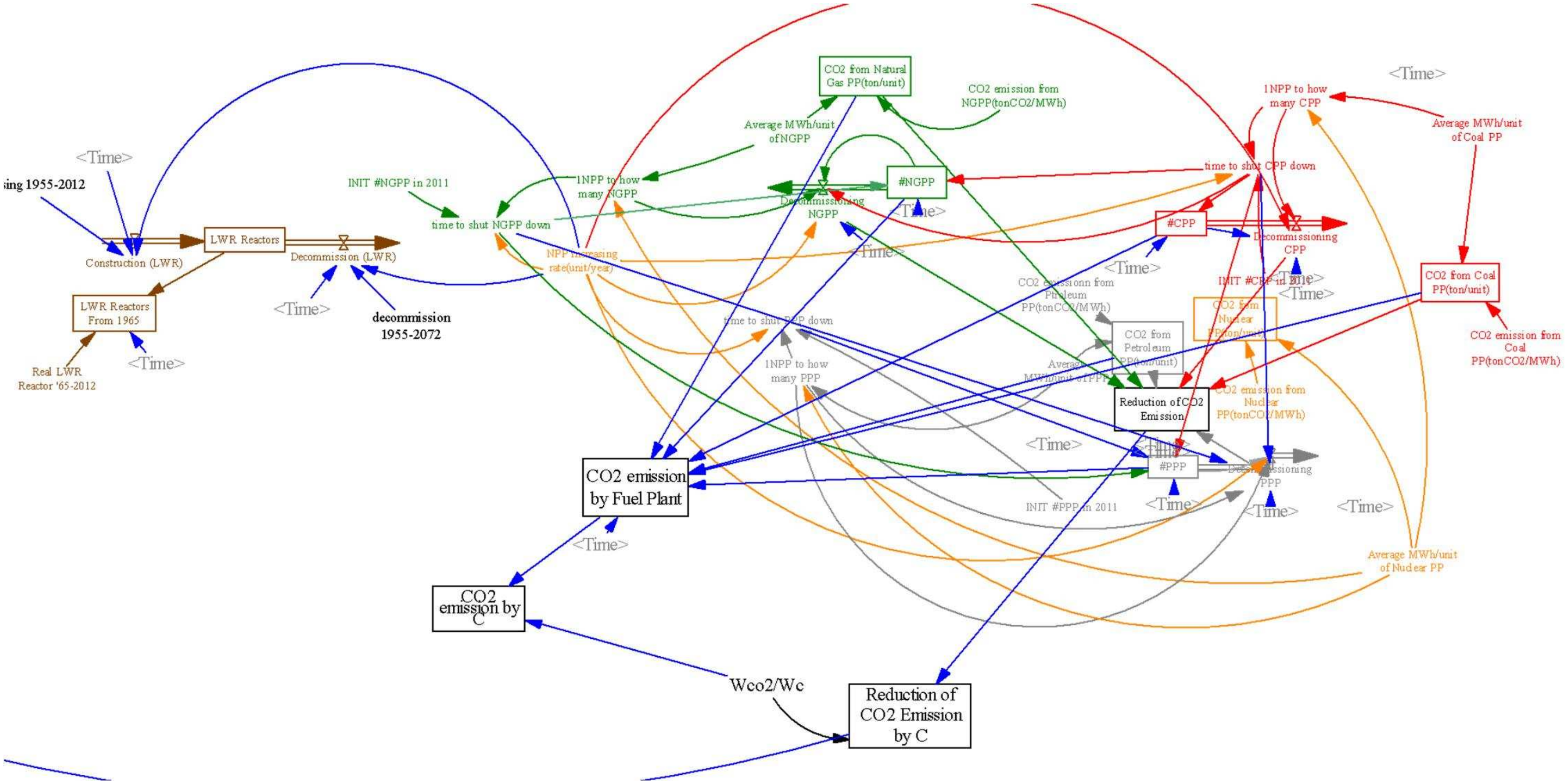


Figure 5.2. Modified portion of the DICE model

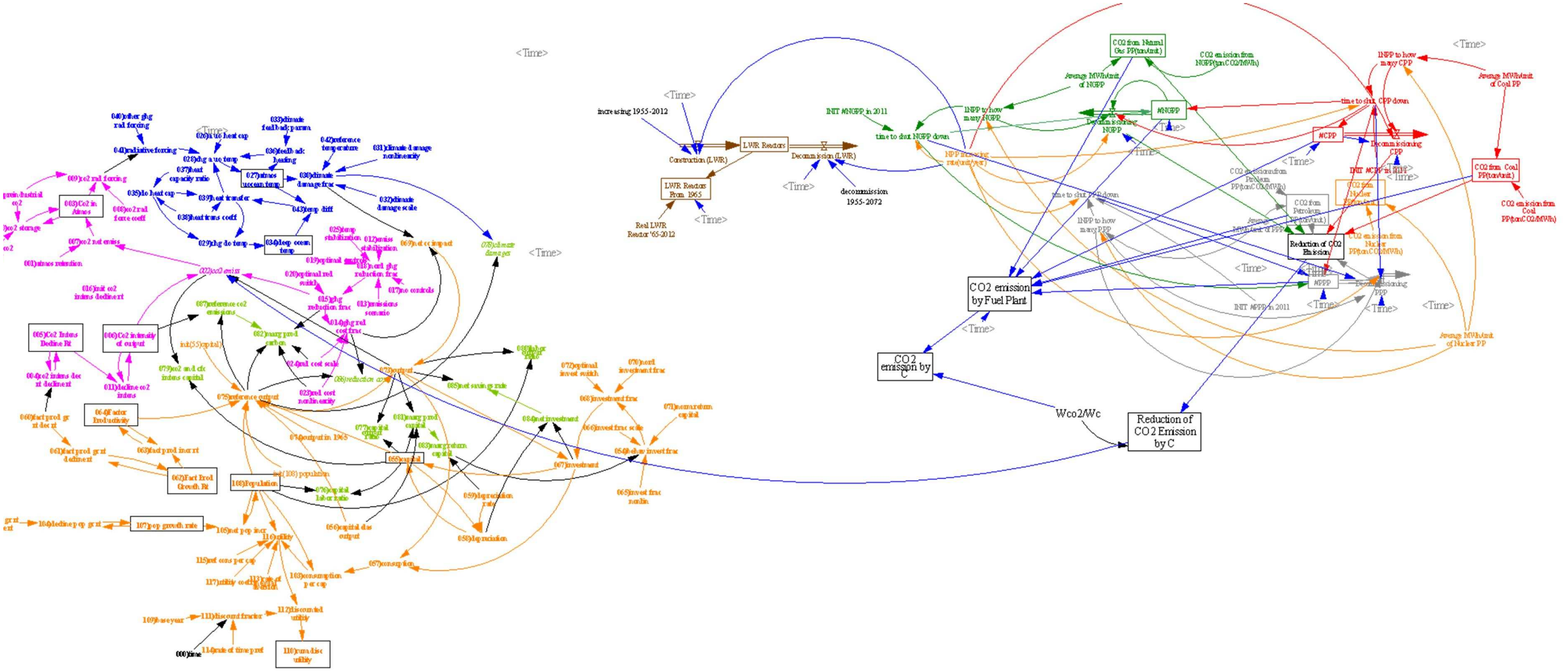


Figure 5.3. DICE model including the modified portion for NPP construction modeling.

5.4. Example Model Run-Through

To clearly illustrate how the model works, this section will run through each stage of the model and display the representative data. For this example, a NPP construction rate of 2 units per year will be used and results from the simulation will be presented through the year 2105. The figures used in this section are taken directly from the Vensim Model. As a comparison to the current NPP construction progress, 2 units are currently being constructed per year, unlike this model which has 2 units being completed and online each year.

The NPP increasing rate (NPP/yr) variable is first changed to 2. This means the model will construct 2 NPPs per year from 2013 to 2105. The model will also decommission NPPs 60 years after their date of construction. This means that over the 92 years 184 units more than the 104 in operation will be built, less the units that are decommissioned after 60 years of operation.

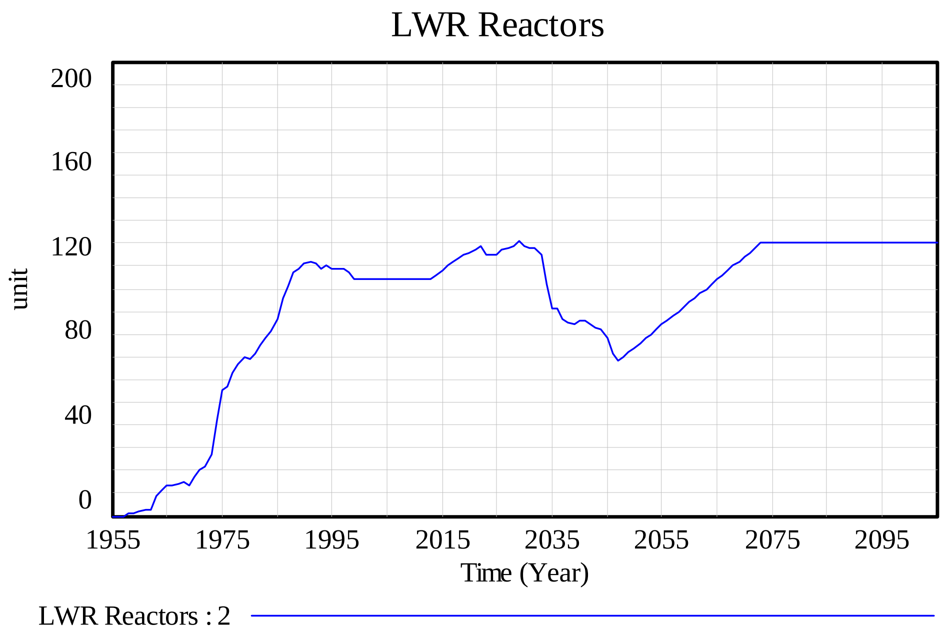


Figure 5.4. Vensim model representation of NPP construction history until 2014 and then 2 NPP/yr until 2105.

Figure 5.4 exhibits the actual NPP construction history until 2014. After 2014, the model simulates construction of 2 NPP each year until 2104. Starting in 2014 the total # of NPPs increases until around 2030 when the current fleet of NPPs begins to be decommissioned. The number of NPPs starts to increase again in 2050 as 2 NPPs continue to be constructed each year. Eventually the model reaches equilibrium in 2070 when the number of NPPs constructed equals the number decommissioned (i.e. 2 NPPs constructed and 2 NPPs decommissioned at 60 years of operation).

The model will then calculate how many coal burning power plants (CPPs) will be decommissioned for each NPP constructed. There are currently 1396 CPPs operating in the U.S. [EIA Electric Power, 2013]. Three CPPs will be decommissioned for each NPP constructed based on the ratio of power output between the two types of power plants. Figure 5.5 shows the rate of CPPs decommissioned versus time.

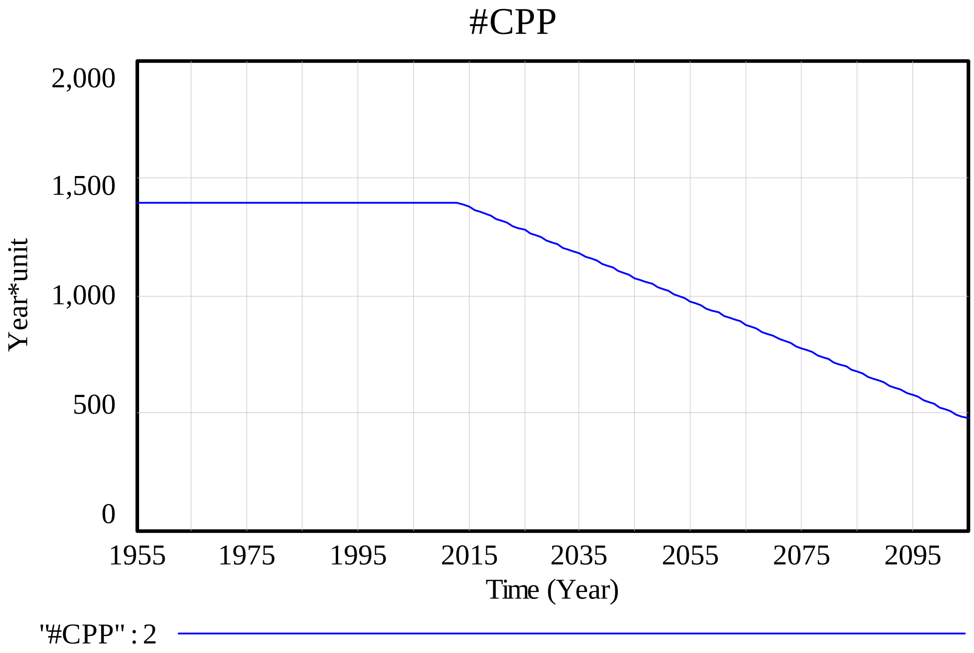


Figure 5.5. Number of CPPs versus time.

Based on a NPP construction rate of 2 per year, around 500 CPPs would remain in operation in 2105. If modeling an increased construction rate, the amount of CPPs decommissioned would increase. Eventually all CPPS would be decommissioned at a high enough NPP construction rate. If this occurs, the model is designed to then decommission natural gas power plants and then petroleum based power plants. Figure 5.6 shows an example of an increased NPP construction rate on CPP, NGPP and PPP decommissioning rates.

Figure 5.6 is based off of a NPP construction rate of 20 NPP per year. The data from the 2 NPP per year rate is shown for comparison. As can be seen, all of the CPPs are decommissioned and replaced by NPPs shortly after the year 2025. The model is designed to start decommissioning NGPPs after CPPs. The power output from a NGPP is much less than that of a CPP. The figure shows the 5529 NGPPs that are currently in operation are all decommissioned in approximately 10 years from 2025 to 2034.

The model will then start to decommission the PPPs once the NGPPs have all been shut down. PPPs generate even less power than NGPPs. Hence, the 3779 PPPs in operation are decommissioned in 2 years when 20 NPPs are constructed per year. Continuing with the 2 NPP per year example, the model will then calculate the amount of CO_2 output will be eliminated for each CPP that is decommissioned. This is determined from the amount of CO_2 emissions from each CPP and the number of CPPs decommissioned.

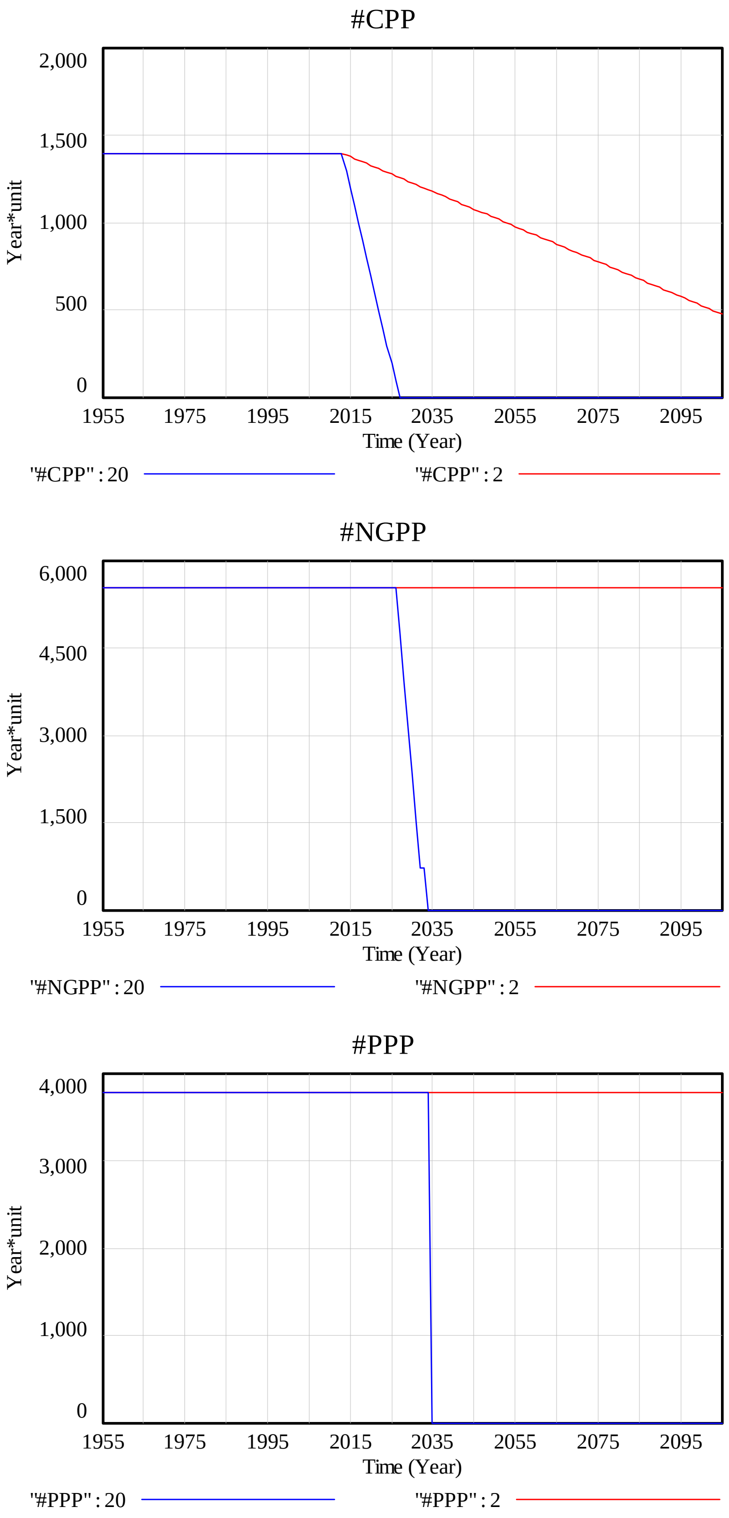


Figure 5.6 Number of CPP, NGPP and PPPs versus time.

In Figure 5.7 it can be seen that 13.02 million tons of CO_2 emissions are avoided each year due to the decommissioning of 6 CPPs when 2 NPPs are constructed. The model will then convert the CO_2 emissions to tons of Carbon.

Figure 5.8 is similar to 5.7, but in tons of carbon vice tons of CO_2 to be compatible with the DICE model. Most scientists report their data in terms of carbon vice CO_2 because they are studying the carbon cycle [Romm, 2008]. The reduction of CO_2 emissions by tons of Carbon is then fed directly into the DICE model. It is fed into the "002) CO_2 emissions" variable which estimates the increase in CO_2 emissions into the atmosphere from predicted economics, population and climate behavior based on historical data.

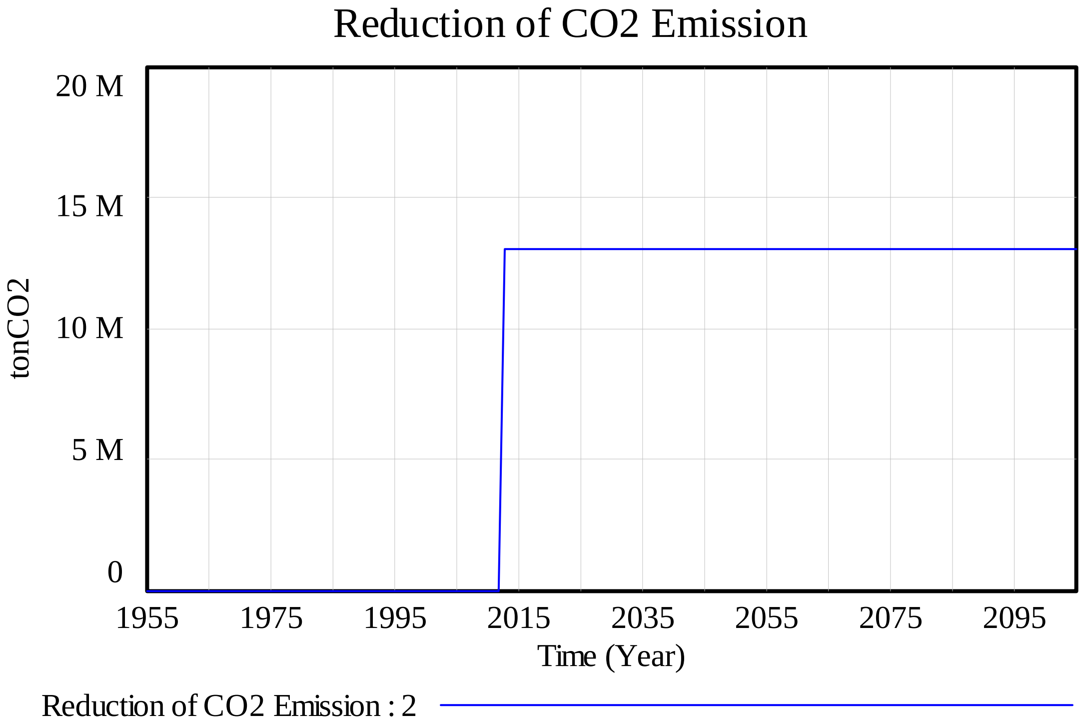


Figure 5.7. Reduction in CO_2 emissions versus time.

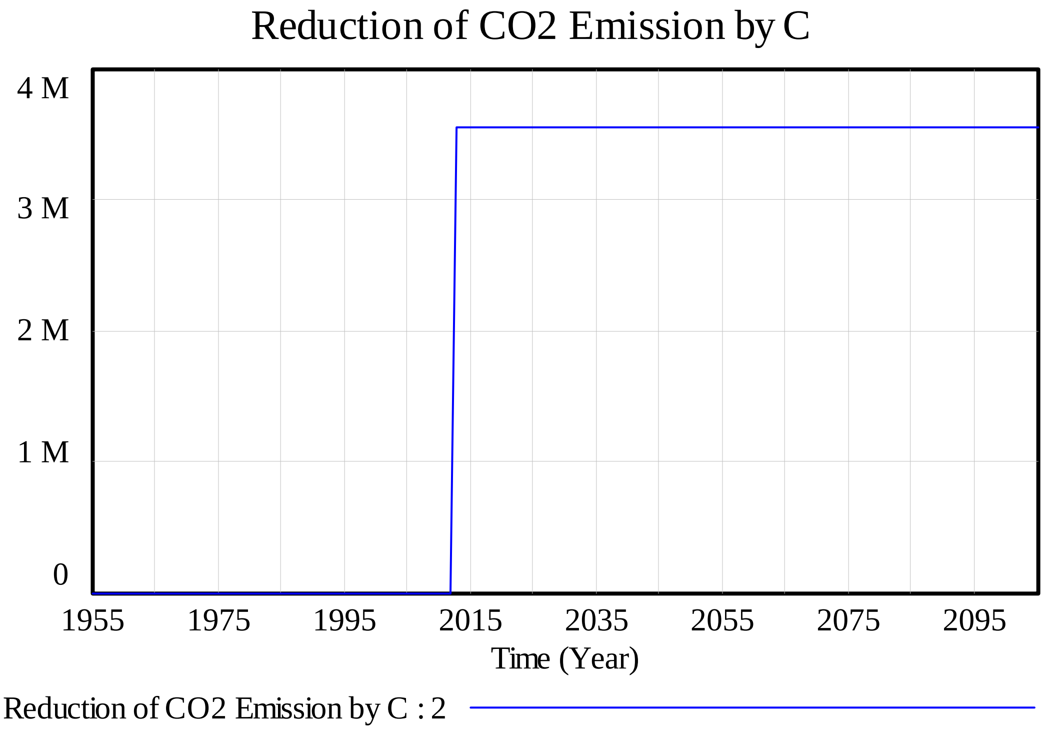


Figure 5.8. Reduction of CO_2 emissions by ton C per year.

The modified DICE model can be used to determine the effect of using different construction rates to decommission CPPs, NGPPs and PPPs in order to reduce the amount of GHG emissions. The different calculated reduction in avoided emissions is fed into Nordhaus's DICE model to predict factors such as CO_2 in the atmosphere, atmospheric temperature increase and deep ocean temperature increase. The overall purpose of this study is to determine if the construction of additional nuclear power plants is a viable alternative to combat global warming.

5.5. Shortfalls of Model

The modified DICE model developed for this analysis allows for modeling of very aggressive NPP construction rates. The largest shortfall that would be encountered if a large number of NPPs was constructed would be the manufacturing capabilities for the large reactor pressure vessel (RPV) forgings. Using the Westinghouse model AP1000 as an example, it requires a 15 kiloton press that can accommodate a 350 ton ingot at a minimum [Heavy Manufacturing]. According to the World Nuclear Association [Heavy Manufacturing], the challenge is not just for heavy forgings such as reactor vessels, steam turbines and generators, but also other highly engineered components. This in turn makes the higher level of output difficult to achieve.

Due to the current political climate after the Fukushima nuclear disaster, it is unlikely that the manufacturing capabilities for NPP forgings or other large components will increase in the immediate future. It would be expected that additional manufacturing facilities would come online to support a greater demand if one developed, but that would not be expected for some time. Some of the NPP manufacturing rates proposed in this study would not be feasible, at least initially. However, for the purpose of analysis, these factors are ignored in the simulation model. The model also uses a constant manufacturing rate for each year. The model does not take into account any changes in production rates due to economic conditions, manufacturing issues, or other additional factors that could limit NPP construction rates. A nuclear disaster in the U.S. similar to Fukushima would likely have a detrimental effect on NPP construction. Additionally, a large number of construction projects would also require a large number of resources including trades skills, laborers, cranes, concrete as well as many others. These resources could also limit the NPP construction rates. For comparison purposes, the highest actual construction rates occurred during the 1970’s when construction of 25-30 new reactors was started worldwide each year [Char and Csik, 1987]. The model also does not consider the considerable length it requires to complete an application for a new NPP. As well as the lengthy construction time of 4.5 years based on the recent construction duration of the Shin Kori NPP in South Korea. The model will construct the inputted NPP construction rate regardless of these factors.

For the purpose of this study, FFPPs are immediately decommissioned. This is not feasible in the sense that it is unlikely the U.S. would shut-down FFPPs that are working perfectly fine. In reality there would be some degree of overlap between decommissioning and new NPP construction.

Another limiting variable for this study would be the availability of enriched uranium. Some of the construction rates analyzed would require an amount of uranium greater than the available reserves. Depending on economics, the amount of uranium reserves could increase if sources including seawater or remote geographical areas are further explored for new reserves. This includes advanced techniques being developed here at the University of Idaho to remove uranium from seawater by Professor Chien Wai [Wai, 2012]. It is also predicted that alternative fuels such as plutonium or thorium may be considered in the future. Reprocessing of used nuclear fuel or the use of breeder reactors could also extend the nuclear fuel available for NPP construction. The availability of uranium for construction of NPPs is not considered for this study.

The amount of radioactive waste that will be generated from the NPPs also needs to be considered. With the larger production rates the radioactive waste will be significant. In addition to the radioactive material waste will be disposal of the spent nuclear fuel (SNF). The U.S currently has not identified a location for long term disposal of SNF. Some states require that a plan for permanent disposal of SNF and radioactive waste is determined prior to construction of any NPPs. Adding this into consideration would impede the construction rates that are modeled in this study.

Chapter 6. Results

6.1. Results of Vensim Model Simulations

After the Vensim DICE model was recreated and the modified portion completed, multiple simulation runs were conducted in order to produce results. The input for the model is a NPP construction rate. A range of simulations between zero (0) NPP/year and 1000 NPP/yr were used. A simulation is performed with no NPPs being constructed as a baseline. This is essentially the amount of CO_2 emissions predicted by the Nordhaus model if no action is taken. The simulations initially involved smaller NPP construction rates that could more accurately reflect potential construction rates in the near future. Increased production rates were then used to determine where the greatest reduction in emissions can be seen. These higher rates are not feasible due to many factors surrounding NPP construction and development.

The model was set up to produce data until the year 2300. This analysis will evaluate the effects of increased NPP construction on GHG emissions over the next 300 years. Discussion will also involve the results from the year 2100 to compare the difference from the next 100 years. The purpose for choosing these periods was to evaluate the near-term effects (<100 years) as well as allow for a larger period of time to elapse (300 years) to allow for the cumulative effects to be determined over a larger period of time.

The model is set up to replace all of the FFPPs in operation in the U.S. Once all of these FFPPs have been decommissioned, additional NPP construction will have no effect on climate change. It will take approximately 390 NPPs to replace all of the FFPPs. Faster rates of construction will replace the FFPPs at an increased pace. Table 6.1 shows how many years it will take for each NPP construction rate to eliminate all of the FFPPs.

Table 6.1. Time in years it will take to replace all FFPPs for each NPP construction rate.

NPP Construction Rate (NPP/yr)	Time to Replace FFPPs (yr)
0	N/A
1	N/A
2	195
3	130
4	97
5	78
10	39
25	16
50	8
100	4
250	2
500	1
1000	1

Table 6.1 gives some perspective into how quickly the FFPPs could be eliminated based on the higher power output of each NPP. This data is important because it relates to the fact that the faster the FFPPs are decommissioned, the less time they have to produce GHGs. This will factor into the results that will be further discussed below.

The first factor evaluated is CO_2 emissions versus time. Per the DICE model, CO_2 emissions are predicted to grow over time. Once NPP construction and FFPP decommissioning starts, the amount of emissions is reduced. As the NPP construction rate increases, the amount of CO_2 emissions will decrease.

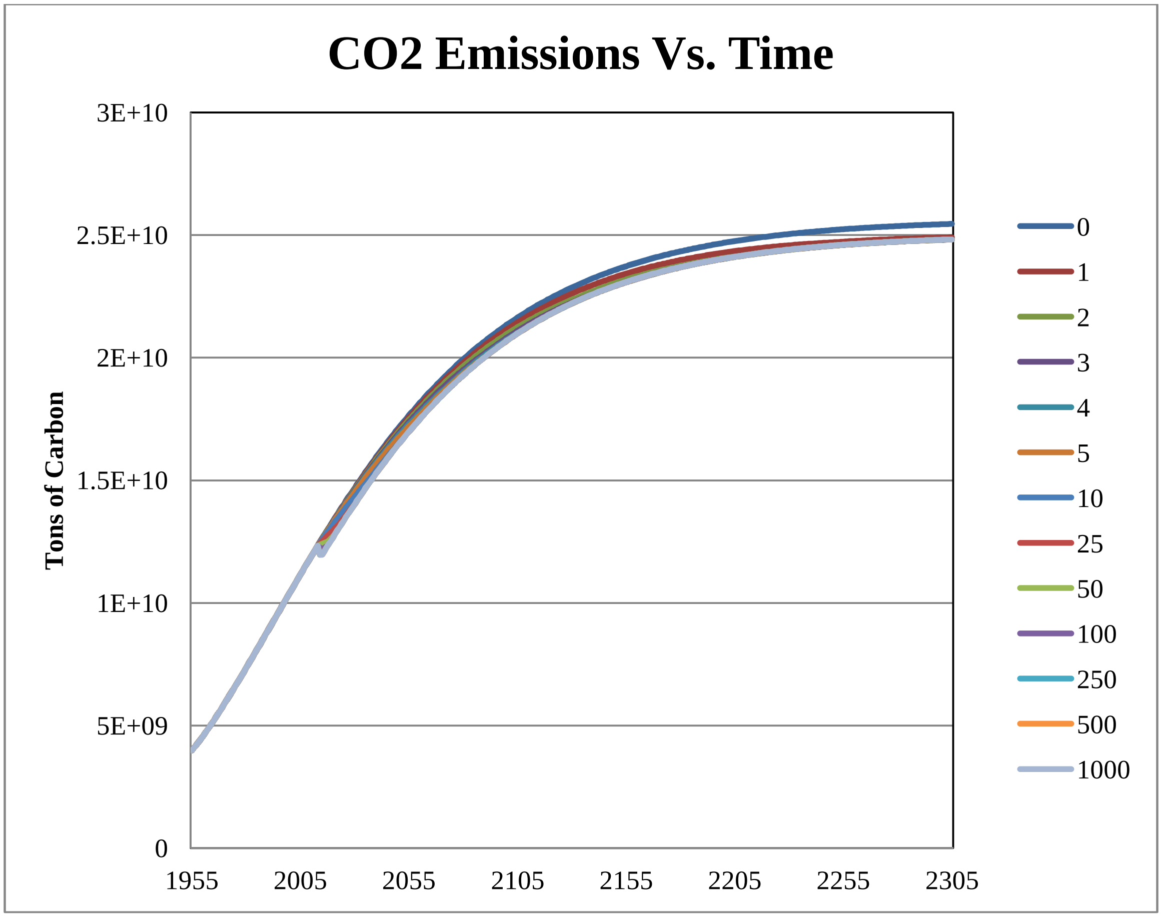


Figure 6.1. CO_2 emissions versus time for multiple NPP construction rates.

Figure 6.1 shows how the CO_2 emissions decrease as the NPPs are simulated to replace the FFPPs. The different construction rates replace the FFPPs at different rates as the NPP construction rate increases. By the year 2300 all of the emissions appear to converge signifying that all of the FFPPs have been decommissioned.

In order to illustrate the effect of NPP construction startup, a enlarged portion of this part of the model is shown in Figure 6.2.

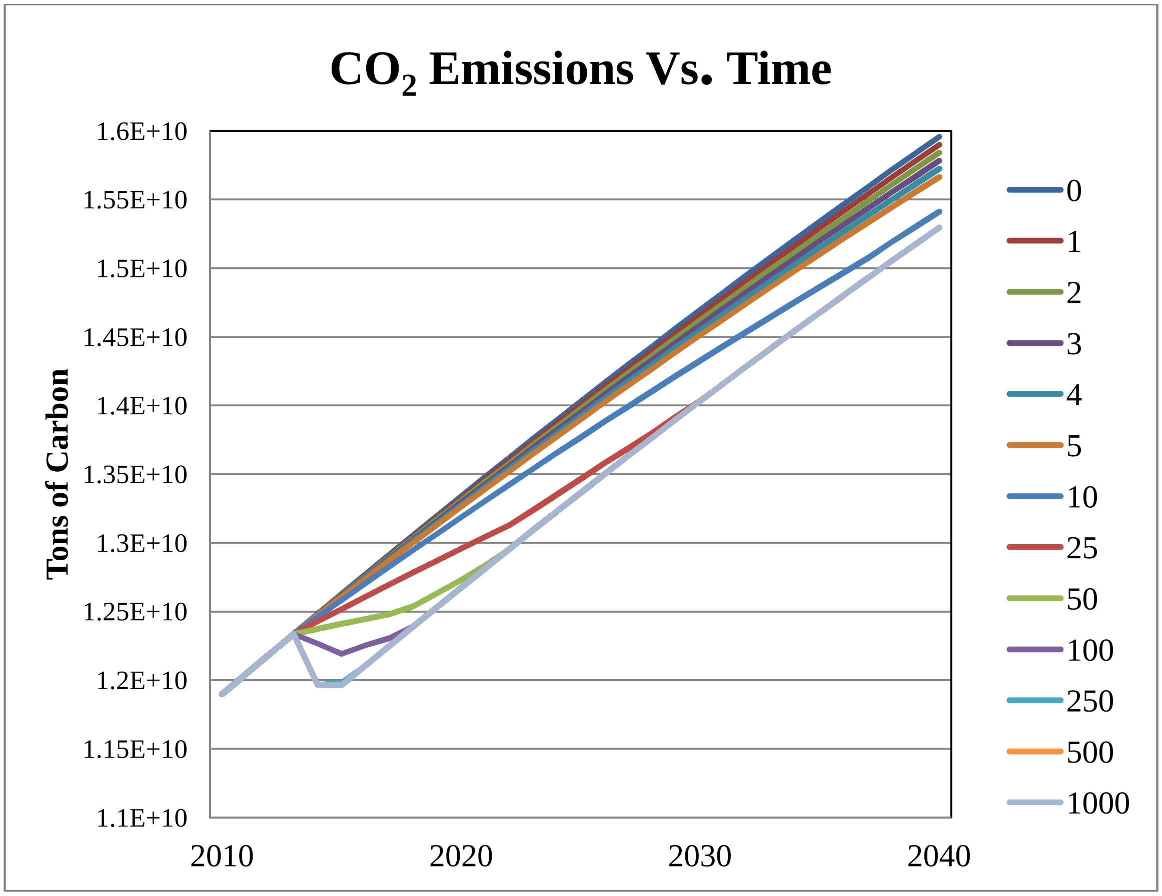


Figure 6.2. Enlarged portion of plot showing the start of NPP construction.

As can be seen in figure 6.2, as the NPP construction rate increases, CO_2 emissions are reduced at a faster rate. Little difference is observable when the production rate increases above 250 NPP/yr because all of the FFPPs are replaced in a matter of a couple years.

Table 6.2 looks at the CO_2 emissions for the different NPP construction rates at year 2100 and year 2300.

Table 6.2. CO_2 emissions in 2100 and 2300.

NPP Construction (Plants/yr)	CO_2 Emissions (Billion TonC/yr)	Reduction of CO_2 Emissions (Billion TonC/yr)	Reduction of CO_2 Emissions (%)	CO_2 Emissions (Billion TonC/yr)	Reduction of CO_2 Emissions (Billion TonC/yr)	Reduction of CO_2 Emissions (%)
	2100			**2300**		
0	21.34	0	0.00%	25.44	0	0.00%
1	21.16	0.19	0.88%	24.90	0.54	2.13%
2	20.97	0.37	1.76%	24.81	0.64	2.50%
3	20.81	0.53	2.49%	24.81	0.63	2.49%
4	20.73	0.61	2.86%	24.81	0.63	2.49%
5	20.69	0.66	3.08%	24.81	0.63	2.49%
10	20.69	0.65	3.07%	24.81	0.63	2.48%
25	20.69	0.65	3.06%	24.81	0.63	2.48%
50	20.69	0.65	3.06%	24.81	0.63	2.48%
100	20.69	0.65	3.05%	24.81	0.63	2.48%
250	20.69	0.65	3.05%	24.81	0.63	2.48%
500	20.69	0.65	3.05%	24.81	0.63	2.48%
1000	20.69	0.65	3.05%	24.81	0.63	2.48%

Table 6.2 also shows the reduction in CO_2 emissions as well as the percentage of total emissions that this represents.

In addition to CO_2 emissions, the amount of CO_2 in the atmosphere was evaluated. CO_2 has a residence time of 35-90 years in the atmosphere. This means the actual concentration and effect of CO_2 in the atmosphere will not be known until a future time. Figure 6.3 shows the amount of CO_2 in the atmosphere until the year 2300 for the selected range of NPP construction rates.

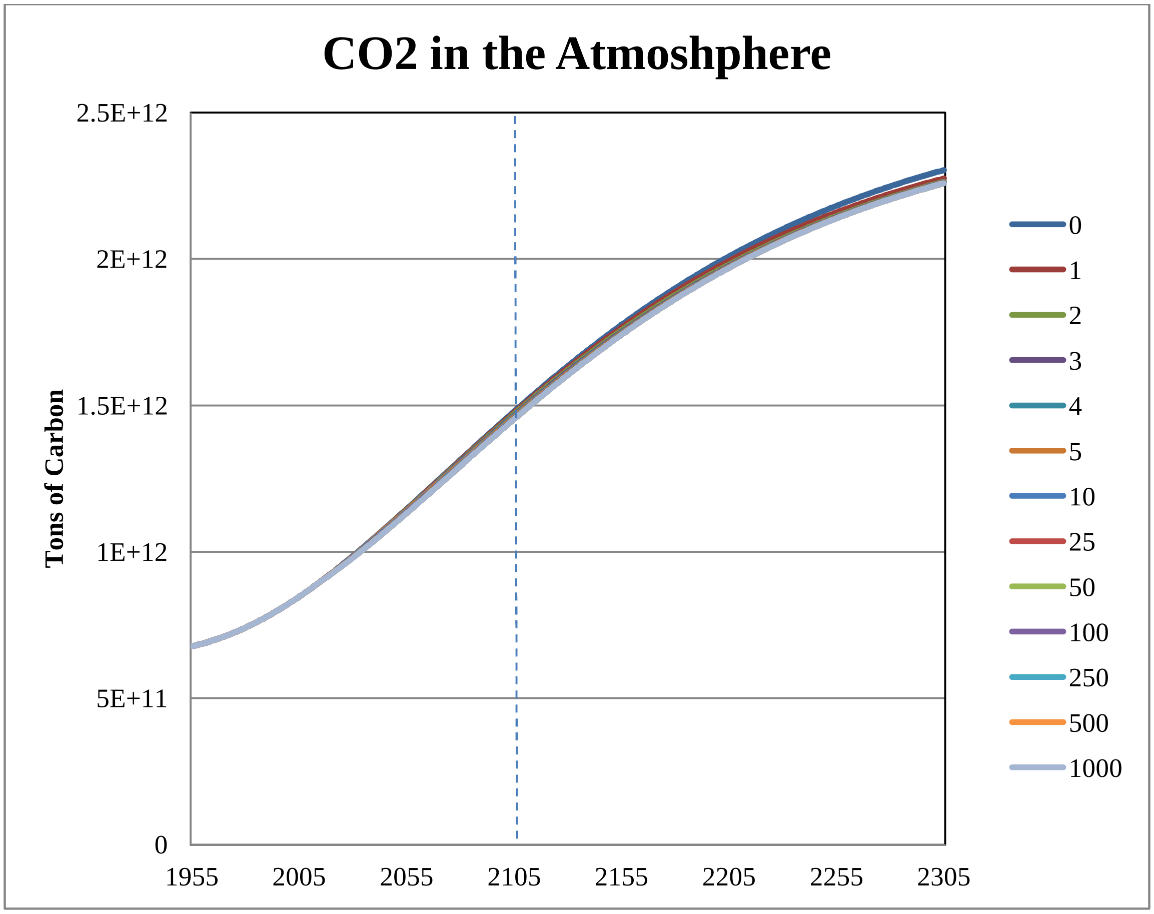


Figure 6.3. CO_2 in the atmosphere until 2300.

The figure shows that as time progresses and the FFPPs are replaced with NPPs, the amount of CO_2 decreases. Figure 6.4 is added to show an enlarged view of the figure from the dashed line (2100) on Figure 6.3 to illustrate the reduced atmospheric CO_2 due to NPP construction.

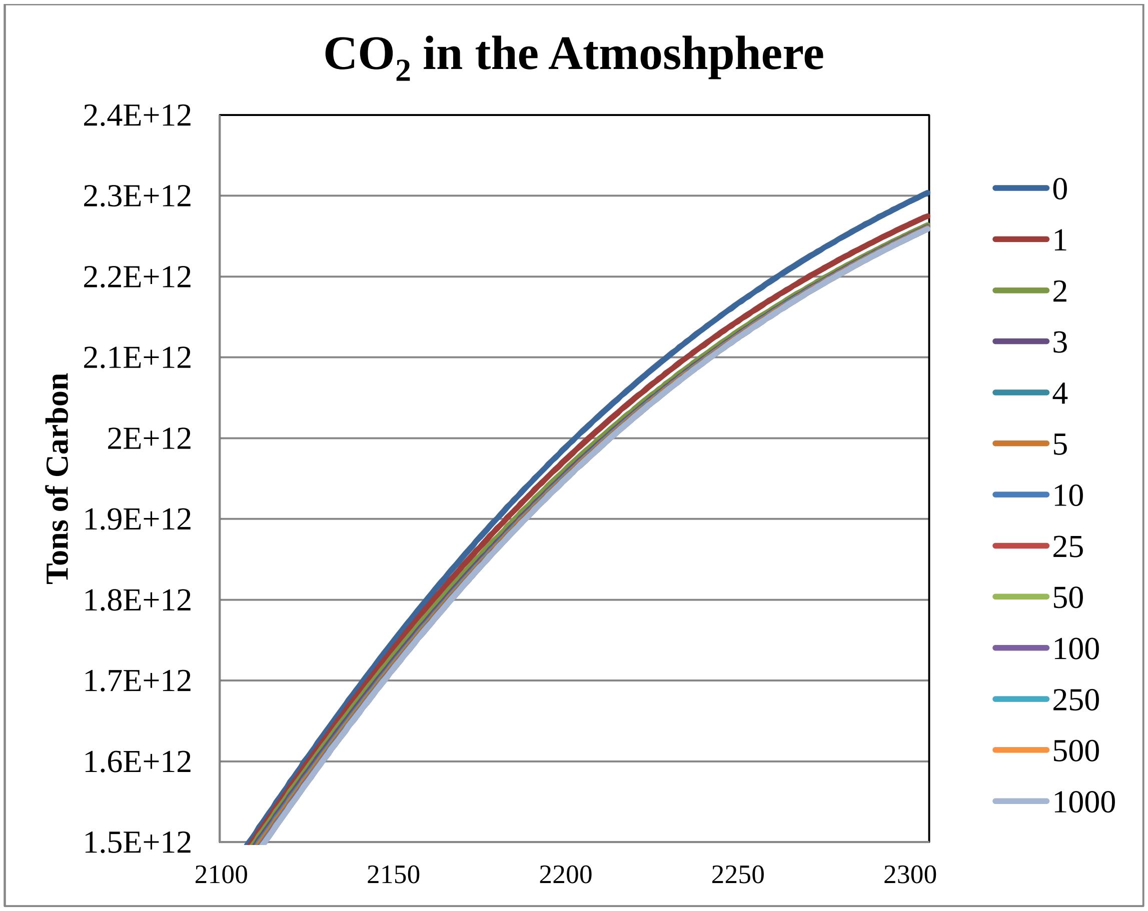


Figure 6.4. Enlarged portion of the CO$_2$ in the atmosphere versus time figure.

Table 6.3 shows the CO$_2$ in the atmosphere at the year 2100 and 2300 for each of the different NPP construction rates.

Table 6.3. CO_2 in the atmosphere for the year 2100 and 2300.

NPP Construction (Plants/yr)	CO_2 in Atmosphere (Billion TonC)	Reduction of CO_2 in the Atmosphere (Billion TonC)	Reduction of CO_2 in the Atmosphere (%)	CO_2 in Atmosphere (Billion TonC)	Reduction of CO_2 in Atmosphere (Billion TonC)	Reduction of CO_2 in the Atmosphere (%)
	2100			2300		
0	1447.44	0.00	0.00%	2293.30	0.00	0.00%
1	1443.30	4.14	0.29%	2265.19	28.12	1.23%
2	1439.16	8.28	0.57%	2253.68	39.63	1.73%
3	1435.09	12.36	0.85%	2251.37	41.93	1.83%
4	1431.99	15.45	1.07%	2250.52	42.78	1.87%
5	1429.56	17.88	1.24%	2250.08	43.22	1.88%
10	1425.05	22.39	1.55%	2249.34	43.96	1.92%
25	1422.79	24.65	1.70%	2248.97	44.33	1.93%
50	1422.08	25.36	1.75%	2248.86	44.45	1.94%
100	1421.76	25.68	1.77%	2248.81	44.50	1.94%
250	1421.54	25.90	1.79%	2248.77	44.54	1.94%
500	1421.54	25.91	1.79%	2248.77	44.54	1.94%
1000	1421.54	25.91	1.79%	2248.77	44.54	1.94%

Table 6.3 illustrates the reduction of CO_2 in the atmosphere as the number of FFPPs being replaced by NPPs increases. The reduction continues and is even greater at the year 2300 compared to 2100. The table also expresses the reduction in CO_2 as a percentage of total CO_2 in the atmosphere. A slight increase is seen from the year 2100 to 2300.

The increase in CO_2 emissions and associated increase of CO_2 in the atmosphere is expected to have a negative effect on climate change. The DICE model also predicts how some of these factors will change with time. The key factors evaluated as part of this study are the upper ocean and atmospheric temperature as well as the deep ocean temperature. The predicted increase in Upper Ocean and atmospheric temperature is shown in Figure 6.5.

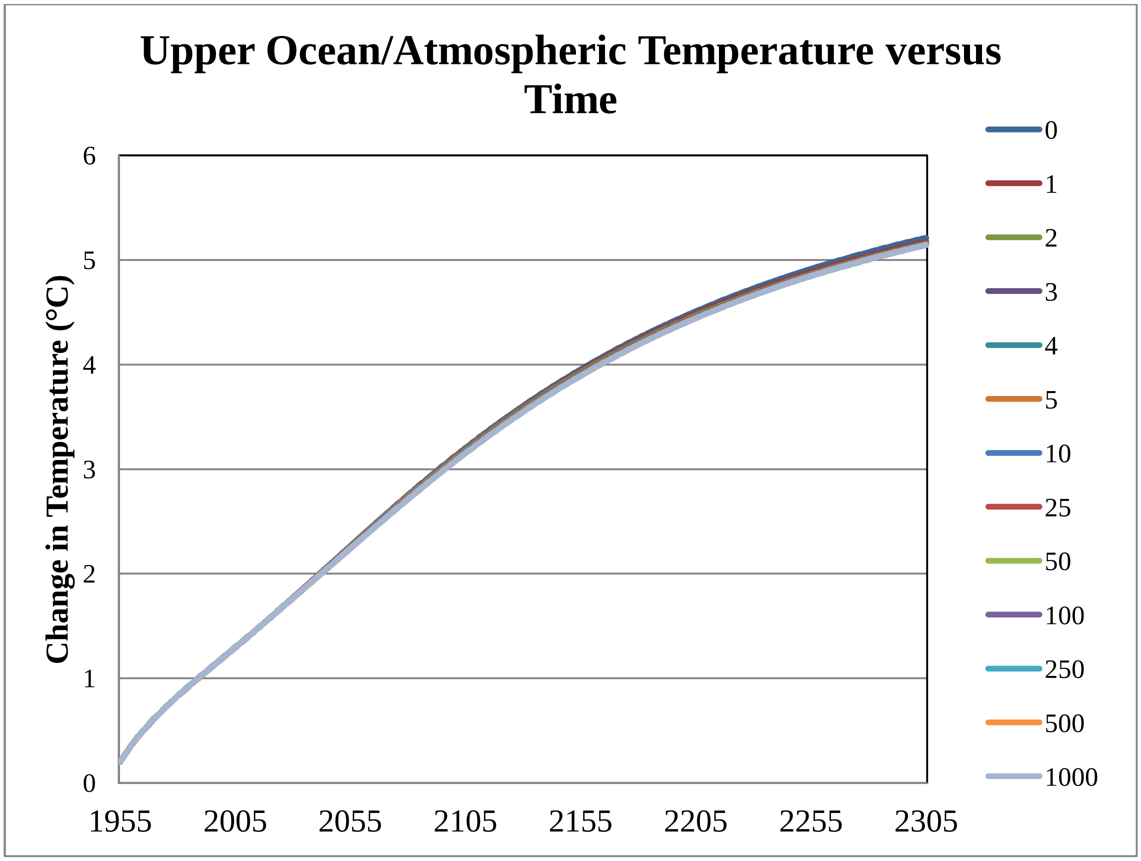


Figure 6.5. Change in Upper Ocean/ atmospheric temperature with time.

A small reduction in temperature increase is seen for the simulations runs where the NPPs replace the FFPPs. A closer look at this data is shown in Table 6.4.

Table 6.4. Upper Ocean/ Atmospheric Temperature data for the years 2100 and 2300.

NPP Construction (Plants/yr)	Atmosphere/ Upper Ocean Temperature Increase (°C)	Reduction (°C)	Reduction (%)	Atmosphere/ Upper Ocean Temperature Increase (°C)	Reduction (°C)	Reduction (%)
	2100			2300		
0	3.117	0.000	0.00%	5.186	0.000	0.00%
1	3.111	0.006	0.19%	5.149	0.038	0.73%
2	3.105	0.012	0.39%	5.130	0.056	1.09%
3	3.099	0.018	0.58%	5.125	0.061	1.18%
4	3.093	0.024	0.76%	5.123	0.063	1.22%
5	3.089	0.028	0.90%	5.122	0.065	1.24%
10	3.078	0.039	1.25%	5.120	0.066	1.28%
25	3.071	0.046	1.46%	5.119	0.067	1.30%
50	3.069	0.048	1.53%	5.119	0.068	1.31%
100	3.068	0.049	1.56%	5.118	0.068	1.31%
250	3.067	0.049	1.59%	5.118	0.068	1.31%
500	3.067	0.049	1.59%	5.118	0.068	1.31%
1000	3.067	0.049	1.59%	5.118	0.068	1.31%

Similar to previous data, a small improvement is noted with the increased NPP construction rates. It can also be seen that even though the actual reduction in temperature increase is greater in the year 2300 compared to 2100, it represents a smaller fraction of the total temperature increase.

Another climate change factor that the DICE model can be used to simulate is the deep ocean temperatures. The oceans are an important part of the temperature regulation on earth and a drastic change in the deep ocean temperature could hinder or eliminate the ability of the ocean to perform this function. Some analysts say that this could result in the ultimate global warming event, an ice age, due to severe alteration of the world’s climate. Figure 6.6 displays the deep ocean temperature increase.

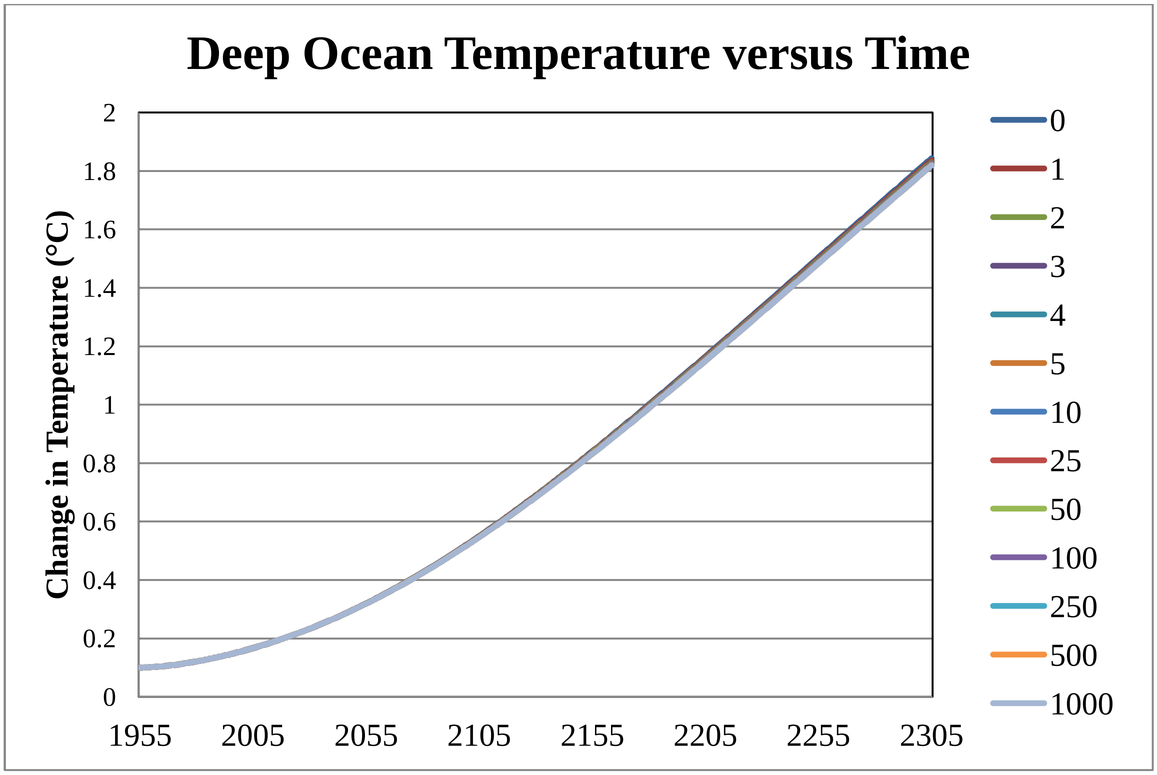


Figure 6.6. Change in Deep Ocean temperature with time.

The increase in deep ocean temperature with time is much less than the Upper Ocean and atmospheric temperature increase. The reason for this is that the higher radiative forcing caused by the CO_2 in the atmosphere warms the atmospheric layer which in turn warms the upper ocean; the upper ocean will then gradually warm the deep ocean leading to smaller temperature fluctuations in the deep ocean [Nordhaus, 2011]. Table 6.5 displays the deep ocean temperature data.

Table 6.5. Deep Ocean Temperature data for the years 2100 and 2300.

NPP Construction (Plants/yr)	Deep Ocean Temperature Increase (°C)	Reduction (°C)	Reduction (%)	Deep Ocean Temperature Increase (°C)	Reduction (°C)	Reduction (%)
	2100			2300		
0	0.524	0.000	0.00%	1.810	0.000	0.00%
1	0.524	0.000	0.06%	1.802	0.008	0.42%
2	0.524	0.001	0.12%	1.797	0.013	0.74%
3	0.523	0.001	0.18%	1.794	0.016	0.91%
4	0.523	0.001	0.24%	1.792	0.018	1.00%
5	0.523	0.002	0.30%	1.791	0.019	1.06%
10	0.522	0.002	0.47%	1.788	0.021	1.19%
25	0.521	0.003	0.63%	1.787	0.023	1.27%
50	0.521	0.004	0.70%	1.786	0.023	1.29%
100	0.521	0.004	0.73%	1.786	0.024	1.31%
250	0.520	0.004	0.75%	1.786	0.024	1.32%
500	0.520	0.004	0.75%	1.786	0.024	1.32%
1000	0.520	0.004	0.75%	1.786	0.024	1.32%

The deep ocean temperature is expected to increase much less than the Upper Ocean and atmospheric temperature. This results in an even smaller reduction in temperature increase. Compared to the Upper Ocean and atmospheric temperature the percentage of reduction of temperature increase is larger at the year 2300 than 2100.

It is also predicted that with climate change and global warming, this will result in climate damages that will cost trillions of dollars. The DICE model allows for modeling the estimated costs or climate damages. Climate damages are calculated as a fraction of the total predicted annual economic output. The fraction is determined as a function of the increase in atmospheric and upper ocean temperature from climate change.

Figure 6.7 illustrates the costs associated with global warming.

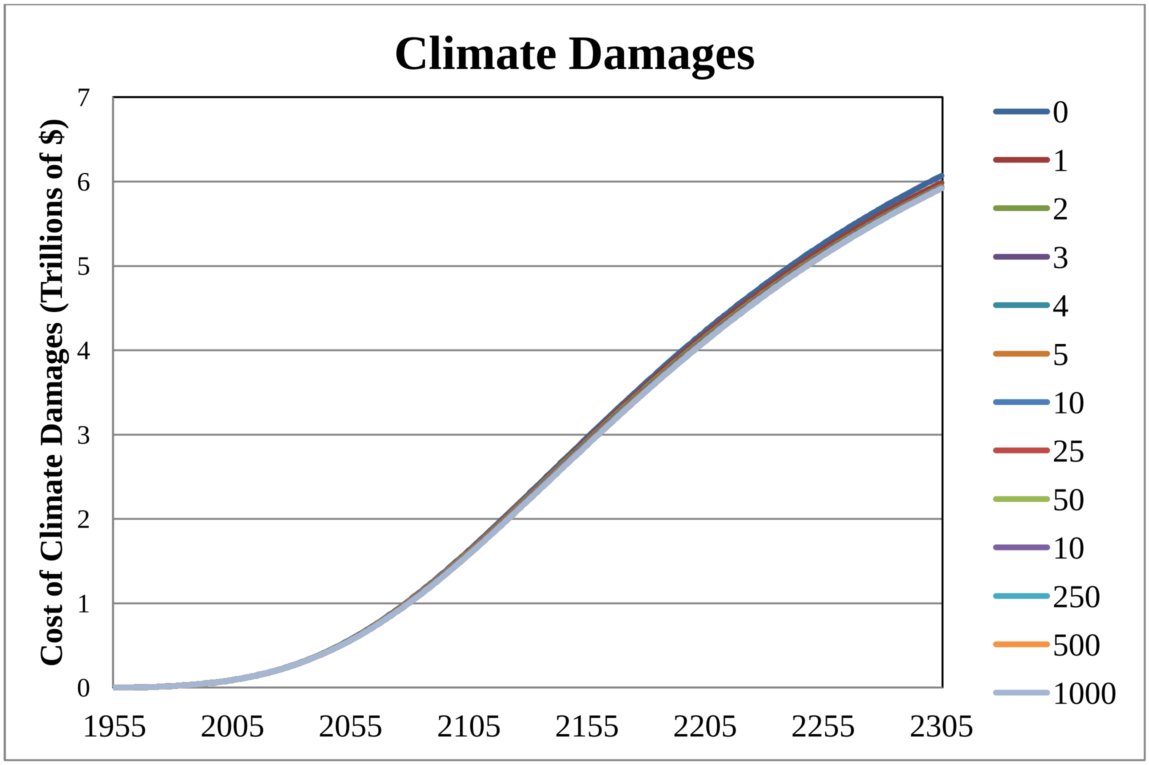


Figure 6.7. Cost of climate damages with time.

Costs are predicted to reach the multi-trillion dollar range. Some reduction in the rate at which ‘damage’ is accrued is seen as NPPs are used to replace FFPPs. Table 6.6 lists the climate damage and predicted reduction for the year 2100 and 2300.

Table 6.6. Climate damage costs and predicted reductions.

NPP Construction (Plants/yr)	Climate Damages (Trillions of $)	Reduction (Trillions of $)	Reduction (%)	Climate Damages (Trillions of $)	Reduction (Trillions of $)	Reduction (%)
	2100			2300		
0	1.50	0.000	0.00%	6.00	0.000	0.00%
1	1.50	0.006	1.10%	5.92	0.082	4.56%
2	1.49	0.011	2.19%	5.87	0.124	6.83%
3	1.49	0.017	3.28%	5.86	0.134	7.43%
4	1.48	0.022	4.25%	5.86	0.139	7.66%
5	1.48	0.026	5.04%	5.86	0.141	7.79%
10	1.47	0.037	7.00%	5.85	0.145	8.03%
25	1.46	0.043	8.17%	5.85	0.148	8.15%
50	1.46	0.045	8.56%	5.85	0.148	8.19%
100	1.46	0.046	8.74%	5.85	0.149	8.21%
250	1.46	0.046	8.86%	5.85	0.149	8.23%
500	1.46	0.047	8.87%	5.85	0.149	8.23%
1000	1.46	0.047	8.87%	5.85	0.149	8.23%

As can be seen by the data, eliminating all of the FFPPs can reduce the damage costs by over 8%. This reduction is the greatest for all variables that were analyzed. 5.85 trillion dollars a year sounds like an enormous amount of money to be paid to battle the effects of climate change in today’s economy. However, based on inflation, this value is estimated to be equivalent to hundreds of millions of dollars of today’s money in the year 2300 which will have less of a devastating effect on the economy.

The data collected above represents the most important data that can be generated from the DICE model. More detailed discussion of this data is presented in section 7.

Chapter 7. Discussion of Results

7.1. CO_2 Emissions to the Atmosphere

Carbon Dioxide emissions are expected to increase over time as the world's population grows and more and more nations become technologically advanced, corresponding to an increase in fossil fuel combustion for energy. The DICE model can be used to predict the increase in CO_2 emissions with time. For the purposes of this study, the DICE model was set to simulate until the year 2300. This was for the purposes of allowing the DICE model to predict any changes in climate change data for approximately 300 years.

Based on the DICE model predictions without taking any actions, the amount of CO_2 emissions in the year 2300 will be 25.44 billion tons of Carbon per year. The model starts with just over 12 billion tons of Carbon per year in 2013. This means the amount of CO_2 emissions will almost double in ~300 years. The next part of this study was to modify the DICE model using Vensim modeling software. This portion of the model was discussed in more detail in chapter 5 of this thesis and will allow for the input of an annual NPP construction rate. The NPPs that are constructed are used to replace the existing fleet of FFPPs in the U.S.. FFPPs produce 74% of the global CO_2 emissions [EPA Global Emissions]. The U.S. is responsible for 19% of the global CO_2 emissions, second only to China (23%) [EPA Global Emissions]. The model eliminates a number of FFPPs based on an equivalent power output from the newly constructed NPPs. The model also calculates the reduction in CO_2 based on the difference in emissions between a NPP and a FFPP. The reduction of CO_2 emissions is then fed into the DICE model to simulate the increase in CO_2

emissions. The model will allow for determination of the advantage of replacing FFPPs with NPPs in order to reduce GHG emissions and combat climate change.

The model allows for any number of NPP construction rates to be specified. The model will replace the current feet of FFPPs in the U.S. and then will have no further effect because all of the power produced by FFPPs is now produced by NPPs. For this study, a number of smaller construction rates were evaluated to simulate potential actual construction rates if the U.S. were to restart NPP construction sometime in the near future. In addition to these production rates, much higher, likely impossible rates were also evaluated. With the modification of the model, a reduction in CO_2 emissions occurs with time. With a construction rate of 1 NPP per year, will reduce the total amount of annual CO_2 emissions in the year 2300 by half a billion tons of Carbon. The total amount will become 24.9 billion tons of Carbon vs. the 25.44 billion tons of Carbon discussed previously. This equates to a reduction of 2.13%.

As the NPP construction rate increases, there continues to be a slight reduction in annual CO_2 emissions in the year 2300. The total reduction levels out at 0.63 billion tons of Carbon with a production rate of 2 NPPs per year. This represents the total CO_2 output reduced by replacing all of the NPPs. Increased production rates will have no further effect on CO_2 emissions. The production rate of 2 NPPs per year will replace all of the FFPPs in year 2209. Increased NPP construction rates will eliminate the FFPPs at a quicker rate, but eventually will all reach the same total reduction of CO_2 emissions, or 0.63 billion tons of Carbon per year. Even though the total amount of emissions is the same with a production rate of 2 NPPs or greater per year, the increased production rates will eliminate the total amount of CO_2 emissions earlier, which reduces the total amount of emissions over a period of time. Since the CO_2 emissions have some residence time in the atmosphere, this should change the amount of CO_2 that remains in the atmosphere.

Analyzing the DICE model for the amount of CO_2 in the atmosphere shows that without taking any action, the total amount will be 2293.3 billion tons of Carbon for the year 2300. This compares with the value at the year 2013 of 888 billion. Meaning the total amount of atmospheric CO_2 will more than double during the period of this simulation. Now taking into account the reduction in emissions through replacement of FFPPs with NPPs, it can be seen that the total amount will be reduced with time. A construction rate of 1 NPP per year reduces the amount of CO_2 in the atmosphere by 28 billion tons in 2300. This is a significant amount of CO_2, but only equates to a reduction of 1.23% of total atmospheric Carbon.

Unlike CO_2 emissions, the total amount of CO_2 in the atmosphere will continue to decrease after a production rate of 2 NPPs per year. The reduction does not level out until a construction rate of 250 NPPs per year. Increased construction rates of 500 or 1000 NPPs per year provide not additional benefit to atmospheric CO_2. At these production rates the reduction of CO_2 in the atmosphere is equal to 44.54 billion tons of Carbon per year in 2300. This amounts to a total reduction of 1.94% in atmospheric Carbon.

Most publications report the amount of CO_2 in the atmosphere using the units parts per million or ppm. A group of climate scientists believe that 350 ppm CO_2 in the atmosphere is the safe upper limit [CO2now org]. Unfortunately the current limit is already measured at over 390. ppm [CO2now org]. Converting the data in this report into ppm to compare with these limits shows the ppm CO_2 will become much greater than this in the future.

Using a conversion factor of 1 ppm = 2.13 Gt C, the total amount of CO_2 in the atmosphere in 2300 if no action is taken will be 1076 ppm [CDIAC]. The greatest reduction seen by constructing 250 NPP per year or greater will equate to a level of 1055 ppm. The reduction is small and the total amount is much greater than the proposed upper safe limit of 350 ppm.

The resulting effect of this increase of CO_2 in the atmosphere is climate change. The CO_2 produced as part of this evaluation is all manmade. The purpose of the DICE model and this study is to analyze the effect of the manmade CO_2 on climate change. The DICE model predicts certain indicators of climate change or global warming including Upper Ocean and atmospheric temperature and the deep ocean temperature.

Performing a simulation run with the DICE model shows a predicted upper ocean and atmospheric temperature increase of 5.186°C in 2300 if no action is taken. A small benefit is seen when FFPPs are replaced with NPPs as part of this study. The greatest decrease in temperature increase is seen at a construction rate of 50 NPPs a year or greater. This improvement is 0.068°C or 1.31% from the predicted value of 5.186°C is no action is taken. This is a relatively small amount considering that this study shuts down all of the FFPPs currently operating in the U.S..

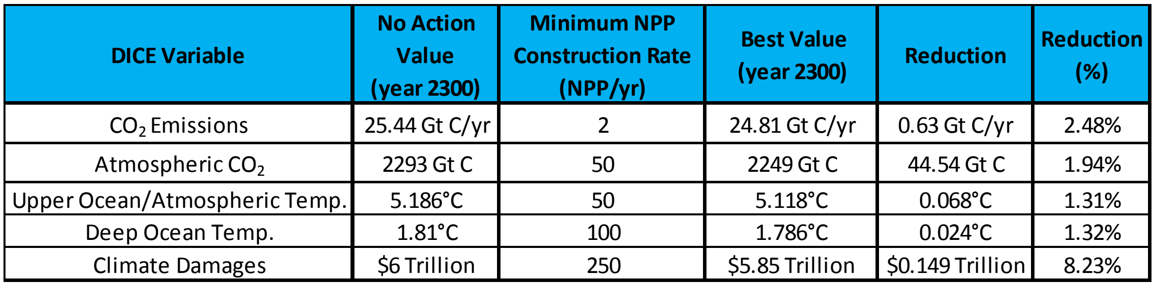
Another indicator of global warming is the deep ocean temperature. The deep ocean temperature is important as part of the earth's thermoregulation. Similar to the upper ocean and atmospheric temperature increase, a small improvement of 1.32% can be realized if all of the U.S's FFPPs are shut down. The DICE model predicts a deep ocean temperature increase of 1.81°C in 2300. This amount would be reduced by 0.024°C in 2300 if at least 25 NPPs are constructed each year.

Climate change can have significant consequences for the planet. It is expected that the damages caused by climate change and global warming will cost trillions of dollars to combat. The DICE model also allows for simulation of these costs. Per the model, climate damages are expected to cost 131 billion dollars per year. In comparison, the model predicts the annual cost to be 6 trillion dollars in 2300. This is a 45 fold increase.

Using the modified portion of this model to predict the reduction in CO_2 from replacing FFPPs with NPPs shows some reduction in these climate damage costs. The range of benefit is from 82 billion with 1 NPP being constructed each year to 149 billion per year if 100 NPPs or greater are constructed each year. The 149 billion dollars is equivalent to 8.23% of the total cost of climate damages.

In summary table 7.1 shows the greatest improvement that can occur if all of the FFPPs operating in the U.S. are replaced with NPPs.

Table 7.1 Summary of data with the greatest effect on climate change.



DICE Variable	No Action Value (year 2300)	Minimum NPP Construction Rate (NPP/yr)	Best Value (year 2300)	Reduction	Reduction (%)
CO_2 Emissions	25.44 Gt C/yr	2	24.81 Gt C/yr	0.63 Gt C/yr	2.48%
Atmospheric CO_2	2293 Gt C	50	2249 Gt C	44.54 Gt C	1.94%
Upper Ocean/Atmospheric Temp.	5.186°C	50	5.118°C	0.068°C	1.31%
Deep Ocean Temp.	1.81°C	100	1.786°C	0.024°C	1.32%
Climate Damages	$6 Trillion	250	$5.85 Trillion	$0.149 Trillion	8.23%

Table 7.1 lists all of the variables analyzed as part of this study. It allows for a comparison between the value predicted as part of a DICE model simulation with no action taken and the best case scenario as simulated with the modified DICE model. The table lists the minimum NPP construction rate that is required to see the largest benefit.

The variable that exhibits the greatest benefit from replacing the FFPPs in operation in the U.S. with NPPs is the cost of climate damages. Based on the simulation results from the DICE model, if at least 25 NPPs are constructed a year, $149 billion dollars or 8.23% of the total annual cost of climate change can be eliminated.

The total cost of climate damages is predicted to be $6 trillion a year in 2300 compared to 131 billion in 2013. Although this 8% reduction in the total cost is the most significant benefit, it is still a very small amount considering the total amount that climate damages are expected to cost in 2300.

Following the cost, the model predicts that CO_2 emissions can be reduced by 2.48% or 630 billion tons of Carbon per year. This is by simple elimination of all of the FFPPs in operation.

The amount of CO_2 in the atmosphere can be reduced by 1.94%. The total amount in the atmosphere is expected to be equivalent to 1076 ppm in 2300. This amount is much greater than the proposed safe upper limit of 350 ppm. Based on these results, elimination of only the FFPPs in the U.S. will not be sufficient to make a significant indent into curbing climate change. This is further represented by the small decreases that are seen in upper ocean and atmospheric and deep ocean temperature increases.

The results of this study show that replacing FFPPs with NPPs will aid in the efforts to fight global warming. However, the benefits that are seen by only eliminating the U.S. fleet of FFPPs are not enough. It is possible that if most or all nations made similar efforts, a sizeable improvement in climate change could occur. Unfortunately, the large construction rates of NPPs are not feasible due to many outstanding factors surrounding the construction NPPs. It is also likely that other manmade CO_2 production from things such as vehicles will need to be addressed to truly prevent further global warming.

Chapter 8. Conclusions

The accumulation of CO_2 in the atmosphere as a result of human activities is occurring at a precipitous rate since the industrial revolution. In recent history the world has seen an increase in the frequency and extent of damage from significant weather events. Some scientists believe that this is a result of the accumulation of GHG emissions in the atmosphere produced through human activities. It is expected that this weather phenomenon will continue to get worse with time if no action is taken to combat these harmful emissions to the atmosphere. There is also concern that climate change will also affect the survival of entire species, human health, agriculture and world economies if these current trends continue.

In order to limit or prevent future climate change related disasters from occurring, the amount of CO_2 emissions must be reduced significantly. There are some that contend that due to the fact that nuclear power produces a much smaller amount of GHG emissions compared to that of fossil fuel power, nuclear power can be part of the solution to counter climate change. The purpose of this study was to use the Dynamic Integrated Climate Economy model to determine if nuclear power could in fact be part of the solution.

The DICE model was replicated using the Fiddaman Vensim simulation software model. After the DICE model was recreated, it was then modified to evaluate the use of NPPs as a method to reduce GHG emissions and offset the associated climate change from these emissions. The modified DICE model allowed for modeling the effect on climate change by replacing the current fleet, or a portion of it, of the more than 10,000 FFPPs currently in operation in the U.S. As a result of replacing FFPPs with NPPs, the GHG emissions will be reduced. NPPs produce about 6% of the emissions per MW than that of a coal fired power plant.

The model created for this study incorporated CO_2 emission reductions generated as a result of replacing FFPPs with NPPs into the DICE model. Variables such as CO_2 in the atmosphere, atmospheric and ocean temperature and climate damage costs were evaluated for different NPP construction rates. As the NPP construction rates increased, the FFPPs are shut down at faster rates. This reduces the overall amount of emissions to the atmosphere. The optimal construction rate can be determined for each variable. After all of the FFPPs are decommissioned, additional NPP construction will have no further effect on climate change as all of the power produced by FFPPs is now produced from NPPs.

The results produced as part of this study show that if all of the FFPPs currently in operation in the U.S. are replaced by NPPs, improvement is possible. However, the actual benefit is relatively small compared to the actual climate change that is predicted to occur from the DICE model. The amount of GHG emissions from the rest of the world is large enough such that even curtailing emissions from the U.S-based FFPPs. a significant increase in CO_2 accumulation in the atmosphere will occur. It is also concluded that the NPP construction rates that are needed to see the largest benefit are not feasible due to construction hurdles including public opposition, availability of materials and construction capacity, disposal of radioactive waste, among others.

The results shows that the total amount of atmospheric CO_2 present in the year 2300 can reduced by approximately 45 billion tons if at least 50 NPP are constructed each year. This production rate will only be required for the first 10 years until all of the FFPPs are decommissioned. This equates to approximately 500 NPPs total, which would require quantities of materials, construction personnel, large forged components that would be challenging in itself. Looking at this in terms of ppm, the total amount predicted by the DICE model if no action is taken is 1076 ppm in 2300. A reduction to 1055 is possible based on the data from this study. This is still significantly greater than the safe upper limit of 350 ppm that some climate scientists have proposed.

With the resulting reduction in atmospheric CO_2 it is expected that the predicted temperature increase or global warming will also be reduced. A reduction in the simulated atmospheric and upper ocean temperature increase of 1.31% in the year 2300 will be realized if all of the FFPPs are quickly replaced. The is a reduction of 0.068°C from the total predicted increase from the DICE model of almost 5.2°C in the year 2300. A similar reduction of 1.32% in the increase of the deep ocean temperature is also possible. The deep ocean temperature is expected to increase by 1.8°C in 2300. This increase could be potentially reduced by 0.024°C.

The largest benefit seen when analyzing the data is to the climate damages factor. Climate damages are calculated as a fraction of the total predicted annual economic output. The fraction is determined as a function of the increase in atmospheric and upper ocean temperature from climate change. The model predicts that a reduction of 8.23% or $149 billion annually can occur for the best case scenario. Although this is the largest fraction, it is in current U.S dollars and the value of this amount of money will be much less in the year 2300. The optimal scenario is to replace the FFPPs as quickly as possible or 250 NPP per year. At this rate, all of the FFPPs would be replaced in approximately 2 years, requiring around 500 total.

Ultimately the results show that a slowing of climate change is possible if all of the operating FFPPs in the U.S. are replaced with NPPs. Unfortunately the amount CO_2 in the atmosphere is much greater than the safe upper limit. This safe upper limit was chosen based on prehistoric data that shows that when atmospheric CO_2 levels went below 450 ± 100 ppm 50 million years ago a dramatic cooling trend began. There is concern that the opposite could happen if the levels exceed the 350 ppm limit in the other direction. The efforts taken through this study would not be enough to control climate change at a substantial level.

In addition, some elements of nuclear power plant construction are not considered in this study. The most important roadblock is the current negative political climate that exists around nuclear power in the U.S. and many other parts of the world. This climate surrounding nuclear power has become increasingly skeptical after the Fukushima nuclear accident. This means that new construction is slow, and in some cases non-existent. Add this to the fact the capacity does not exist to reach these construction rates, makes the rates simulated in this study unlikely. And even if there were a positive view of nuclear power, significant hurdles including construction capacity, would still exist in reaching these rates.

The study also does not consider other resources needed for construction that would likely not be available in the quantities needed for the rates simulated. Resources such as enriched uranium fuel would likely not be readily available in the quantities necessary. The increased construction rate would also lead to an enormous amount of radioactive waste that would need a location to be disposed of. Additionally the used nuclear fuel that will be generated from these plants assuming an open fuel cycle will need to be disposed. The U.S. does not currently have a plan for disposal of spent nuclear fuel since Yucca Mountain development has been defunded. President Obama has since established the "Blue Ribbon Commission on America's Future" with the primary goal of conducting a review of policies for managing the back end of the nuclear fuel cycle and proposing a new plan [brc.gov]. The actual start of these higher production rates would likely not start any time in the future and would likely not meet the rates studied. The longer it takes to start construction of new NPPs, the more time FFPPs will have to emit GHGs into the atmosphere. Meaning, the longer the world waits to increase NPP construction, the greater the effort required to counter the GHG emissions becomes.

Some countries have embraced nuclear power and are increasing their production rates. China for example, the largest CO_2 emitter with 23.5% of the world's emissions, has 30 NPPs under construction and plan to build many more to support their exceedingly rising electricity needs. China has set a target goal of 40 GW by the year 2020 [Nuclear safer]. Some in the industry suggest that even 80 GW is feasible. China's argument is that nuclear power is safer than coal and will reduce their CO_2 emissions. This is true and based on China's plan to add 88 GW of all power plant types each year until 2030, will be a significant amount [Hill, 2013]. However, based on this research, this will not be enough to truly counter the unknown, uncertain impacts from global warming. Thus the entire world will need to make significant efforts, addressing all GHG emissions in order to limit or prevent catastrophic events that may occur as a result of these emissions.

Chapter 9. Recommendations

Based on the results of this study and the model that has been modified, suggestions for further research has been identified. The model has specific constants that are used for the various numbers of NPPs, CPPs, NGPPs and PPPs currently in operation in the U.S. The model has the potential to be modified to do additional studies for other countries or regions in order to evaluate a much larger effort to use NPPs to replace FFPPs. With additional effort the model could also be developed to analyze other regions of the world where NPP construction exists.

It is noted that expanding the study to analyze a larger part of the world would generate some interesting data; however, the same obstacles to these larger construction rates would need to be considered. The model could be further modified to simulate the NPP construction rates in China or other countries to see the real effect the NPP construction will have on climate change. Based on the previously discussed data, it is expected that the actual construction of NPPs that is currently in progress and scheduled, will have a very minor effect on climate change.

It needs to be evaluated whether the model can also be modified to take into account future power plant construction. This means the model can simulate replacement of the current FFPPs, but it could also simulate future power plant construction and simulated fractions of NPPs. The DICE model predicts climate change using some fraction of nuclear power. The model may be able to be enhanced to change this variable and assume different fractions of nuclear power with time.

References

2013 Proposed Carbon Pollution Standard for New Power Plants, http://www2.epa.gov/carbon-pollution-standards/2013-proposed-carbon-pollution-standard-new-power-plants, 2013.

Blue Ribbon Commission, “About the Commission”, http://cybercemetery.unt.edu/archive/brc/20120620211605/http:/brc.gov//, 2013.

U.S. Department of Energy, Energy Efficiency and Renewable Energy, “President Obama Sets a Target for Cutting U.S. Greenhouse Gas Emissions”, http://apps1.eere.energy.gov/news/news_detail.cfm/news_id=15650, 2009.

Brinton, S., Tokuhiro, A., “An Initial Study on Modeling the Existing and Anticipated Fleet of Thermal and Fast Reactors using VENSIM”, Paper Number: ICONE15-10381, 2009.

C(Lie)mate #3 - What Doesn't Make The News, https://www.youtube.com/watch?v=2hOhq0vHfMI&feature=c4-overview&list=UUTiL1q9YbrVam5nP2xzFTWQ, 2013.

Carbon Dioxide information Analysis Center, http://cdiac.ornl.gov/.
“Nuclear safer than coal, China official says”, Reuters, 25 March 2011, http://news.cnet.com/8301-11128_3-20047087-54.html.

Char, N., Csik, B., “Nuclear power development: History and outlook”, *IAEA Bulletin*, 3(1987), 19-25.

Doran, P., Zimmerman, M., “Examining the Scientific Consensus on Climate Change”, *EOS Transactions American Geophysical Union*’, 90 (2009), 22.

Environmental Protection Agency, http://www.epa.gov/climatechange/.

Environmental Protection Agency (EPA), “Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2011”, EPA 430-R-13-001, 12 April 2013, http://www.epa.gov/climatechange/Downloads/ghgemissions/US-GHG-Inventory-2013-Main-Text.pdf.

Environmental Protection Agency, “Global Greenhouse Gas Emissions”, http://www.epa.gov/climatechange/ghgemissions/global.html#one.

Fiddaman, T., “Dynamic Integrated Climate Economy model”, http://www.metasd.com/models/Library/ClimatePolicy/NordhausDICE/dice4.html, 2007.

Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D., Zachos, J., “Target Atmospheric CO_2: Where Should Humanity Aim?, *The Open Atmospheric Science Journal*, 2 (2008), 217-231. http://pubs.giss.nasa.gov/docs/2008/2008_Hansen_etal.pdf

“Heavy Manufacturing of Power Plants”, *World Nuclear Association*, Updated 2013, http://world-nuclear.org/info/Nuclear-Fuel-Cycle/Power-Reactors/Heavy-Manufacturing-of-Power-Plants/.

Hill, J., “A Cleaner Future for China Lays Ahead”, theenergycollective, 6 September 2013, http://theenergycollective.com/joshshill/267561/cleaner-future-china-lays-ahead.

Kolstad, C., “George Bush versus Al Gore: Irreversibilities in greenhouse gas accumulation and emission control investment”, *Energy Policy*, 22 (1994), 771-778.

Lenzen, M., “Life cycle energy and greenhouse gas emissions of nuclear energy: A review”, *Energy Conversion and Management*, 49 (2008), 2178-2199.

Macalister, T., “Fukushima proved turn-off point for nuclear power”, The Guardian, 20 October 2013.

NASA, Global Climate Change, http://climate.nasa.gov/.

Newbold, S., “Summary of the DICE model”, U.S. EPA, National Center for Environmental Economics, 2010.

Nordhaus, W., “Integrated Economic and Climate Modeling”, *Cowles Foundation Discussion Paper No. 1839*, 19 November 2011.

Nordhaus, W., “Reflections on the Economics of Climate Change”, *Journal of Economic Perspectives*, Volume 7, Number 4 (1993), 11-25.

Nordhaus, W., “Rolling the ‘DICE’: An optimal transition path for controlling greenhouse gases”, *Resource and Energy Economics*, 15 (1993), 27-50.

Nordhaus, W., “New Estimates of the Economic Impacts of Climate Change”, *National Science Foundation*, 1998, 1-23.

Nordhaus, W., “A Question of Balance”, 2008, pages 30-37, Yale University Press.
CO2Now.org, http://co2now.org/

“Nuclear Power in the USA”, *World Nuclear Association*, Updated 2013, http://www.world-nuclear.org/info/Country-Profiles/Countries-T-Z/USA--Nuclear-Power/

“Nuclear Power in the World Today”, *World Nuclear Association*, Updated 2012, http://www.world-nuclear.org/info/Current-and-Future-Generation/Nuclear-Power-in-the-World-Today/.

Romm, J., “A factor of 3.67 makes a big difference when discussing climate”, Grist.org, 26 March 2008, http://grist.org/article/the-biggest-source-of-mistakes-carbon-vs-carbon-dioxide/.

Schneider, S., “Abrupt non-linear climate change, irreversibility and surprise”, *Global Environmental Change*, 14 (2004), 245-258.

Sovacool, B., “Valuing the greenhouse gas emissions from nuclear power: A critical survey”, *Energy Policy*, 36 (2008) 2940-2953.

They Want to Blame You – (A21CS Section 1.2), http://www.youtube.com/watch?v=l-RvUedfKpk&feature=youtu.be, 2013.

United Nations Framework Convention on Climate Change, http://unfccc.int/kyoto_protocol/items/2830.php, 2012.
U.S. Energy Information Administration, “Electric Power Annual 2011”, http://www.eia.gov/electricity/annual/pdf/epa.pdf, 2013.

U.S. Energy Information Administration, “International Energy Statistics”, http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm, 2013.

U.S. Energy Information Administration, “What are Greenhouse Gases”, http://www.eia.gov/oiaf/1605/ggccebro/chapter1.html, 2013.

U.S. Energy Information Administration, “The Economics of Nuclear Power”, http://www.world-nuclear.org/info/Economic-Aspects/Economics-of-Nuclear-Power/, 2013.

U.S. Nuclear Regulatory Commission, “Power Uprates for Nuclear Power Plants”, http://www.nrc.gov/reading-rm/doc-collections/fact-sheets/power-uprates.html, 2013.

Vensim, Ventana Simulation Environment, “User’s Guide Version 5”, 2002.

Ventana Systems, Inc., Vensim Software, http://vensim.com/vensim-software/.

Wai, C., “Ionic Liquid and Supercritical Fluid Hyphenated Techniques For Dissolution and Separation of Lanthanides and Actinides”, DOE-NEUP Project (TO 00058), 2012.

World Nuclear New, “Nuclear essential for climate stability”, http://www.world-nuclear-news.org/EE-Nuclear-essential-for-climate-stability-0411137.html, 2013.

Appendix A:

Nordhaus DICE Model Vensim Equations

http://www.metasd.com/models/Library/ClimatePolicy/NordhausDICE/dice4.html

.Carbon

Emissions, carbon cycle and related variables.

(001) Atmos_Retention = 0.64

Units: dmnl

Atmospheric Retention Fraction [beta] (dimensionless) Fraction of Greenhouse Gas Emissions which accumulate in the atmosphere. [Cowles, pg. 21]

Uses:

- (007)CO2_Net_Emiss - Net Greenhouse Gas Emissions (tons carbon equivalent/year) Greenhouse gas emissions less short-run uptake from the atmosphere. Where does the portion not retained go in the long run? [Cowles, pg. 21]

(002) CO2_Emiss = (1-GHG_Reduction_Frac)*CO2_Intensity_of_Output*Output

Units: TonC/year

Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]

Causes:

- (006)CO2_Intensity_of_Output - Greenhouse Gas Intensity of Output [sigma(t)] (tons carbon equivalent/$) [Managing Global Commons, pg. 21] Conflicts with value reported on Cowles, pg. 24: .5368*.9875^(TIME-1990)/1000 = .7352/1000
- (015)GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

Uses:

- (079)CO2_And_CFC_Intens_Capital - CO2 and CFC Emissions per Unit of Capital (tons carbon equiv/year/$)
- (007)CO2_Net_Emiss - Net Greenhouse Gas Emissions (tons carbon equivalent/year) Greenhouse gas emissions less short-run uptake from the atmosphere. Where does the portion not retained go in the long run? [Cowles, pg. 21]

(003) CO2_in_Atmos = INTEG(CO2_Net_Emiss - CO2_Storage, 6.77e+011)

Units: TonC

Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]

Causes:

- (007)CO2_Net_Emiss - Net Greenhouse Gas Emissions (tons carbon equivalent/year) Greenhouse gas emissions less short-run uptake from the atmosphere. Where does the portion not retained go in the long run? [Cowles, pg. 21]
- (010)CO2_Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

Uses:

- (009)CO2_Rad_Forcing - Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO2. [Cowles, pg. 22]
- (010)CO2_Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

(004) CO2_Intens_Dec_Rt_Decline_Rt =
CO2_Intens_Decline_Rt*Fact_Prod_Gr_Rt_Dec_Rt

Units: 1/year/year

Causes:

- (005)CO2_Intens_Decline_Rt - Rate of Decline of Greenhouse Gas Intensity of Output [g-sigma] (1/year) Note that Nordhaus decompounds the decadal rate of .1168 to yield an annual rate of .0125. This does not work with time steps smaller than Nordhaus' 10 years, so I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]
- (060)Fact_Prod_Gr_Rt_Dec_Rt - Rate of Decline of Factor Productivity Growth Rate [delta-A] (1/year/year) Factor productivity growth rate declines 11% per decade. [Cowles, pg. 18]

Uses:

- (005)CO2_Intens_Decline_Rt - Rate of Decline of Greenhouse Gas Intensity of Output [g-sigma] (1/year) Note that Nordhaus decompounds the decadal rate of .1168 to yield an annual rate of .0125. This does not work with time steps smaller than Nordhaus' 10 years, so I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

(005) CO2_Intens_Decline_Rt = INTEG(- CO2_Intens_Dec_Rt_Decline_Rt,
init_co2_intens_decline_rt)

Units: 1/year

Rate of Decline of Greenhouse Gas Intensity of Output [g-sigma] (1/year) Note that Nordhaus decompounds the decadal rate of .1168 to yield an annual rate of .0125. This does not work with time steps smaller than Nordhaus' 10 years, so I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

Causes:

- (004)CO2_Intens_Dec_Rt_Decline_Rt -
- (016)init_co2_intens_decline_rt -

Uses:

- (004)CO2_Intens_Dec_Rt_Decline_Rt -
- (011)Decline_CO2_Intens - Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]

(006) CO2_Intensity_of_Output = INTEG(- Decline_CO2_Intens, 0.000519)

Units: TonC/$

Greenhouse Gas Intensity of Output [sigma(t)] (tons carbon equivalent/$) [Managing Global Commons, pg. 21] Conflicts with value reported on Cowles, pg. 24: .5368*.9875^(TIME-1990)/1000 = .7352/1000

Causes:

- (011)Decline_CO2_Intens - Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]

Uses:

- (002)CO2_Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]
- (011)Decline_CO2_Intens - Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]
- (087)Reference_CO2_Emissions - Reference CO2 Emissions Emissions at normal CO2 intensity, with no abatement.

(007) CO2_Net_Emiss = Atmos_Retention*CO2_Emiss

Units: TonC/year

Net Greenhouse Gas Emissions (tons carbon equivalent/year) Greenhouse gas emissions less short-run uptake from the atmosphere. Where does the portion not retained go in the long run? [Cowles, pg. 21]

Causes:

- (001)Atmos_Retention - Atmospheric Retention Fraction [beta] (dimensionless) Fraction of Greenhouse Gas Emissions which accumulate in the atmosphere. [Cowles, pg. 21]
- (002)CO2_Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]

Uses:

- (003)CO2_in_Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]

(008) CO2_Rad_Force_Coeff = 4.1

Units: watt/meter/meter

Coefficient of Radiative Forcing from CO2 (W/m^2) Coeff. of additional surface warming from accumulation of CO2. [Cowles, pg. 22]

Uses:

- (009)CO2_Rad_Forcing - Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO2. [Cowles, pg. 22]

(009) CO2_Rad_Forcing =
CO2_Rad_Force_Coeff*LOG(CO2_in_Atmos/Preindustrial_CO2 ,2)

Units: watt/meter/meter

Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO2. [Cowles, pg. 22]

Causes:

- (003)CO2_in_Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]
- (008)CO2_Rad_Force_Coeff - Coefficient of Radiative Forcing from CO2 (W/m^2) Coeff. of additional surface warming from accumulation of CO2. [Cowles, pg. 22]
- (021)Preindustrial_CO2 -

Uses:

- (041)Radiative_Forcing - Radiative Forcing from All GHGs (W/m^2) Additional surface warming from accumulation of CO2 & CFCs. [Cowles, Sec. III.F]

(010) CO2_Storage = (CO2_in_Atmos-Preindustrial_CO2)*Rate_of_CO2_Transfer

Units: TonC/year

Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

Causes:

- (003)CO2_in_Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]
- (021)Preindustrial_CO2 -
- (022)Rate_of_CO2_Transfer - Rate of Storage of Atmospheric Greenhouse Gases [delta-m] (1/year) Inverse yields average residence time of gases (120 years). Note that the validity and stability of this factor is highly questionable. [Cowles, pg. 21]

Uses:

- (003)CO2_in_Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]

(011) Decline_CO2_Intens = CO2_Intensity_of_Output*CO2_Intens_Decline_Rt

Units: TonC/$/year

Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]

Causes:

- (005)CO2_Intens_Decline_Rt - Rate of Decline of Greenhouse Gas Intensity of Output [g-sigma] (1/year) Note that Nordhaus decompounds the decadal rate of .1168 to yield an annual rate of .0125. This does not work with time steps smaller than Nordhaus' 10 years, so I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]
- (006)CO2_Intensity_of_Output - Greenhouse Gas Intensity of Output [sigma(t)] (tons carbon equivalent/$) [Managing Global Commons, pg. 21] Conflicts with value reported on Cowles, pg. 24: .5368*.9875^(TIME-1990)/1000 = .7352/1000

Uses:

- (006)CO2_Intensity_of_Output - Greenhouse Gas Intensity of Output [sigma(t)] (tons carbon equivalent/$) [Managing Global Commons, pg. 21] Conflicts with value reported on Cowles, pg. 24: .5368*.9875^(TIME-1990)/1000 = .7352/1000

(012) Emiss_Stabilization

Units: dmnl

Fraction of CO2 and CFC Emissions Controlled (dimensionless) Stabilization of Emissions. Estimated from graph in [Science, Fig. 1].

Uses:

- (018)Nord_GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]

(013) Emissions_Scenario = 1

Units: dmnl

Uses:

- (018)Nord_GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]

(014) GHG_Red_Cost_Frac = 1-Red_Cost_Scale*if_then_else(GHG_Reduction_Frac> 0,GHG_Reduction_Frac^Red_Cost_Nonlinearity ,0)

Units: dmnl

Fraction of Output devoted to cost of GHG emissions reductions (dimensionless)

Causes:

- (015)GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.
- (023)Red_Cost_Nonlinearity - Nonlinearity of GHG Reduction Cost [b2] (dimensionless) [Cowles, pg. 13 & 24]
- (024)Red_Cost_Scale - Scale of GHG Reduction Cost [b1] (dimensionless) [Cowles, pg. 13 & 24]

Uses:

- (069)Net_CC_Impact - Net Climate Change Impact [Omega(t)] (dimensionless) The fraction of output lost to GHG emissions reduction and climate change damage costs. [Cowles, pg. 13]
- (086)Reduction_Costs - Flow of greenhouse gas abatement costs.

(015) GHG_Reduction_Frac = Optimal_Red_Switch*Optimal_GHG_Reduction_Frac + (1-Optimal_Red_Switch)*Nord_GHG_Reduction_Frac

Units: dmnl

Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.

Causes:

- (018)Nord_GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]
- (094)Optimal_GHG_Reduction_Frac - GHG Reduction Fraction derived from optimization.
- (020)Optimal_Red_Switch - Switches GHG Reduction Frac between Nordhaus' time path and time path from optimization.

Uses:

- (002)CO2_Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]
- (014)GHG_Red_Cost_Frac - Fraction of Output devoted to cost of GHG emissions reductions (dimensionless)
- (082)Marg_Prod_Carbon - Marginal Productivity of CO2 Emissions

(016) init_co2_intens_decline_rt = 0.01168

Units: 1/year

Uses:

- (005)CO2_Intens_Decline_Rt - Rate of Decline of Greenhouse Gas Intensity of Output [g-sigma] (1/year) Note that Nordhaus decompounds the decadal rate of .1168 to yield an annual rate of .0125. This does not work with time steps smaller than Nordhaus' 10 years, so I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

(017) No_Controls = 0

Units: dmnl

Fraction of CO2 and CFC Emissions Controlled (dimensionless) Uncontrolled scenario.

Uses:

- (018)Nord_GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]

(018) Nord_GHG_Reduction_Frac = if_then_else(Emissions_Scenario=1,No_Controls ,if_then_else(Emissions_Scenario =2

,Optimal_Controls,if_then_else(Emissions_Scenario=3,Emiss_Stabilization,Temp_Stabilization)))

Units: dmnl

Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]

Causes:

- (012)Emiss_Stabilization - Fraction of CO2 and CFC Emissions Controlled (dimensionless) Stabilization of Emissions. Estimated from graph in [Science, Fig. 1].
- (013)Emissions_Scenario -
- (017)No_Controls - Fraction of CO2 and CFC Emissions Controlled (dimensionless) Uncontrolled scenario.
- (019)Optimal_Controls - Fraction of CO2 and CFC Emissions Controlled (dimensionless) Optimal control scenario. [Cowles, table IV-3]
- (025)Temp_Stabilization - Fraction of CO2 and CFC Emissions Controlled Stabilization of temperature. Estimated from graph. [Science, Fig. 1].

Uses:

- (015)GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.

(019) Optimal_Controls

Units: dmnl

Fraction of CO2 and CFC Emissions Controlled (dimensionless) Optimal control scenario. [Cowles, table IV-3]

Uses:

- (018)Nord_GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]

(020) Optimal_Red_Switch = 1

Units: dmnl

Switches GHG Reduction Frac between Nordhaus' time path and time path from optimization.

Uses:

- (015)GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.

(021) Preindustrial_CO2 = 5.9e+011

Units: TonC

Uses:

- (009)CO2_Rad_Forcing - Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO2. [Cowles, pg. 22]
- (010)CO2_Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

(022) Rate_of_CO2_Transfer = 0.008333

Units: 1/year

Rate of Storage of Atmospheric Greenhouse Gases [delta-m] (1/year) Inverse yields average residence time of gases (120 years). Note that the validity and stability of this factor is highly questionable. [Cowles, pg. 21]

Uses:

- (010)CO2_Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

(023) Red_Cost_Nonlinearity = 2.887

Units: dmnl

Nonlinearity of GHG Reduction Cost [b2] (dimensionless) [Cowles, pg. 13 & 24]

Uses:

- (014)GHG_Red_Cost_Frac - Fraction of Output devoted to cost of GHG emissions reductions (dimensionless)
- (082)Marg_Prod_Carbon - Marginal Productivity of CO2 Emissions

(024) Red_Cost_Scale = 0.0686

Units: dmnl

Scale of GHG Reduction Cost [b1] (dimensionless) [Cowles, pg. 13 & 24]

Uses:

- (014)GHG_Red_Cost_Frac - Fraction of Output devoted to cost of GHG emissions reductions (dimensionless)
- (082)Marg_Prod_Carbon - Marginal Productivity of CO2 Emissions

(025) Temp_Stabilization

Units: dmnl

Fraction of CO2 and CFC Emissions Controlled Stabilization of temperature. Estimated from graph. [Science, Fig. 1].

Uses:

- (018)Nord_GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] (dimensionless) Selects one of three scenarios. [Cowles, pg. 20]

.Climate

(026) A_UO_Heat_Cap = 44.248

Units: watt*year/DegreesC/(meter*meter)

Atmosphere & Upper Ocean Heat Capacity per Unit Area [1/R1] (W-yr/m^2/degrees C) Note: equals 1/0.0226 [Managing the Global Commons, pg. 21]

Uses:

- (028)Chg_A_UO_Temp - Change in the Atmosphere & Upper Ocean Temperature (degrees C/yr) [Cowles, pg. 27]

(027) Atmos_UOcean_Temp = INTEG(Chg_A_UO_Temp, 0.2)

Units: DegreesC

Temperature of the Atmosphere and Upper Ocean [T] (degrees C) [Cowles, pg. 24]

Causes:

- (028)Chg_A_UO_Temp - Change in the Atmosphere & Upper Ocean Temperature (degrees C/yr) [Cowles, pg. 27]

Uses:

- (030)Climate_Damage_Frac - Fraction of Output lost to combating Climate Change (1/Degrees C^2)

- (036)Feedback_Heating - Feedback Heating (W/m^2) Additional heating of the atmosphere/upper ocean system from feedback effects of warming. [Cowles, pg. 27]
- (043)Temp_Diff - Temperature Difference between Upper and Deep Ocean (degrees C)

(028) Chg_A_UO_Temp = (Radiative_Forcing-Feedback_Heating-Heat_Transfer)/A_UO_Heat_Cap

Units: DegreesC/year

Change in the Atmosphere & Upper Ocean Temperature (degrees C/yr) [Cowles, pg. 27]

Causes:

- (026)A_UO_Heat_Cap - Atmosphere & Upper Ocean Heat Capacity per Unit Area [1/R1] (W-yr/m^2/degrees C) Note: equals 1/0.0226 [Managing the Global Commons, pg. 21]
- (036)Feedback_Heating - Feedback Heating (W/m^2) Additional heating of the atmosphere/upper ocean system from feedback effects of warming. [Cowles, pg. 27]
- (039)Heat_Transfer - Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean
- (041)Radiative_Forcing - Radiative Forcing from All GHGs (W/m^2) Additional surface warming from accumulation of CO2 & CFCs. [Cowles, Sec. III.F]

Uses:

- (027)Atmos_UOcean_Temp - Temperature of the Atmosphere and Upper Ocean [T] (degrees C) [Cowles, pg. 24]

(029) Chg_DO_Temp = Heat_Transfer/DO_Heat_Cap

Units: DegreesC/year

Change in the Deep Ocean Temperature (degrees C/yr) [Cowles, pg. 30]

Causes:

- (035)DO_Heat_Cap - Deep Ocean Heat Capacity per Unit Area [R2] (W-yr/m^2/degrees C) Note: Managing Global Commons uses .44*Heat_Trans_Coeff = 220; Cowles report uses 223.7 (page 30). [Managing Global Commons, pg. 21]
- (039)Heat_Transfer - Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean

Uses:

- (034)Deep_Ocean_Temp - Temperature of the Deep Ocean [T*] (degrees C) [Cowles, pg. 24]

(030) Climate_Damage_Frac = 1/(1+Climate_Damage_Scale*(Atmos_UOcean_Temp/Reference_Temperature)^Climate_Damage_Nonlinearity)

Units: dmnl

Fraction of Output lost to combating Climate Change (1/Degrees C^2)

Causes:

- (027)Atmos_UOcean_Temp - Temperature of the Atmosphere and Upper Ocean [T] (degrees C) [Cowles, pg. 24]
- (031)Climate_Damage_Nonlinearity - Nonlinearity of Climate Damage Cost Fraction [Theta2] (dimensionless) [Cowles, pg. 13 & 24]
- (032)Climate_Damage_Scale - Climate Damage Fraction at Reference Temperature [part of Nordhaus' variable Theta1] (dimensionless) [Managing Global Commons, pg. 18 and 21]
- (042)Reference_Temperature - Reference Temperature for Calculation of Climate Damages [part of Nordhaus' variable theta1] [Managing Global Commons, pg. 18 and 21]

Uses:

- (078)Climate_Damages - Flow of damages from climate change.
- (069)Net_CC_Impact - Net Climate Change Impact [Omega(t)] (dimensionless) The fraction of output lost to GHG emissions reduction and climate change damage costs. [Cowles, pg. 13]

(031) Climate_Damage_Nonlinearity = 2

Units: dmnl

Nonlinearity of Climate Damage Cost Fraction [Theta2] (dimensionless) [Cowles, pg. 13 & 24]

Uses:

- (030)Climate_Damage_Frac - Fraction of Output lost to combating Climate Change (1/Degrees C^2)

(032) Climate_Damage_Scale = 0.013

Units: dmnl

Climate Damage Fraction at Reference Temperature [part of Nordhaus' variable Theta1] (dimensionless) [Managing Global Commons, pg. 18 and 21]

Uses:

- (030)Climate_Damage_Frac - Fraction of Output lost to combating Climate Change (1/Degrees C^2)

(033) Climate_Feedback_Param = 1.41

Units: watt/meter/meter/DegreesC

Climate Feedback Parameter [lambda] (W-m^2/degree C) The crucial climate sensitivity parameter - determines feedback warming from temperature increase. The Schneider-Thompson 2-stock model uses 1.33 [Cowles, Table III-B1]. [Managing Global Commons, pg. 21]

Uses:

- (036)Feedback_Heating - Feedback Heating (W/m^2) Additional heating of the atmosphere/upper ocean system from feedback effects of warming. [Cowles, pg. 27]

(034) Deep_Ocean_Temp = INTEG(Chg_DO_Temp, 0.1)

Units: DegreesC

Temperature of the Deep Ocean [T*] (degrees C) [Cowles, pg. 24]

Causes:

- (029)Chg_DO_Temp - Change in the Deep Ocean Temperature (degrees C/yr) [Cowles, pg. 30]

Uses:

- (043)Temp_Diff - Temperature Difference between Upper and Deep Ocean (degrees C)

(035) DO_Heat_Cap = Heat_Capacity_Ratio*Heat_Trans_Coeff

Units: watt*year/DegreesC/meter/meter

Deep Ocean Heat Capacity per Unit Area [R2] (W-yr/m^2/degrees C) Note: Managing Global Commons uses .44*Heat_Trans_Coeff = 220; Cowles report uses 223.7 (page 30). [Managing Global Commons, pg. 21]

Causes:

- (037)Heat_Capacity_Ratio - Ratio of Thermal Capacity of Deep Ocean to Heat Transfer Time Constant [R2/Tau12] [Managing Global Commons, pg. 21]
- (038)Heat_Trans_Coeff - Heat Transfer Coefficient [tau12] (years) Coefficient of heat transfer between the atmosphere & upper ocean and the deep ocean. May be interpreted as a mixing time constant. Schneider & Thompson use a slightly higher estimate of 550. [Cowles, pg. 31]

Uses:

- (029)Chg_DO_Temp - Change in the Deep Ocean Temperature (degrees C/yr) [Cowles, pg. 30]
- (039)Heat_Transfer - Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean

(036) Feedback_Heating = Atmos_UOcean_Temp*Climate_Feedback_Param

Units: watt/meter/meter

Feedback Heating (W/m^2) Additional heating of the atmosphere/upper ocean system from feedback effects of warming. [Cowles, pg. 27]

Causes:

- (027)Atmos_UOcean_Temp - Temperature of the Atmosphere and Upper Ocean [T] (degrees C) [Cowles, pg. 24]
- (033)Climate_Feedback_Param - Climate Feedback Parameter [lambda] (W-m^2/degree C) The crucial climate sensitivity parameter - determines feedback warming from temperature increase. The Schneider-Thompson 2-stock model uses 1.33 [Cowles, Table III-B1]. [Managing Global Commons, pg. 21]

Uses:

- (028)Chg_A_UO_Temp - Change in the Atmosphere & Upper Ocean Temperature (degrees C/yr) [Cowles, pg. 27]

(037) Heat_Capacity_Ratio = 0.44

Units: watt/(meter*meter*DegreesC)

Ratio of Thermal Capacity of Deep Ocean to Heat Transfer Time Constant [R2/Tau12] [Managing Global Commons, pg. 21]

Uses:

- (035)DO_Heat_Cap - Deep Ocean Heat Capacity per Unit Area [R2] (W-yr/m^2/degrees C) Note: Managing Global Commons uses .44*Heat_Trans_Coeff = 220; Cowles report uses 223.7 (page 30). [Managing Global Commons, pg. 21]

(038) Heat_Trans_Coeff = 500

Units: year

Heat Transfer Coefficient [tau12] (years) Coefficient of heat transfer between the atmosphere & upper ocean and the deep ocean. May be interpreted as a mixing time constant. Schneider & Thompson use a slightly higher estimate of 550. [Cowles, pg. 31]

Uses:

- (035)DO_Heat_Cap - Deep Ocean Heat Capacity per Unit Area [R2] (W-yr/m^2/degrees C) Note: Managing Global Commons uses .44*Heat_Trans_Coeff = 220; Cowles report uses 223.7 (page 30). [Managing Global Commons, pg. 21]
- (039)Heat_Transfer - Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean

(039) Heat_Transfer = Temp_Diff*DO_Heat_Cap/Heat_Trans_Coeff

Units: watt/meter/meter

Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean

Causes:

- (035)DO_Heat_Cap - Deep Ocean Heat Capacity per Unit Area [R2] (W-yr/m^2/degrees C) Note: Managing Global Commons uses .44*Heat_Trans_Coeff = 220; Cowles report uses 223.7 (page 30). [Managing Global Commons, pg. 21]
- (038)Heat_Trans_Coeff - Heat Transfer Coefficient [tau12] (years) Coefficient of heat transfer between the atmosphere & upper ocean and the deep ocean. May be interpreted as a mixing time constant. Schneider & Thompson use a slightly higher estimate of 550. [Cowles, pg. 31]
- (043)Temp_Diff - Temperature Difference between Upper and Deep Ocean (degrees C)

Uses:

- (028)Chg_A_UO_Temp - Change in the Atmosphere & Upper Ocean Temperature (degrees C/yr) [Cowles, pg. 27]
- (029)Chg_DO_Temp - Change in the Deep Ocean Temperature (degrees C/yr) [Cowles, pg. 30]

(040) Other_GHG_Rad_Forcing

Units: watt/meter/meter

Radiative Forcing from Other GHGs (W/m^2) Additional surface warming from accumulation of other GHGs (NOx and Methane). [Table 4.9B, Managing Global Commons, pg. 73]

Uses:

- (041)Radiative_Forcing - Radiative Forcing from All GHGs (W/m^2) Additional surface warming from accumulation of CO2 & CFCs. [Cowles, Sec. III.F]

(041) Radiative_Forcing = CO2_Rad_Forcing+Other_GHG_Rad_Forcing

Units: watt/meter/meter

Radiative Forcing from All GHGs (W/m^2) Additional surface warming from accumulation of CO2 & CFCs. [Cowles, Sec. III.F]

Causes:

- (009)CO2_Rad_Forcing - Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO2. [Cowles, pg. 22]
- (040)Other_GHG_Rad_Forcing - Radiative Forcing from Other GHGs (W/m^2) Additional surface warming from accumulation of other GHGs (NOx and Methane). [Table 4.9B, Managing Global Commons, pg. 73]

Uses:

- (028)Chg_A_UO_Temp - Change in the Atmosphere & Upper Ocean Temperature (degrees C/yr) [Cowles, pg. 27]

(042) Reference_Temperature = 3

Units: DegreesC

Reference Temperature for Calculation of Climate Damages [part of Nordhaus' variable theta1] [Managing Global Commons, pg. 18 and 21]

Uses:

- (030)Climate_Damage_Frac - Fraction of Output lost to combating Climate Change (1/Degrees C^2)

(043) Temp_Diff = Atmos_UOcean_Temp-Deep_Ocean_Temp

Units: DegreesC

Temperature Difference between Upper and Deep Ocean (degrees C)

Causes:

- (027)Atmos_UOcean_Temp - Temperature of the Atmosphere and Upper Ocean [T] (degrees C) [Cowles, pg. 24]
- (034)Deep_Ocean_Temp - Temperature of the Deep Ocean [T*] (degrees C) [Cowles, pg. 24]

Uses:

- (039)Heat_Transfer - Heat Transfer from the Atmosphere & Upper Ocean to the Deep Ocean

.Control

(044) FINAL_TIME = 2105

Units: year

(045) INITIAL_TIME = 1965

Units: year

Uses: (000)Time - Internally defined simulation time.

(046) SAVEPER = 5

Units: year

(047) TIME_STEP = 5

Units: year

.Data

(048) IPCC_CO2_CFC_Rad_Force

Units: watt/meter/meter

IPCC Scenario for Radiative Forcing from CO2 and CFCs (W/m^2) As interpolated by Nordhaus. [Cowles, Table III.E-5]

(049) Nord_CO2_in_Atm

Units: GTonC

Nordhaus' CO2 & CFC Concentrations (Gt Carbon Equivalent) Uncontrolled scenario [Cowles, Table IV-4].

(050) Nord_CO2_Intensity

Units: GTonC/$

(051) Nord_Emiss

Units: GTonC/year

Nordhaus' CO2 & CFC Emissions (Gt Carbon Equivalent) Uncontrolled scenario [Cowles, Table IV-4].

(052) Nord_Output

Units: $/year

Nordhaus' Output ($/year) [Cowles, Table IV-1]

(053) Nord_Temp

Units: DegreesC

Nordhaus' Atmospher & Upper Ocean Temperature Difference (degrees C) Uncontrolled scenario [Cowles, Table IV-5].

.Econ

(054) Behav_Invest_Frac = Invest_Frac_Scale*(Marg_Return_Capital/Norm_Return_Capital)^Invest_Frac_Nonlin

Units: dmnl

A simple behavioral heuristic for investment; closely replicates results of the optimal time path.

Causes:

- (065)Invest_Frac_Nonlin -
- (066)Invest_Frac_Scale -
- (083)Marg_Return_Capital - Marginal Return to Capital Equals the marginal product of capital less depreciation.
- (071)Norm_Return_Capital -

Uses:

- (068)Investment_Frac - Fraction of Output Invested May be switched between path derived from optimization and Nordhaus' path

(055) Capital = INTEG(Investment - Depreciation, 1.6e+013)

Units: $

Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]

Causes:

- (058)Depreciation - Depreciation ($/year)
- (067)Investment - Gross Investment ($/year)

Uses:

- (076)Capital_Labor_Ratio - Ratio of Capital Inputs to Labor Inputs ($/person)
- (077)Capital_Output_Ratio - Capital per Unit Output ($ per $/year)
- (079)CO2_And_CFC_Intens_Capital - CO2 and CFC Emissions per Unit of Capital (tons carbon equiv/year/$)
- (058)Depreciation - Depreciation ($/year)
- (081)Marg_Prod_Capital - Marginal Productivity of Capital
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(056) Capital_Elast_Output = 0.25

Units: dmnl

Capital Elasticity of Output [alpha] (dimensionless) Derived from share of capital in national income. [Cowles, pg. 17]

Uses:

- (081)Marg_Prod_Capital - Marginal Productivity of Capital
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(057) Consumption = Output-Investment

Units: $/year

Consumption ($/year) Output less investment (savings).

Causes:

- (067)Investment - Gross Investment ($/year)
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

Uses:

- (103)Consumption_per_Cap - Consumption per Capita ($/person/year)

(058) Depreciation = Capital*Depreciation_Rate

Units: $/year

Depreciation ($/year)

Causes:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (059)Depreciation_Rate - Depreciation Rate [delta-k] (1/year) Note that Nordhaus assumes a 10-year capital life, then chooses a value of 0.065 to correct for the lack of compounding in the 10-year time step he uses. This is simply wrong, as the capital stock has an inflow as well as an outflow, and it is the net rate (investment-depreciation) that must be compounded. Also, using a value of 0.065 results in an average residence time of units in the capital stock of 15 years, even with the 10-year time step. I have preserved the value 0.065 for replication; a 15-year capital life is perfectly reasonable anyway. [Managing Global Commons, pg. 21]

Uses:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (084)Net_Investment - Net Investment Investment less depreciation

(059) Depreciation_Rate = 0.065

Units: 1/year

Depreciation Rate [delta-k] (1/year) Note that Nordhaus assumes a 10-year capital life, then chooses a value of 0.065 to correct for the lack of compounding in the 10-year time step he uses. This is simply wrong, as the capital stock has an inflow as well as an outflow, and it is the net rate (investment-depreciation) that must be compounded. Also, using a value of 0.065 results in an average residence time of units in the capital stock of 15 years, even with the 10-year time step. I have preserved the value 0.065 for replication; a 15-year capital life is perfectly reasonable anyway. [Managing Global Commons, pg. 21]

Uses:

- (058)Depreciation - Depreciation ($/year)
- (083)Marg_Return_Capital - Marginal Return to Capital Equals the marginal product of capital less depreciation.

(060) Fact_Prod_Gr_Rt_Dec_Rt = 0.011

Units: 1/year

Rate of Decline of Factor Productivity Growth Rate [delta-A] (1/year/year) Factor productivity growth rate declines 11% per decade. [Cowles, pg. 18]

Uses:

- (004)CO2_Intens_Dec_Rt_Decline_Rt -
- (061)Fact_Prod_Gr_Rt_Decline_Rt - Decline of Factor Productivity Growth Rate (1/year/year)

(061) Fact_Prod_Gr_Rt_Decline_Rt = Fact_Prod_Growth_Rt*Fact_Prod_Gr_Rt_Dec_Rt

Units: 1/year/year

Decline of Factor Productivity Growth Rate (1/year/year)

Causes:

- (062)Fact_Prod_Growth_Rt - Growth Rate of Factor Productivity [gA(t)] (1/year) Growth rate declines over time. Value reported in [Cowles, pg. 17]: .0152 for period 1965-1987, matches statement in [Science, pg. 1317] that average was 1.3% from 1965-1989, with an 11%/decade rate of decline. Note that Nordhaus decompounds the decadal rate of .150 to yield an annual rate of .0141; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21] [Managing the Global Commons, pg. 21]
- (060)Fact_Prod_Gr_Rt_Dec_Rt - Rate of Decline of Factor Productivity Growth Rate [delta-A] (1/year/year) Factor productivity growth rate declines 11% per decade. [Cowles, pg. 18]

Uses:

- (062)Fact_Prod_Growth_Rt - Growth Rate of Factor Productivity [gA(t)] (1/year) Growth rate declines over time. Value reported in [Cowles, pg. 17]: .0152 for period 1965-1987, matches statement in [Science, pg. 1317] that average was 1.3% from 1965-1989, with an 11%/decade rate of decline. Note that Nordhaus decompounds the decadal rate of .150 to yield an annual rate of .0141; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21] [Managing the Global Commons, pg. 21]

(062) Fact_Prod_Growth_Rt = INTEG(- Fact_Prod_Gr_Rt_Decline_Rt, 0.015)

Units: 1/year

Growth Rate of Factor Productivity [gA(t)] (1/year) Growth rate declines over time. Value reported in [Cowles, pg. 17]: .0152 for period 1965-1987, matches statement in [Science, pg. 1317] that average was 1.3% from 1965-1989, with an 11%/decade rate of decline. Note that Nordhaus decompounds the decadal rate of .150 to yield an annual rate of .0141; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21] [Managing the Global Commons, pg. 21]

Causes:

- (061)Fact_Prod_Gr_Rt_Decline_Rt - Decline of Factor Productivity Growth Rate (1/year/year)

Uses:

- (061)Fact_Prod_Gr_Rt_Decline_Rt - Decline of Factor Productivity Growth Rate (1/year/year)
- (063)Fact_Prod_Incr_Rt - Change in Factor Productivity (1/year)

(063) Fact_Prod_Incr_Rt = Factor_Productivity*Fact_Prod_Growth_Rt

Units: 1/year

Change in Factor Productivity (1/year)

Causes:

- (062)Fact_Prod_Growth_Rt - Growth Rate of Factor Productivity [gA(t)] (1/year) Growth rate declines over time. Value reported in [Cowles, pg. 17]: .0152 for period 1965-1987, matches statement in [Science, pg. 1317] that average was 1.3% from 1965-1989, with an 11%/decade rate of decline. Note that Nordhaus decompounds the decadal rate of .150 to yield an annual rate of .0141; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21] [Managing the Global Commons, pg. 21]
- (064)Factor_Productivity - Total Factor Productivity [A(t)] (dimensionless) May be interpreted as level of technology. [Cowles pg. 17]

Uses:

- (064)Factor_Productivity - Total Factor Productivity [A(t)] (dimensionless) May be interpreted as level of technology. [Cowles pg. 17]

(064) Factor_Productivity = INTEG(Fact_Prod_Incr_Rt, 1)

Units: dmnl

Total Factor Productivity [A(t)] (dimensionless) May be interpreted as level of technology. [Cowles pg. 17]

Causes:

- (063)Fact_Prod_Incr_Rt - Change in Factor Productivity (1/year)

Uses:

- (063)Fact_Prod_Incr_Rt - Change in Factor Productivity (1/year)
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(065) Invest_Frac_Nonlin = 1

Units: dmnl

Uses:

- (054)Behav_Invest_Frac - A simple behavioral heuristic for investment; closely replicates results of the optimal time path.

(066) Invest_Frac_Scale = 0.2

Units: dmnl

Uses:

- (054)Behav_Invest_Frac - A simple behavioral heuristic for investment; closely replicates results of the optimal time path.

(067) Investment = Output*Investment_Frac

Units: $/year

Gross Investment ($/year)

Causes:

- (068)Investment_Frac - Fraction of Output Invested May be switched between path derived from optimization and Nordhaus' path
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

Uses:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (057)Consumption - Consumption ($/year) Output less investment (savings).
- (084)Net_Investment - Net Investment Investment less depreciation

(068) Investment_Frac = if_then_else(Optimal_Invest_Switch=1,Optimal_Invest_Frac , if_then_else(Optimal_Invest_Switch=2,Behav_Invest_Frac,Nord_Investment_Frac))

Units: dmnl

Fraction of Output Invested May be switched between path derived from optimization and Nordhaus' path

Causes:

- (054)Behav_Invest_Frac - A simple behavioral heuristic for investment; closely replicates results of the optimal time path.
- (070)Nord_Investment_Frac - Fraction of Output allocated to Investment (dimensionless) Time path derived from results of optimization reported in [Cowles, Table IV-2, Optimal]. Intermediate points interpolated linearly. Points after 2075 estimated from [Cowles, Fig. IV-5].
- (095)Optimal_Invest_Frac - Investment Fraction derived from optimization.
- (072)Optimal_Invest_Switch - Switches Investment Frac between Nordhaus' time path and time path from optimization.

Uses:

- (067)Investment - Gross Investment ($/year)

(069) Net_CC_Impact = GHG_Red_Cost_Frac*Climate_Damage_Frac

Units: dmnl

Net Climate Change Impact [Omega(t)] (dimensionless) The fraction of output lost to GHG emissions reduction and climate change damage costs. [Cowles, pg. 13]

Causes:

- (030)Climate_Damage_Frac - Fraction of Output lost to combating Climate Change (1/Degrees C^2)
- (014)GHG_Red_Cost_Frac - Fraction of Output devoted to cost of GHG emissions reductions (dimensionless)

Uses:

- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

(070) Nord_Investment_Frac

Units: dmnl

Fraction of Output allocated to Investment (dimensionless) Time path derived from results of optimization reported in [Cowles, Table IV-2, Optimal]. Intermediate points interpolated linearly. Points after 2075 estimated from [Cowles, Fig. IV-5].

Uses:

- (068)Investment_Frac - Fraction of Output Invested May be switched between path derived from optimization and Nordhaus' path

(071) Norm_Return_Capital = 0.08

Units: 1/year

Uses:

- (054)Behav_Invest_Frac - A simple behavioral heuristic for investment; closely replicates results of the optimal time path.

(072) Optimal_Invest_Switch = 1

Units: dmnl

Switches Investment Frac between Nordhaus' time path and time path from optimization.

Uses:

- (068)Investment_Frac - Fraction of Output Invested May be switched between path derived from optimization and Nordhaus' path

(073) Output = Reference_Output*Net_CC_Impact

Units: $/year

Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

Causes:

- (069)Net_CC_Impact - Net Climate Change Impact [Omega(t)] (dimensionless) The fraction of output lost to GHG emissions reduction and climate change damage costs. [Cowles, pg. 13]
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

Uses:

- (077)Capital_Output_Ratio - Capital per Unit Output ($ per $/year)
- (002)CO2_Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]
- (057)Consumption - Consumption ($/year) Output less investment (savings).
- (067)Investment - Gross Investment ($/year)
- (080)Labor_Output_Ratio - Ratio of Labor to Output (persons/$)
- (081)Marg_Prod_Capital - Marginal Productivity of Capital
- (085)Net_Savings_Rate - Net Savings Rate Equal to the ratio of net investment to output.

(074) Output_in_1965 = 8.519e+012

Units: $/year

Output in 1965 ($/yr) [Managing Global Commons, pg. 21]

Uses:

- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(075) Reference_Output = Output_in_1965*Factor_Productivity*(Capital/INIT(Capital))^Capital_Elast_Output *(Population/INIT(Population))^(1-Capital_Elast_Output)

Units: $/year

Reference Output before effects of climate damage and emissions abatement are considered

Causes:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (064)Factor_Productivity - Total Factor Productivity [A(t)] (dimensionless) May be interpreted as level of technology. [Cowles pg. 17]
- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]
- (056)Capital_Elast_Output - Capital Elasticity of Output [alpha] (dimensionless) Derived from share of capital in national income. [Cowles, pg. 17]
- (074)Output_in_1965 - Output in 1965 ($/yr) [Managing Global Commons, pg. 21]

Uses:

- (078)Climate_Damages - Flow of damages from climate change.
- (082)Marg_Prod_Carbon - Marginal Productivity of CO2 Emissions
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]
- (086)Reduction_Costs - Flow of greenhouse gas abatement costs.
- (087)Reference_CO2_Emissions - Reference CO2 Emissions Emissions at normal CO2 intensity, with no abatement.

.Indices

(076) Capital_Labor_Ratio = Capital/Population

Units: $/person

Ratio of Capital Inputs to Labor Inputs ($/person)

Causes:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]

(077) Capital_Output_Ratio = Capital/Output

Units: $/($/year)

Capital per Unit Output ($ per $/year)

Causes:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

(078) Climate_Damages = Reference_Output*(1-Climate_Damage_Frac)

Units: $/year

Flow of damages from climate change.

Causes:

- (030)Climate_Damage_Frac - Fraction of Output lost to combating Climate Change (1/Degrees C^2)
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(079) CO2_And_CFC_Intens_Capital = CO2_Emiss/Capital

Units: TonC/year/$

CO2 and CFC Emissions per Unit of Capital (tons carbon equiv/year/$)

Causes:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (002)CO2_Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]

(080) Labor_Output_Ratio = Population/Output

Units: person/($/year)

Ratio of Labor to Output (persons/$)

Causes:

- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

(081) Marg_Prod_Capital = Capital_Elast_Output*Output/Capital

Units: 1/year

Marginal Productivity of Capital

Causes:

- (055)Capital - Capital ($) Capital stock in 1989 dollars. [Managing Global Commons, pg. 21]
- (056)Capital_Elast_Output - Capital Elasticity of Output [alpha] (dimensionless) Derived from share of capital in national income. [Cowles, pg. 17]
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

Uses:

- (083)Marg_Return_Capital - Marginal Return to Capital Equals the marginal product of capital less depreciation.

(082) Marg_Prod_Carbon = Reference_Output/Reference_CO2_Emissions*Red_Cost_Scale *Red_Cost_Nonlinearity *if_then_else(GHG_Reduction_Frac&gt0,(GHG_Reduction_Frac)^(Red_Cost_Nonlinearity -1),0)

Units: $/TonC

Marginal Productivity of CO2 Emissions

Causes:

- (015)GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.
- (023)Red_Cost_Nonlinearity - Nonlinearity of GHG Reduction Cost [b2] (dimensionless) [Cowles, pg. 13 & 24]
- (024)Red_Cost_Scale - Scale of GHG Reduction Cost [b1] (dimensionless) [Cowles, pg. 13 & 24]
- (087)Reference_CO2_Emissions - Reference CO2 Emissions Emissions at normal CO2 intensity, with no abatement.
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(083) Marg_Return_Capital = Marg_Prod_Capital-Depreciation_Rate

Units: 1/year

Marginal Return to Capital Equals the marginal product of capital less depreciation.

Causes:

- (059)Depreciation_Rate - Depreciation Rate [delta-k] (1/year) Note that Nordhaus assumes a 10-year capital life, then chooses a value of 0.065 to correct for the lack of compounding in the 10-year time step he uses. This is simply wrong, as the capital stock has an inflow as well as an outflow, and it is the net rate (investment-depreciation) that must be compounded. Also, using a value of 0.065 results in an average residence time of units in the capital stock of 15 years, even with the 10-year time step. I have preserved the value 0.065 for replication; a 15-year capital life is perfectly reasonable anyway. [Managing Global Commons, pg. 21]
- (081)Marg_Prod_Capital - Marginal Productivity of Capital

Uses:

- (054)Behav_Invest_Frac - A simple behavioral heuristic for investment; closely replicates results of the optimal time path.

(084) Net_Investment = Investment-Depreciation

Units: $/year

Net Investment Investment less depreciation

Causes:

- (058)Depreciation - Depreciation ($/year)
- (067)Investment - Gross Investment ($/year)

Uses:

- (085)Net_Savings_Rate - Net Savings Rate Equal to the ratio of net investment to output.

(085) Net_Savings_Rate = Net_Investment/Output

Units: dmnl

Net Savings Rate Equal to the ratio of net investment to output.

Causes:

- (084)Net_Investment - Net Investment Investment less depreciation
- (073)Output - Output [Q(t)] ($/year) Cobb-Douglas capital-labor formulation. [Cowles, pgs. 17 & 24]

(086) Reduction_Costs = (1-GHG_Red_Cost_Frac)*Reference_Output

Units: $/year

Flow of greenhouse gas abatement costs.

Causes:

- (014)GHG_Red_Cost_Frac - Fraction of Output devoted to cost of GHG emissions reductions (dimensionless)
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

(087) Reference_CO2_Emissions = Reference_Output*CO2_Intensity_of_Output

Units: TonC/year

Reference CO2 Emissions Emissions at normal CO2 intensity, with no abatement.

Causes:

- (006)CO2_Intensity_of_Output - Greenhouse Gas Intensity of Output [sigma(t)] (tons carbon equivalent/$) [Managing Global Commons, pg. 21] Conflicts with value reported on Cowles, pg. 24: .5368*.9875^(TIME-1990)/1000 = .7352/1000
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered

Uses:

- (082)Marg_Prod_Carbon - Marginal Productivity of CO2 Emissions

.Optimization

Structures for allowing optimization of decisions as an arbitrary time path.

(088) GHG_Red_Fracs[T] = INTEG(Zero,Init_GHG_Red_Fracs[T])

Units: dmnl

GHG Reduction Fractions at policy time T

Causes:

- (089)Init_GHG_Red_Fracs - GHG Reduction Fractions at policy time T
- (102)Zero - Dummy variable to provide a 0 with units 1/year.

Uses:

- (094)Optimal_GHG_Reduction_Frac - GHG Reduction Fraction derived from optimization.
- (098)Shift_Red - Shifts reduction stack values.

(089) Init_GHG_Red_Fracs[T] = 0,0,0,0,0,0,0,0,0,0

Units: dmnl

GHG Reduction Fractions at policy time T

Uses:

- (088)GHG_Red_Fracs - GHG Reduction Fractions at policy time T

(090) Init_Invest_Fracs[T] = 0.17,0.17,0.17,0.17,0.17,0.18,0.19,0.2,0.21,0.22

Units: dmnl

Investment Fractions at policy time T

Uses:

- (093)Invest_Fracs - Investment Fractions at policy time T

(091) Init_Policy_Times[T] = 2305,2205,2105,2050,2025,2005,2000,1995,1985,1965

Units: year

Year of implementation of Tth policy

Uses:

- (096)Policy_Times - Year of implementation of Tth policy

(092) Interpolation_Frac = max(0,zidz(Time-Policy_Times[T10],Policy_Times[T9]-Policy_Times[T10]))

Units: dmnl

Fraction of interval between policy times elapsed. (000)Time - Internally defined simulation time.

Causes:

- (096)Policy_Times - Year of implementation of Tth policy

Uses:

- (094)Optimal_GHG_Reduction_Frac - GHG Reduction Fraction derived from optimization.
- (095)Optimal_Invest_Frac - Investment Fraction derived from optimization.

(093) Invest_Fracs[T] = INTEG(Zero,Init_Invest_Fracs[T])

Units: dmnl

Investment Fractions at policy time T

Causes:

- (090)Init_Invest_Fracs - Investment Fractions at policy time T
- (102)Zero - Dummy variable to provide a 0 with units 1/year.

Uses:

- (095)Optimal_Invest_Frac - Investment Fraction derived from optimization.
- (097)Shift_Invest - Shifts investment stack values.

(094) Optimal_GHG_Reduction_Frac = GHG_Red_Fracs[T10] + (GHG_Red_Fracs[T9]-GHG_Red_Fracs[T10])*Interpolation_Frac

Units: dmnl

GHG Reduction Fraction derived from optimization.

Causes:

- (088)GHG_Red_Fracs - GHG Reduction Fractions at policy time T
- (092)Interpolation_Frac - Fraction of interval between policy times elapsed.

Uses:

- (015)GHG_Reduction_Frac - Fraction of Greenhouse Gas Emissions Abated [mu(t)] May be switched between path from optimization and Nordhaus' path.

(095) Optimal_Invest_Frac = Invest_Fracs[T10] + (Invest_Fracs[T9]-Invest_Fracs [T10])*Interpolation_Frac

Units: dmnl

Investment Fraction derived from optimization.

Causes:

- (093)Invest_Fracs - Investment Fractions at policy time T
- (092)Interpolation_Frac - Fraction of interval between policy times elapsed.

Uses:

- (068)Investment_Frac - Fraction of Output Invested May be switched between path derived from optimization and Nordhaus' path

(096) Policy_Times[T] = INTEG(0,Init_Policy_Times[T])

Units: year

Year of implementation of Tth policy

Causes:

- (091)Init_Policy_Times - Year of implementation of Tth policy

Uses:

- (092)Interpolation_Frac - Fraction of interval between policy times elapsed.
- (099)shift_switch -
- (100)Shift_Times - Shifts time stack values.

(097) Shift_Invest =
SHIFT_IF_TRUE(Invest_Fracs[T1],shift_switch=1,T10,0,Invest_Fracs [T1])

Units: dmnl

Shifts investment stack values. (000)T10 -

Causes:

- (093)Invest_Fracs - Investment Fractions at policy time T
- (099)shift_switch -

(098) Shift_Red =
SHIFT_IF_TRUE(GHG_Red_Fracs[T1],shift_switch=1,T10,0,GHG_Red_Fracs [T1])

Units: dmnl

Shifts reduction stack values. (000)T10 -

Causes:

- (088)GHG_Red_Fracs - GHG Reduction Fractions at policy time T
- (099)shift_switch -

(099) shift_switch = if_then_else(Time > Policy_Times[T9],1,0)

Units: dmnl

(000)Time - Internally defined simulation time.

Causes:

- (096)Policy_Times - Year of implementation of Tth policy

Uses:

- (097)Shift_Invest - Shifts investment stack values.
- (098)Shift_Red - Shifts reduction stack values.
- (100)Shift_Times - Shifts time stack values.

(100) Shift_Times = SHIFT_IF_TRUE(Policy_Times[T1],shift_switch=1,T10,0,Policy_Times [T1])

Units: dmnl

Shifts time stack values. (000)T10 -

Causes:

- (096)Policy_Times - Year of implementation of Tth policy
- (099)shift_switch -

(101) T : (T1-T10) Subscript for policy optimization arrays

(102) Zero = 0

Units: 1/year

Dummy variable to provide a 0 with units 1/year.

Uses:

- (088)GHG_Red_Fracs - GHG Reduction Fractions at policy time T
- (093)Invest_Fracs - Investment Fractions at policy time T

.Population

(103) Consumption_per_Cap = Consumption/Population

Units: $/person/year

Consumption per Capita ($/person/year)

Causes:

- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]
- (057)Consumption - Consumption ($/year) Output less investment (savings).

Uses:

- (116)Utility - Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

(104) Decline_Pop_Gr_Rt = Pop_Growth_Rate*Pop_Gr_Rt_Decline_Rt

Units: 1/year/year

Decline of Population Growth Rate (1/year/year)

Causes:

- (107)Pop_Growth_Rate - Population Growth Rate [gpop(t)] (1/year) Note that Nordhaus decompounds the decadal rate of .224 to yield an annual rate of .0203; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]
- (106)Pop_Gr_Rt_Decline_Rt - Rate of Decline of Population Growth Rate [delta-pop] (1/year) 19.5 % per decade. [Cowles, pg. 16] Real data looks closer to 10 % per decade before 1990. Note that Nordhaus decompounds the decadal rate of .195 to yield an annual rate of .02; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

Uses:

- (107)Pop_Growth_Rate - Population Growth Rate [gpop(t)] (1/year) Note that Nordhaus decompounds the decadal rate of .224 to yield an annual rate of .0203; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

(105) Net_Pop_Incr = Population*Pop_Growth_Rate

Units: person/year

Net Population Increase (persons/year)

Causes:

- (107)Pop_Growth_Rate - Population Growth Rate [gpop(t)] (1/year) Note that Nordhaus decompounds the decadal rate of .224 to yield an annual rate of .0203; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]
- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]

Uses:

- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]

(106) Pop_Gr_Rt_Decline_Rt = 0.0195

Units: 1/year

Rate of Decline of Population Growth Rate [delta-pop] (1/year) 19.5 % per decade. [Cowles, pg. 16] Real data looks closer to 10 % per decade before 1990. Note that Nordhaus decompounds the decadal rate of .195 to yield an annual rate of .02; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

Uses:

- (104)Decline_Pop_Gr_Rt - Decline of Population Growth Rate (1/year/year)

(107) Pop_Growth_Rate = INTEG(- Decline_Pop_Gr_Rt, 0.0224)

Units: 1/year

Population Growth Rate [gpop(t)] (1/year) Note that Nordhaus decompounds the decadal rate of .224 to yield an annual rate of .0203; I have simply divided by 10 to convert the decadal rate to an annual rate. [Managing Global Commons, pg. 21]

Causes:

- (104)Decline_Pop_Gr_Rt - Decline of Population Growth Rate (1/year/year)

Uses:

- (104)Decline_Pop_Gr_Rt - Decline of Population Growth Rate (1/year/year)
- (105)Net_Pop_Incr - Net Population Increase (persons/year)

(108) Population = INTEG(Net_Pop_Incr, 3.369e+009)

Units: person

Population [L(t)] (persons) [Cowles, pg. 16]

Causes:

- (105)Net_Pop_Incr - Net Population Increase (persons/year)

Uses:

- (076)Capital_Labor_Ratio - Ratio of Capital Inputs to Labor Inputs ($/person)
- (103)Consumption_per_Cap - Consumption per Capita ($/person/year)

- (080)Labor_Output_Ratio - Ratio of Labor to Output (persons/$)
- (105)Net_Pop_Incr - Net Population Increase (persons/year)
- (075)Reference_Output - Reference Output before effects of climate damage and emissions abatement are considered
- (116)Utility - Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

.Utility

(109) Base_Year = 1989

Units: year

Base Year for Discounting (year) Model is denominated in 1989 dollars, and discounting is performed relative to 1989.

Uses:

- (111)Discount_Factor -

(110) Cum_Disc_Utility = INTEG(Discounted_Utility, 0)

Units: utiles

Cumulative Discounted Utility (log$) This is Nordhaus' objective function. The results in [Science, Table 1] apparently accumulate only the period from 1990-2045. [Cowles, pg. 15]

Causes:

- (112)Discounted_Utility - Discounted Current Utility (log$/year) Current Utility discounted to 1989.

(111) Discount_Factor = EXP(-Rate_of_Time_Pref*(Time-Base_Year))

Units: dmnl

(000)Time - Internally defined simulation time.

Causes:

- (109)Base_Year - Base Year for Discounting (year) Model is denominated in 1989 dollars, and discounting is performed relative to 1989.
- (114)Rate_of_Time_Pref - Pure Rate of Social Time Preference [rho] (1/year) The social discount rate. [Cowles, pg. 15]

Uses:

- (112)Discounted_Utility - Discounted Current Utility (log$/year) Current Utility discounted to 1989.

(112) Discounted_Utility = Utility*Discount_Factor

Units: utiles/year

Discounted Current Utility (log$/year) Current Utility discounted to 1989.

Causes:

- (111)Discount_Factor -
- (116)Utility - Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

Uses:

- (110)Cum_Disc_Utility - Cumulative Discounted Utility (log$) This is Nordhaus' objective function. The results in [Science, Table 1] apparently accumulate only the period from 1990-2045. [Cowles, pg. 15]

(113) Rate_of_Inequal_Aversion = 1

Units: dmnl

Rate of Inequality Aversion [alpha] (dimensionless) Measure of marginal utility or social valuation of different levels of consumption. [Cowles, pg. 16]

Uses:

- (116)Utility - Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

(114) Rate_of_Time_Pref = 0.03

Units: 1/year

Pure Rate of Social Time Preference [rho] (1/year) The social discount rate. [Cowles, pg. 15]

Uses:

- (111)Discount_Factor -

(115) Ref_Cons_per_Cap = 1000

Units: $/person/year

Reference Consumption per Capita

Uses:

- (116)Utility - Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

(116) Utility = Utility_Coeff*Population*if_then_else(Rate_of_Inequal_Aversion =1,LN(Consumption_per_Cap/Ref_Cons_per_Cap), ((Consumption_per_Cap/Ref_Cons_per_Cap)^(1-Rate_of_Inequal_Aversion)-1)/(1-Rate_of_Inequal_Aversion))

Units: utiles/year

Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

Causes:

- (108)Population - Population [L(t)] (persons) [Cowles, pg. 16]
- (103)Consumption_per_Cap - Consumption per Capita ($/person/year)
- (113)Rate_of_Inequal_Aversion - Rate of Inequality Aversion [alpha] (dimensionless) Measure of marginal utility or social valuation of different levels of consumption. [Cowles, pg. 16]
- (115)Ref_Cons_per_Cap - Reference Consumption per Capita
- (117)Utility_Coeff - Reference Rate of Utility Generation (utiles/person/year)

Uses:

- (112)Discounted_Utility - Discounted Current Utility (log$/year) Current Utility discounted to 1989.

(117) Utility_Coeff = 1

Units: utiles/person/year

Reference Rate of Utility Generation (utiles/person/year)

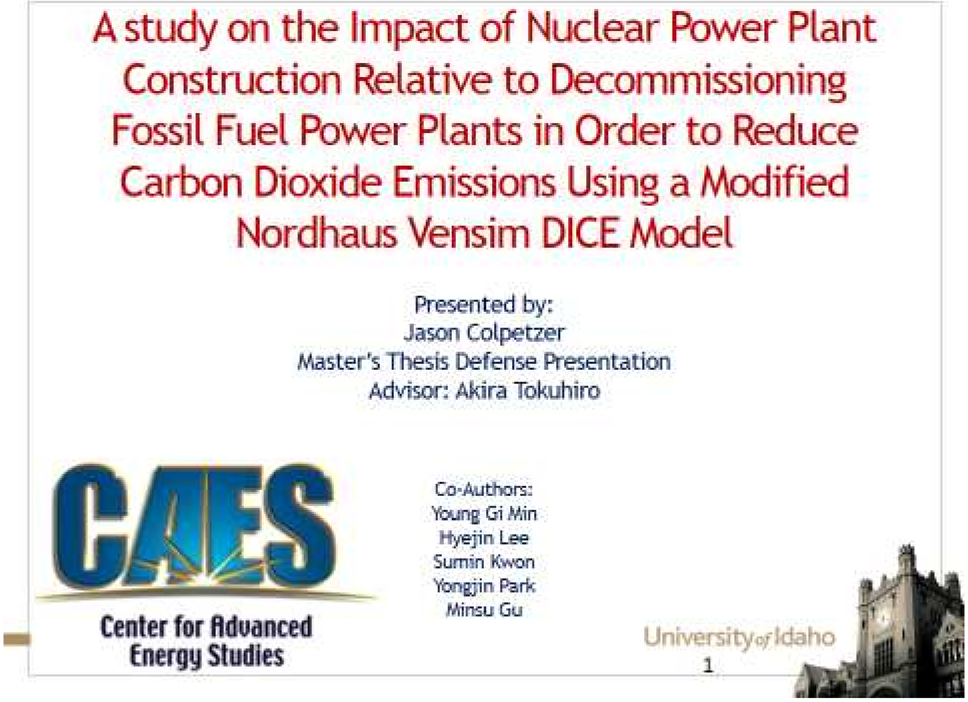
Uses:

- (116)Utility - Current Utility [U(t)] (utiles/year) Reduces to Logarithmic or Bernoullian utility function: Population*(Log(Consumption_per_Cap)) when the Rate of Inequality Aversion -&gt 1 Note that doubling your population with half the consumption per capita is an improvement with this formula. [Cowles, pg. 16]

  Your Title/Your Name/Your e-mail

Appendix B

Thesis Defense Presentation

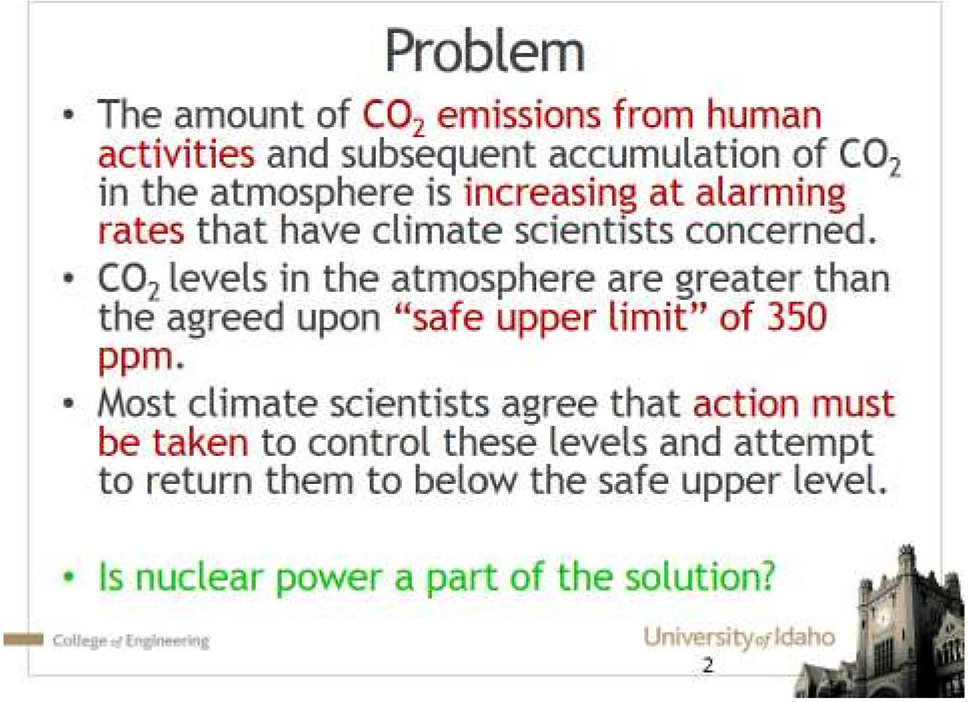


A study on the Impact of Nuclear Power Plant Construction Relative to Decommissioning Fossil Fuel Power Plants in Order to Reduce Carbon Dioxide Emissions Using a Modified Nordhaus Vensim DICE Model

Presented by:
Jason Colpetzer
Master's Thesis Defense Presentation
Advisor: Akira Tokuhiro

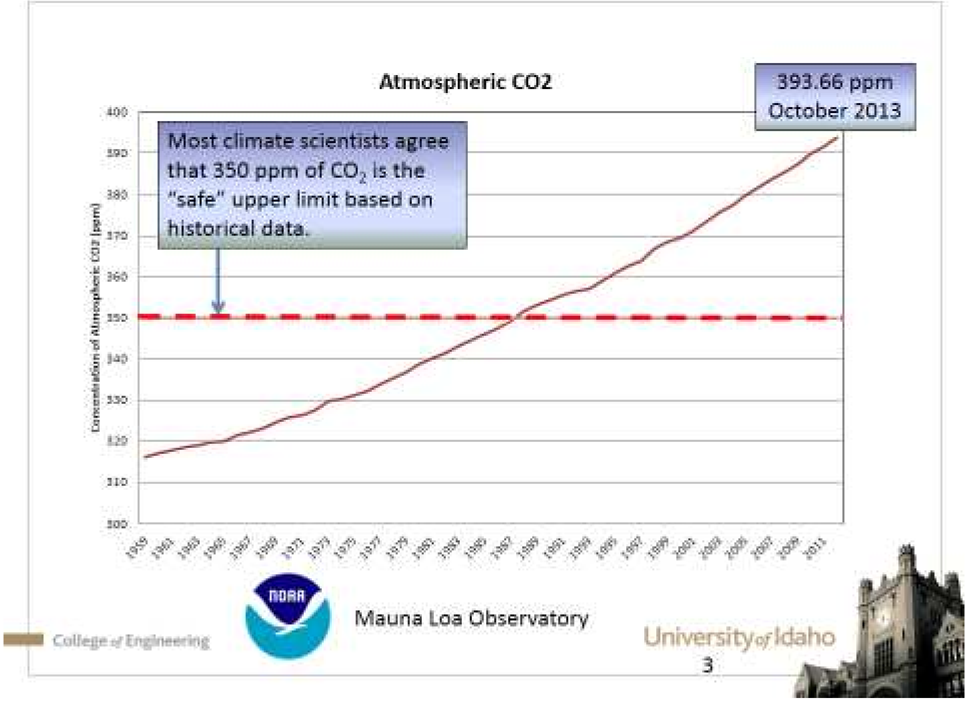
Co-Authors:
Young Gi Min
Hyejin Lee
Sumin Kwon
Yongjin Park
Minsu Gu

Center for Advanced Energy Studies



Problem

- The amount of CO_2 emissions from human activities and subsequent accumulation of CO_2 in the atmosphere is increasing at alarming rates that have climate scientists concerned.
- CO_2 levels in the atmosphere are greater than the agreed upon "safe upper limit" of 350 ppm.
- Most climate scientists agree that action must be taken to control these levels and attempt to return them to below the safe upper level.
- Is nuclear power a part of the solution?



Atmospheric CO2

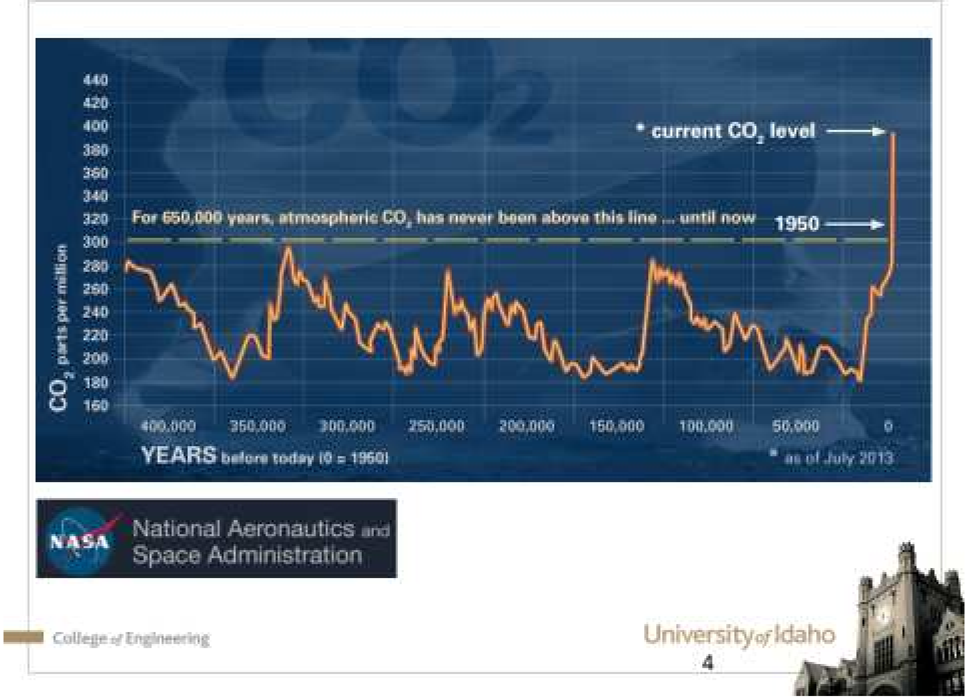
393.66 ppm
October 2013

Most climate scientists agree that 350 ppm of CO_2 is the "safe" upper limit based on historical data.

Mauna Loa Observatory

College of Engineering

University of Idaho



* current CO_2 level

For 650,000 years, atmospheric CO_2 has never been above this line ... until now

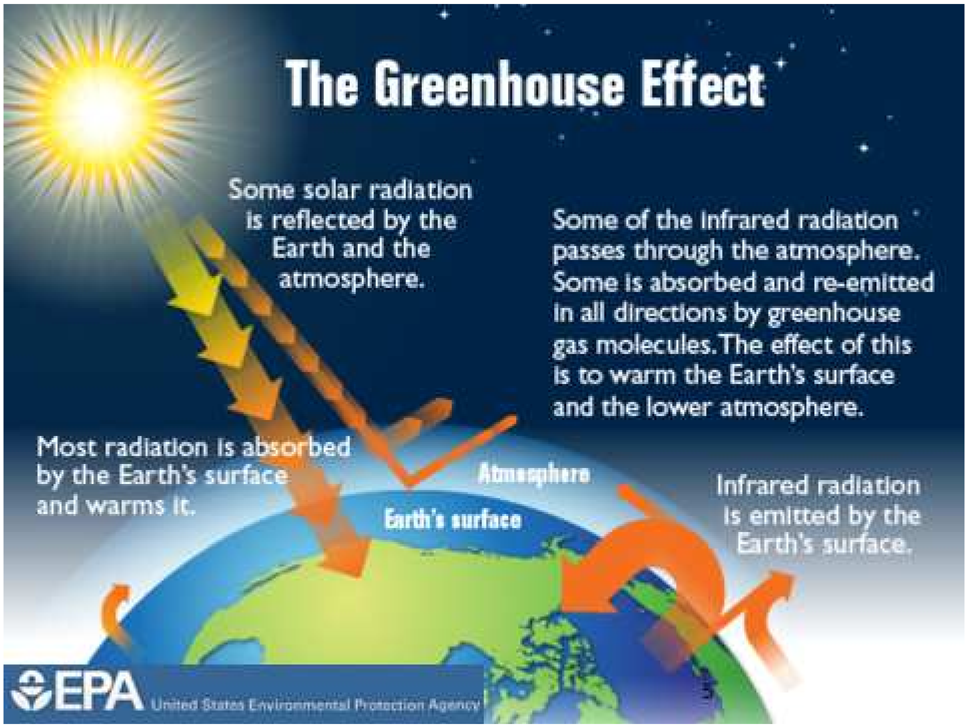
1950

* as of July 2013

National Aeronautics and Space Administration

College of Engineering

University of Idaho



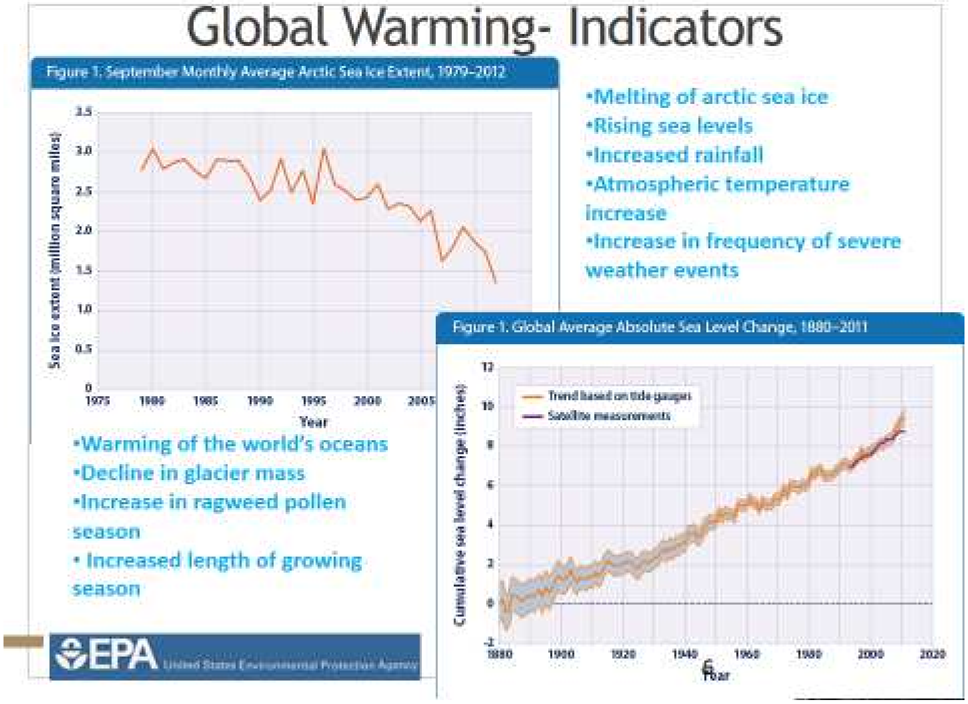
The Greenhouse Effect

Some solar radiation is reflected by the Earth and the atmosphere.

Some of the infrared radiation passes through the atmosphere. Some is absorbed and re-emitted in all directions by greenhouse gas molecules. The effect of this is to warm the Earth's surface and the lower atmosphere.

Most radiation is absorbed by the Earth's surface and warms it.

Infrared radiation is emitted by the Earth's surface.



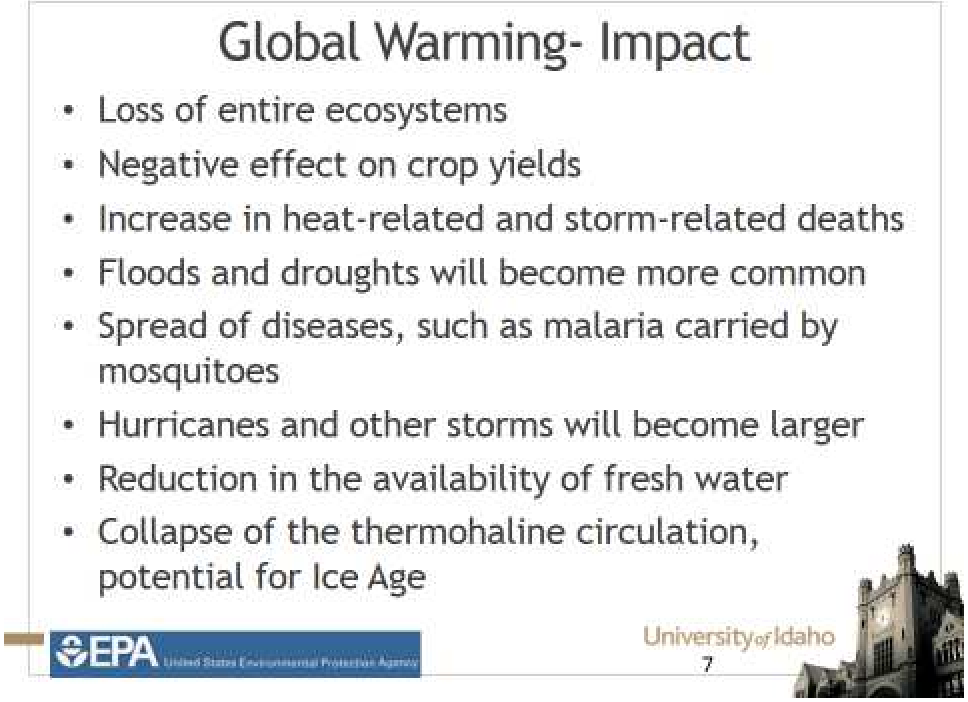
Global Warming- Indicators

Figure 1. September Monthly Average Arctic Sea Ice Extent, 1979–2012

- Melting of arctic sea ice
- Rising sea levels
- Increased rainfall
- Atmospheric temperature increase
- Increase in frequency of severe weather events

Figure 1. Global Average Absolute Sea Level Change, 1880–2011

- Warming of the world's oceans
- Decline in glacier mass
- Increase in ragweed pollen season
- Increased length of growing season



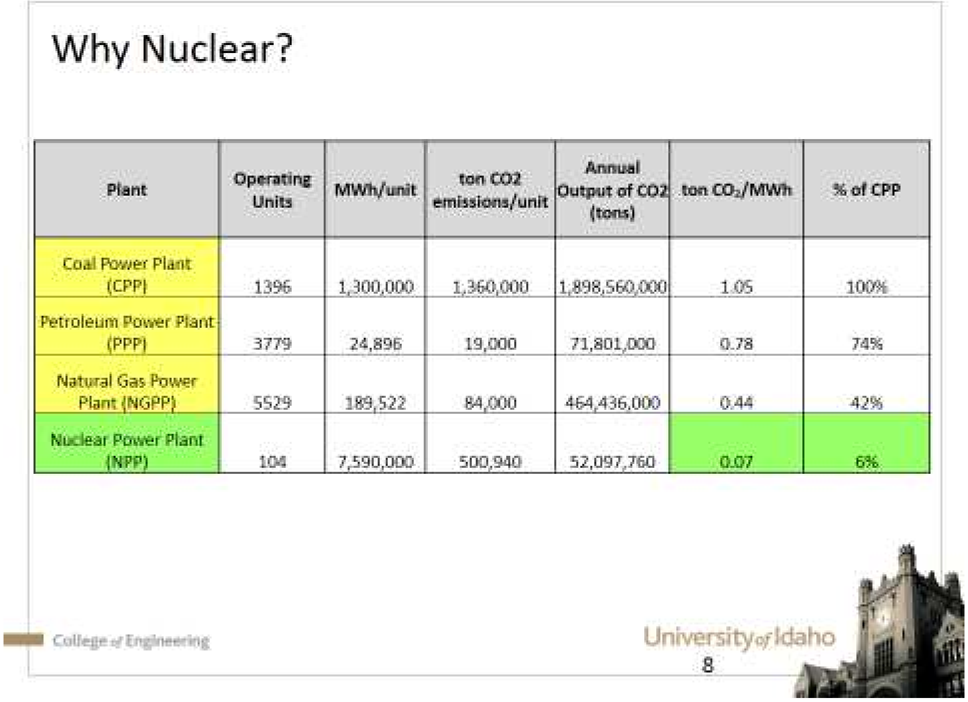
Global Warming- Impact

- Loss of entire ecosystems
- Negative effect on crop yields
- Increase in heat-related and storm-related deaths
- Floods and droughts will become more common
- Spread of diseases, such as malaria carried by mosquitoes
- Hurricanes and other storms will become larger
- Reduction in the availability of fresh water
- Collapse of the thermohaline circulation, potential for Ice Age

EPA United States Environmental Protection Agency

University of Idaho

7



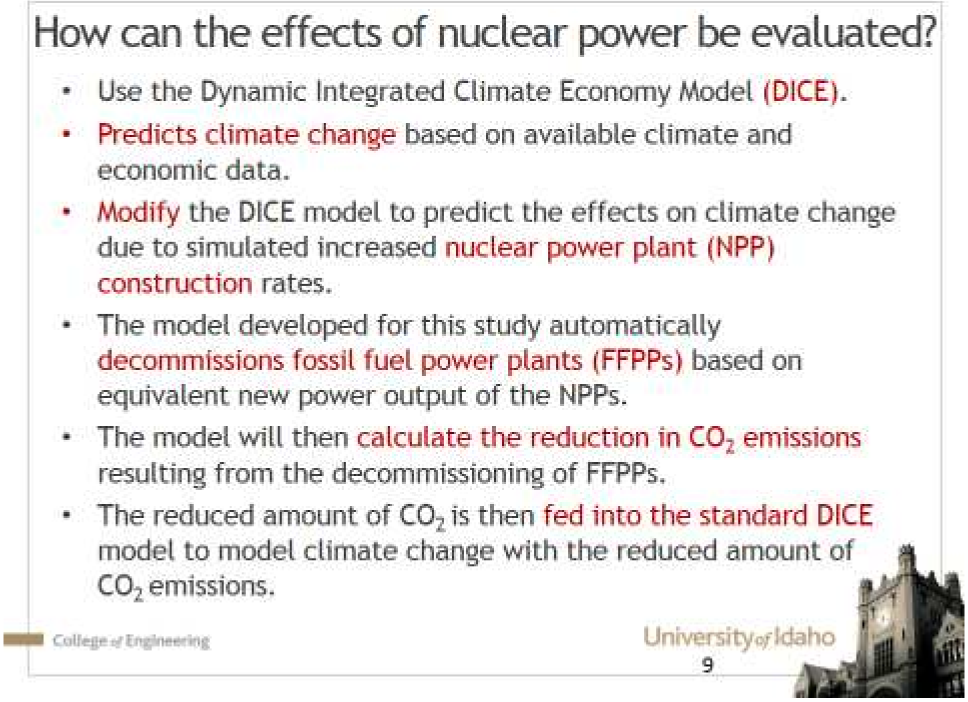
Why Nuclear?

Plant	Operating Units	MWh/unit	ton CO2 emissions/unit	Annual Output of CO2 (tons)	ton CO_2/MWh	% of CPP
Coal Power Plant (CPP)	1396	1,300,000	1,360,000	1,898,560,000	1.05	100%
Petroleum Power Plant (PPP)	3779	24,896	19,000	71,801,000	0.78	74%
Natural Gas Power Plant (NGPP)	5529	189,522	84,000	464,436,000	0.44	42%
Nuclear Power Plant (NPP)	104	7,590,000	500,940	52,097,760	0.07	6%

College of Engineering

University of Idaho

8

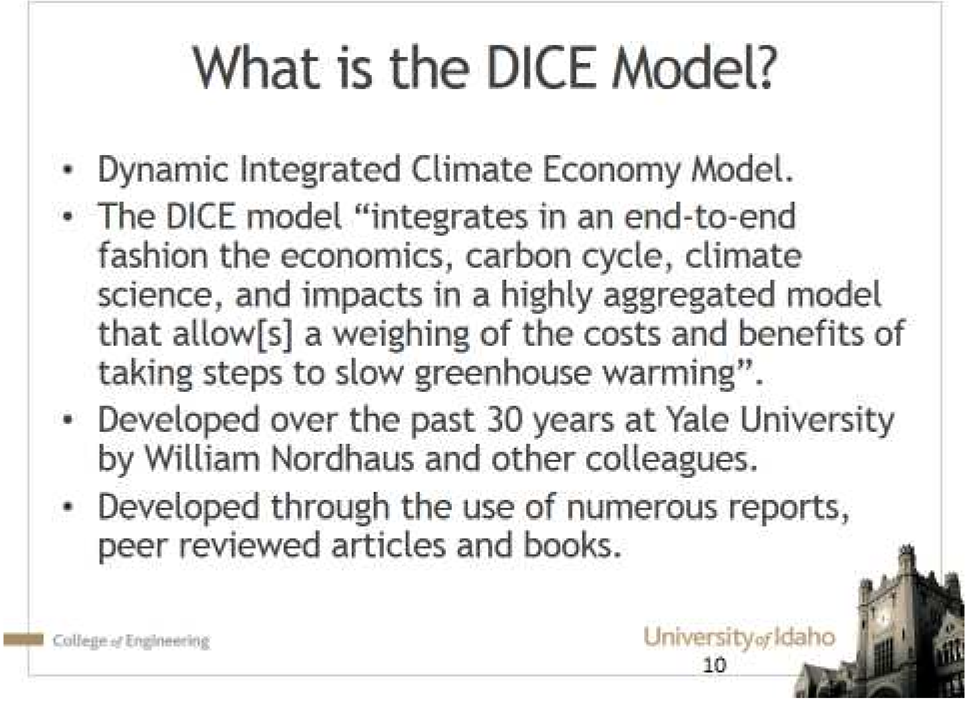


How can the effects of nuclear power be evaluated?

- Use the Dynamic Integrated Climate Economy Model (DICE).
- Predicts climate change based on available climate and economic data.
- Modify the DICE model to predict the effects on climate change due to simulated increased nuclear power plant (NPP) construction rates.
- The model developed for this study automatically decommissions fossil fuel power plants (FFPPs) based on equivalent new power output of the NPPs.
- The model will then calculate the reduction in CO_2 emissions resulting from the decommissioning of FFPPs.
- The reduced amount of CO_2 is then fed into the standard DICE model to model climate change with the reduced amount of CO_2 emissions.

College of Engineering

University of Idaho

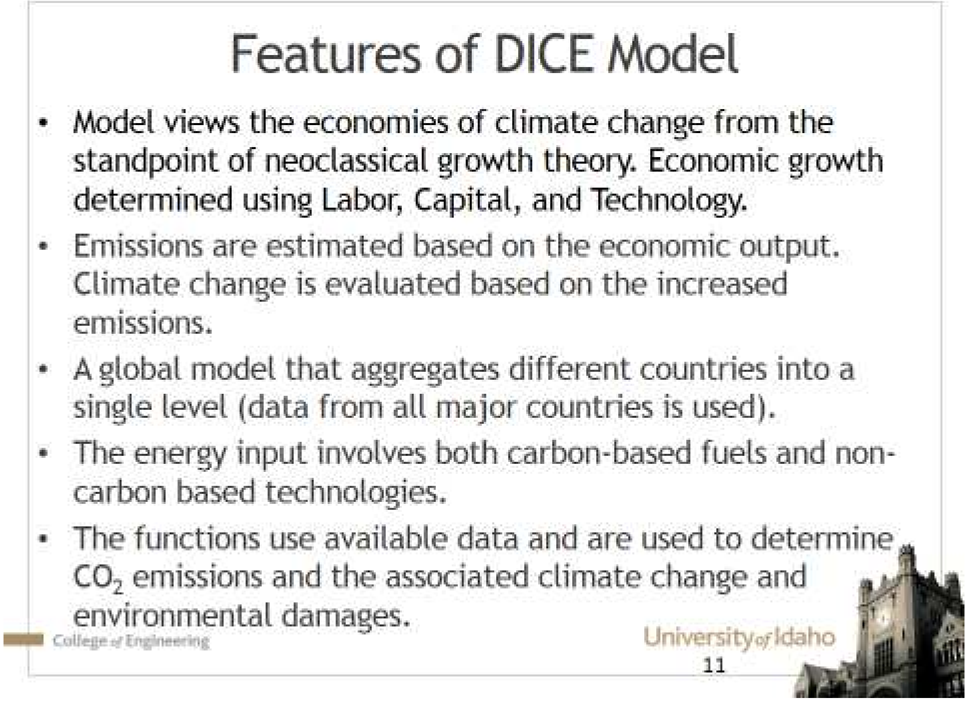


What is the DICE Model?

- Dynamic Integrated Climate Economy Model.
- The DICE model "integrates in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allow[s] a weighing of the costs and benefits of taking steps to slow greenhouse warming".
- Developed over the past 30 years at Yale University by William Nordhaus and other colleagues.
- Developed through the use of numerous reports, peer reviewed articles and books.

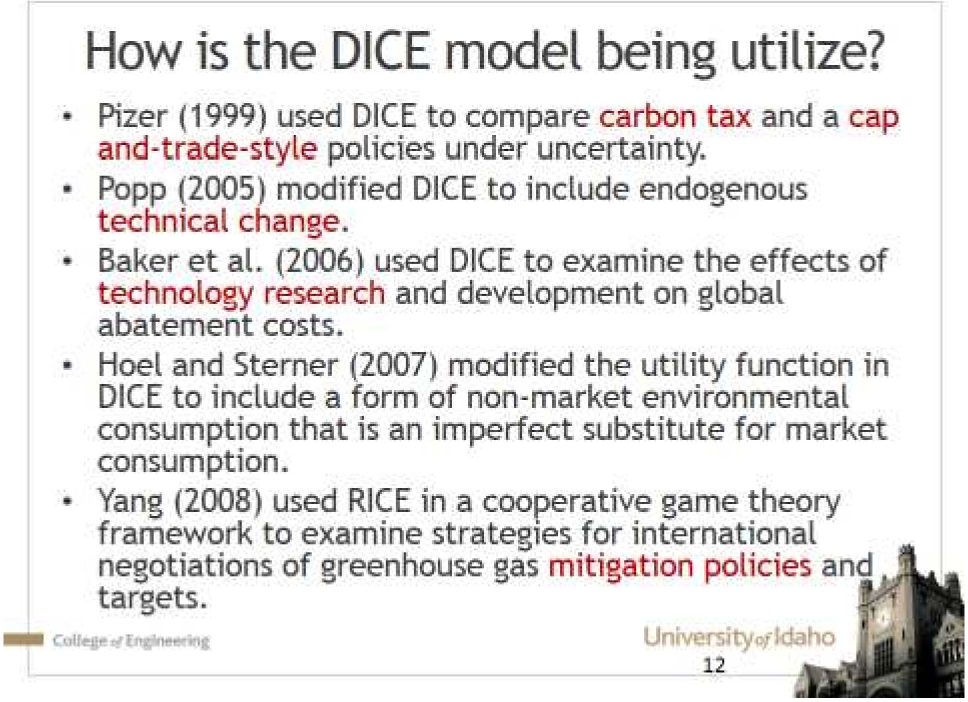
College of Engineering

University of Idaho



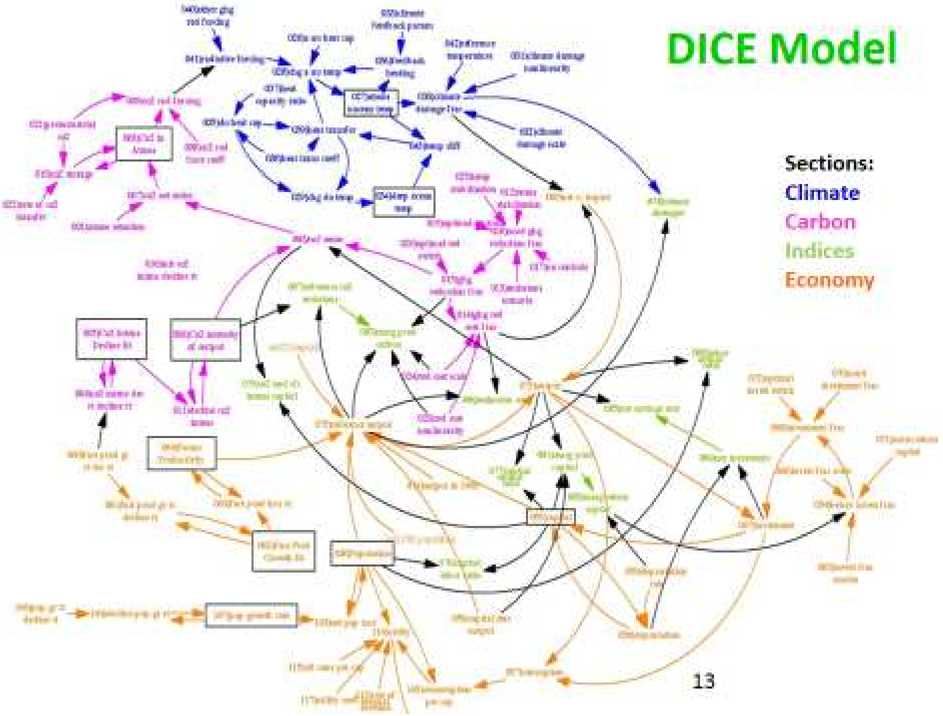
Features of DICE Model

- Model views the economies of climate change from the standpoint of neoclassical growth theory. Economic growth determined using Labor, Capital, and Technology.
- Emissions are estimated based on the economic output. Climate change is evaluated based on the increased emissions.
- A global model that aggregates different countries into a single level (data from all major countries is used).
- The energy input involves both carbon-based fuels and non-carbon based technologies.
- The functions use available data and are used to determine CO_2 emissions and the associated climate change and environmental damages.



How is the DICE model being utilize?

- Pizer (1999) used DICE to compare carbon tax and a cap and-trade-style policies under uncertainty.
- Popp (2005) modified DICE to include endogenous technical change.
- Baker et al. (2006) used DICE to examine the effects of technology research and development on global abatement costs.
- Hoel and Sterner (2007) modified the utility function in DICE to include a form of non-market environmental consumption that is an imperfect substitute for market consumption.
- Yang (2008) used RICE in a cooperative game theory framework to examine strategies for international negotiations of greenhouse gas mitigation policies and targets.

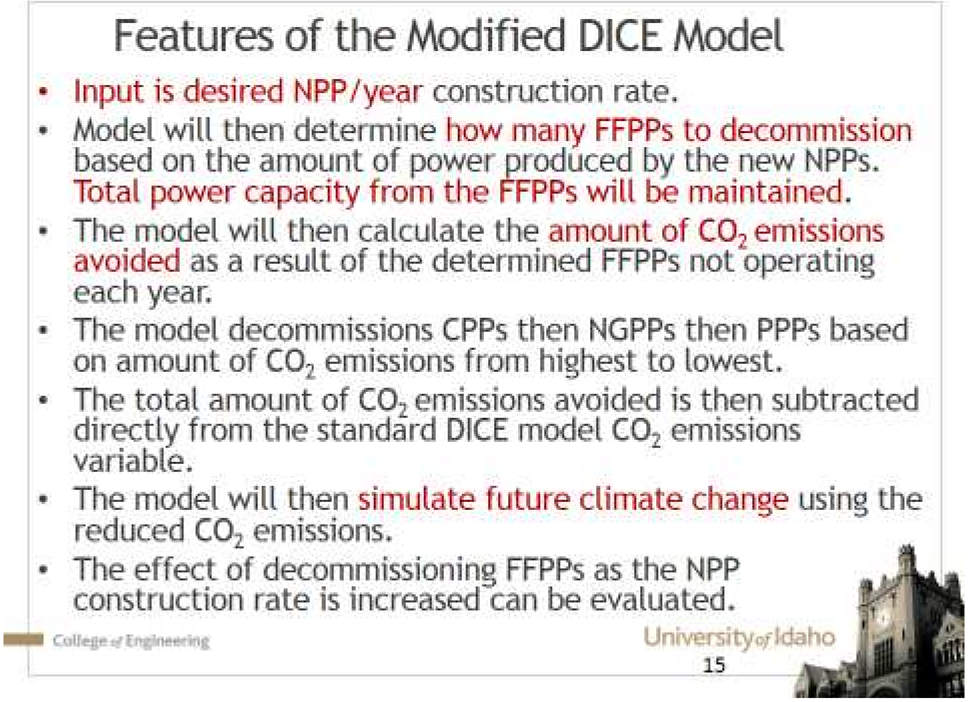


DICE Model

Sections:
Climate
Carbon
Indices
Economy

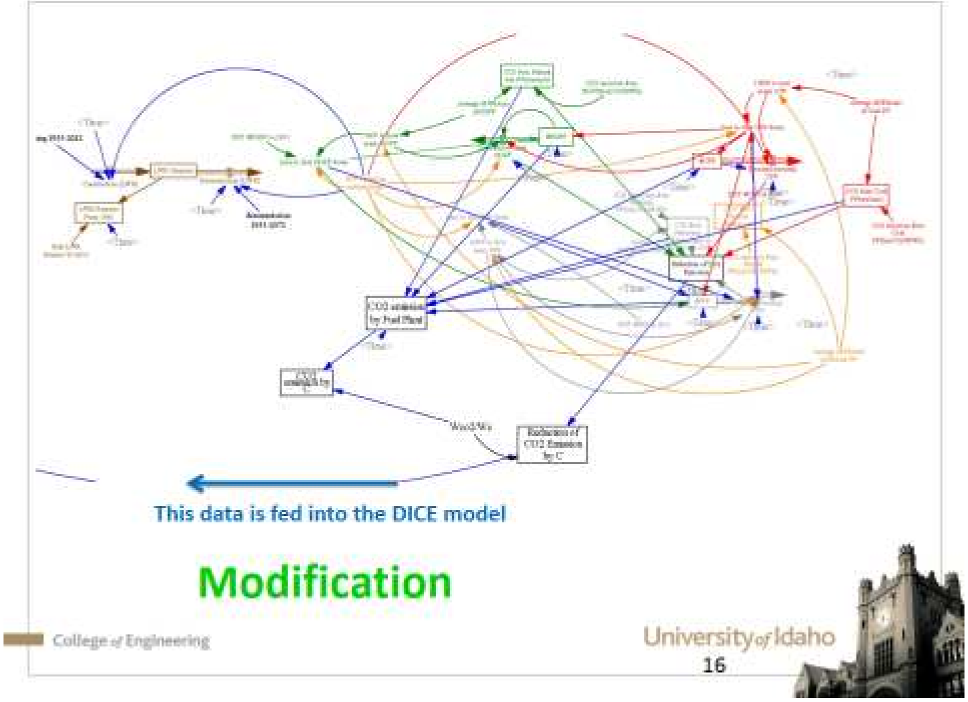
Modification to the DICE Model

- Vensim Standard and Vensim Professional software were used to recreate the DICE model. The DICE model was recreated by Korea West interns working for Dr. Akira Tokuhiro.
- Vensim software is a modeling tool that allows you to conceptualize, document, simulate, analyze, and optimize models of dynamic systems.
- Model replicated for Vensim by Tom Fiddaman of MIT.
- Added features to model to simulate the amount of CO_2 emissions avoided when a selected manufacturing rate of NPPs is used to replace the existing fleet of FFPPs in the U.S.
- Climate change is then modeled using the reduced emissions values.



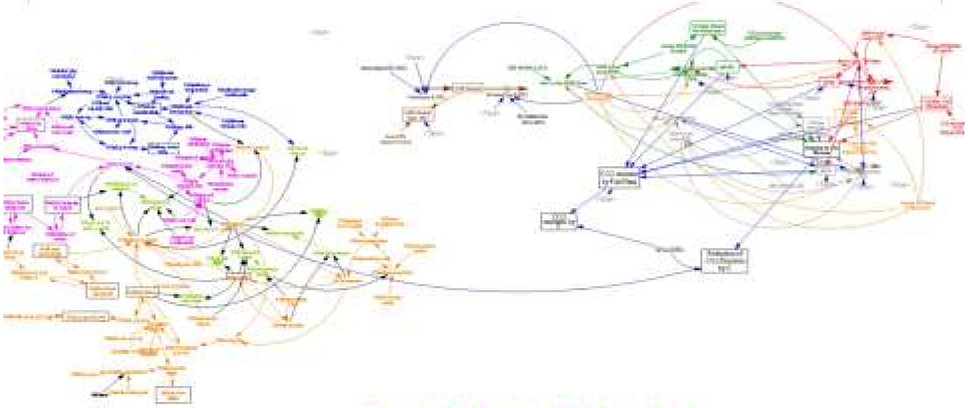
Features of the Modified DICE Model

- Input is desired NPP/year construction rate.
- Model will then determine how many FFPPs to decommission based on the amount of power produced by the new NPPs. Total power capacity from the FFPPs will be maintained.
- The model will then calculate the amount of CO_2 emissions avoided as a result of the determined FFPPs not operating each year.
- The model decommissions CPPs then NGPPs then PPPs based on amount of CO_2 emissions from highest to lowest.
- The total amount of CO_2 emissions avoided is then subtracted directly from the standard DICE model CO_2 emissions variable.
- The model will then simulate future climate change using the reduced CO_2 emissions.
- The effect of decommissioning FFPPs as the NPP construction rate is increased can be evaluated.



This data is fed into the DICE model

Modification

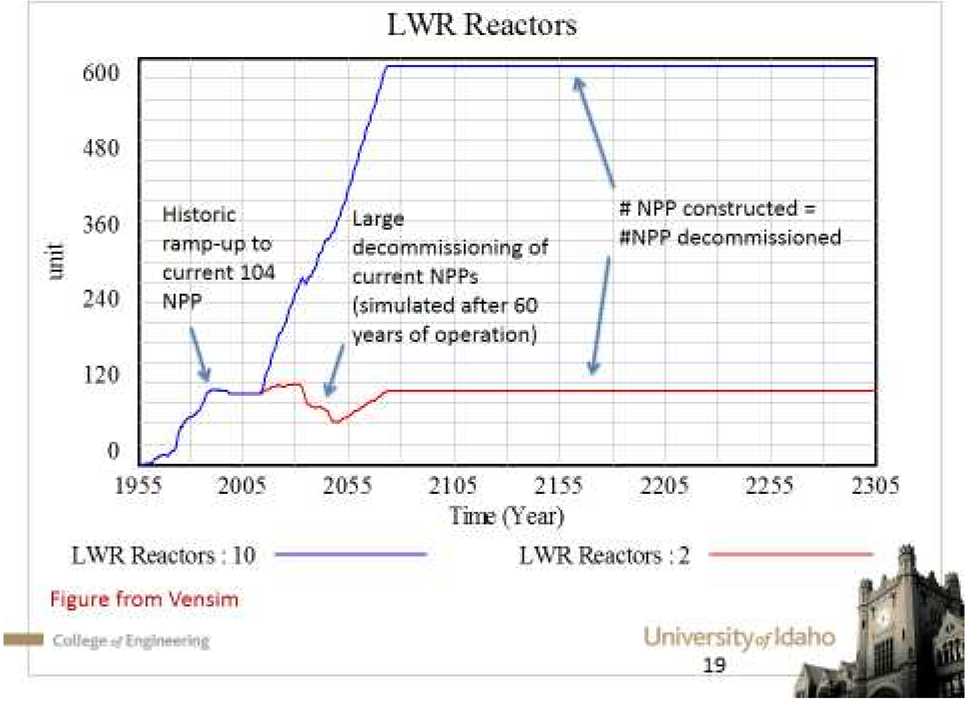


Combined Model

- Number of years until all of the FFPPs in the U.S. have been replaced by NPPs based on the different production rates.
- Model will not continue to further reduce CO_2 emissions after all of the FFPPs have been decommissioned.
- Model only calculates CO_2 reduction from decommissioned FFPPs.

NPP Construction Rate (NPP/yr)	Time to Replace FFPPs (yr)
0	N/A
1	N/A
2	195
3	130
4	97
5	78
10	39
25	16
50	8
100	4
250	2
500	1
1000	1

10704 FFPPs Total



Historic ramp-up to current 104 NPP

Large decommissioning of current NPPs (simulated after 60 years of operation)

NPP constructed = #NPP decommissioned

Figure from Vensim

College of Engineering

University of Idaho

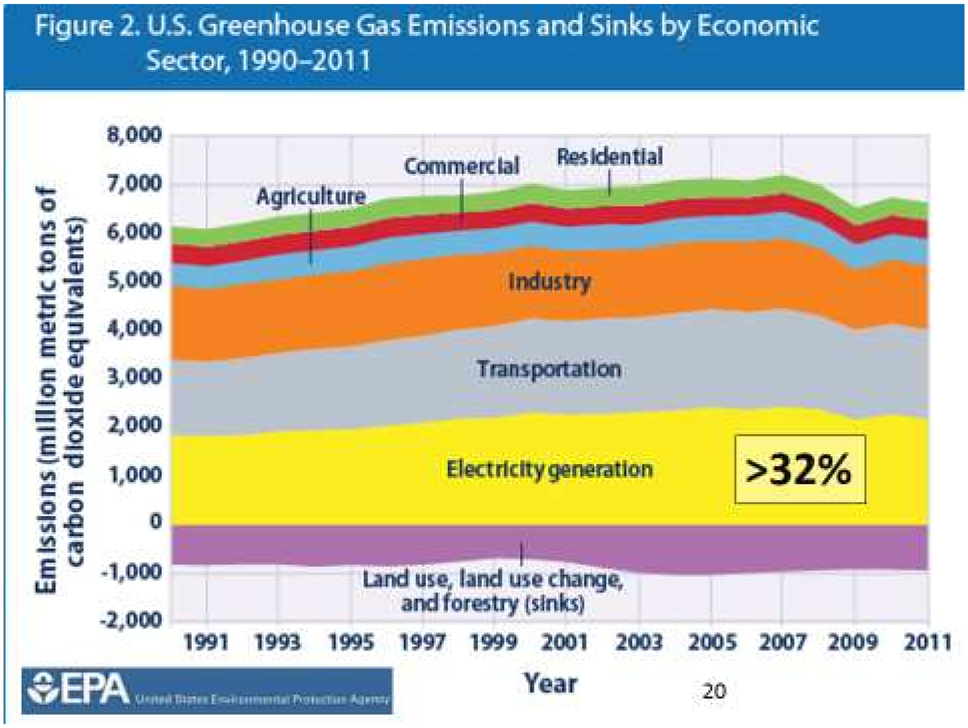
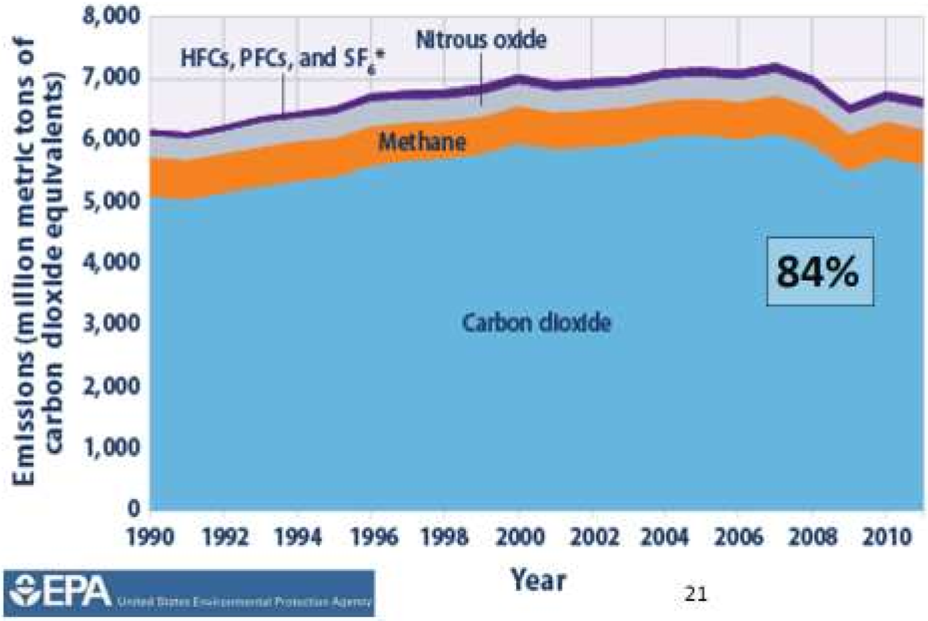
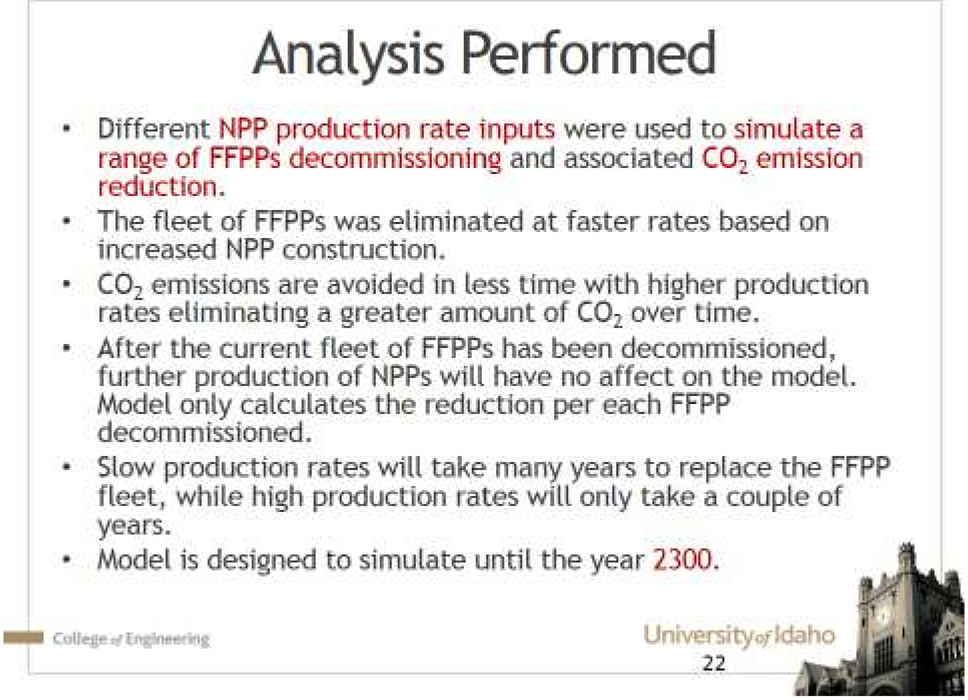


Figure 2. U.S. Greenhouse Gas Emissions and Sinks by Economic Sector, 1990–2011

>32%

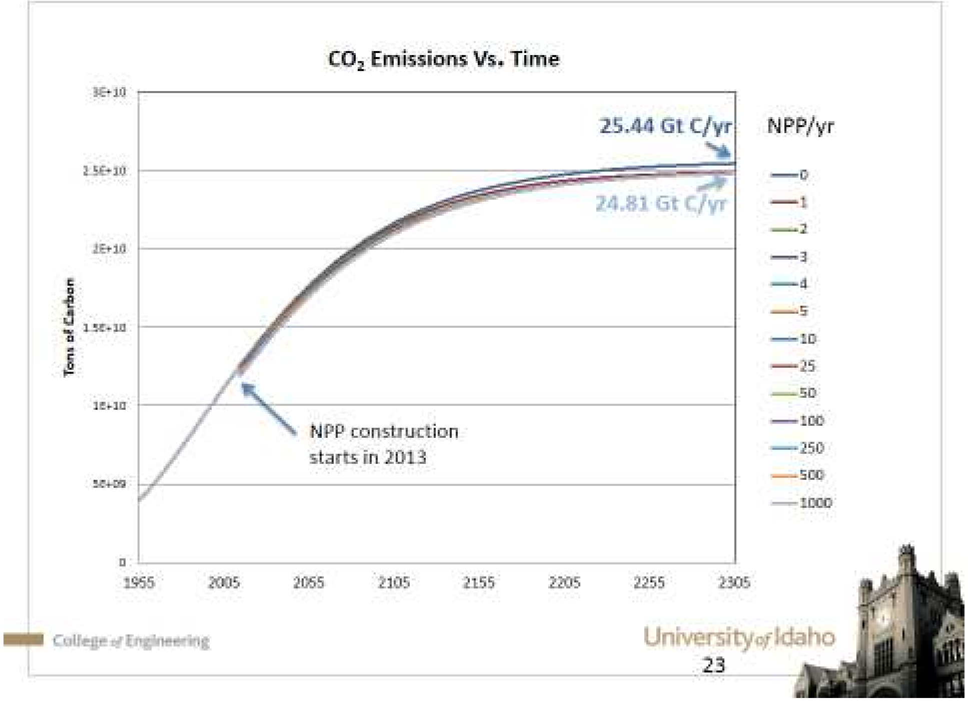
Figure 1. U.S. Greenhouse Gas Emissions by Gas, 1990–2011





Analysis Performed

- Different NPP production rate inputs were used to simulate a range of FFPPs decommissioning and associated CO_2 emission reduction.
- The fleet of FFPPs was eliminated at faster rates based on increased NPP construction.
- CO_2 emissions are avoided in less time with higher production rates eliminating a greater amount of CO_2 over time.
- After the current fleet of FFPPs has been decommissioned, further production of NPPs will have no affect on the model. Model only calculates the reduction per each FFPP decommissioned.
- Slow production rates will take many years to replace the FFPP fleet, while high production rates will only take a couple of years.
- Model is designed to simulate until the year 2300.



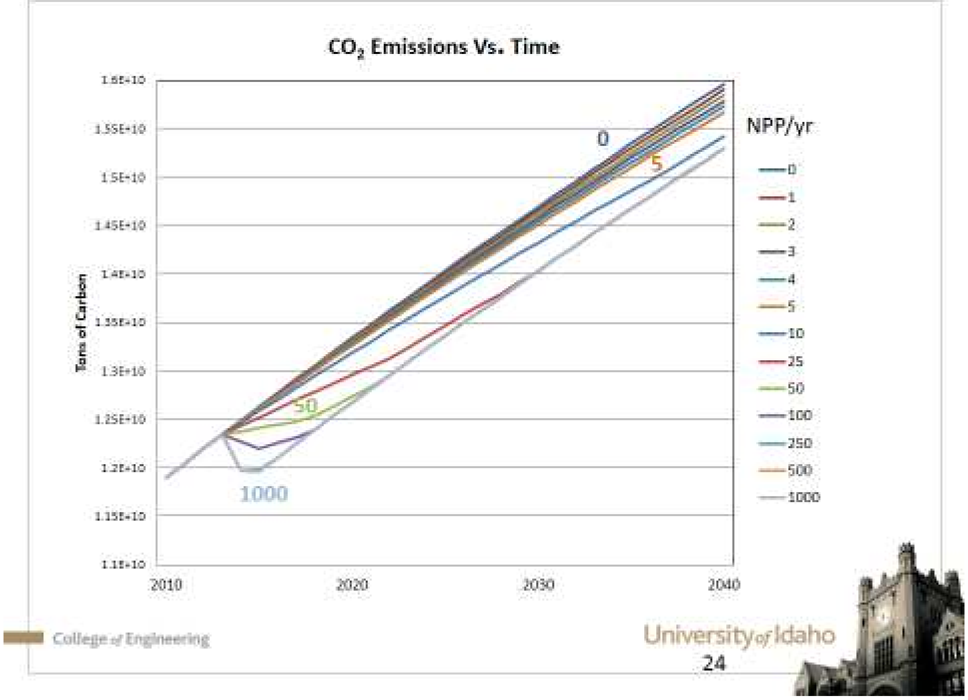
CO$_2$ Emissions Vs. Time

NPP construction starts in 2013

College of Engineering

University of Idaho

23

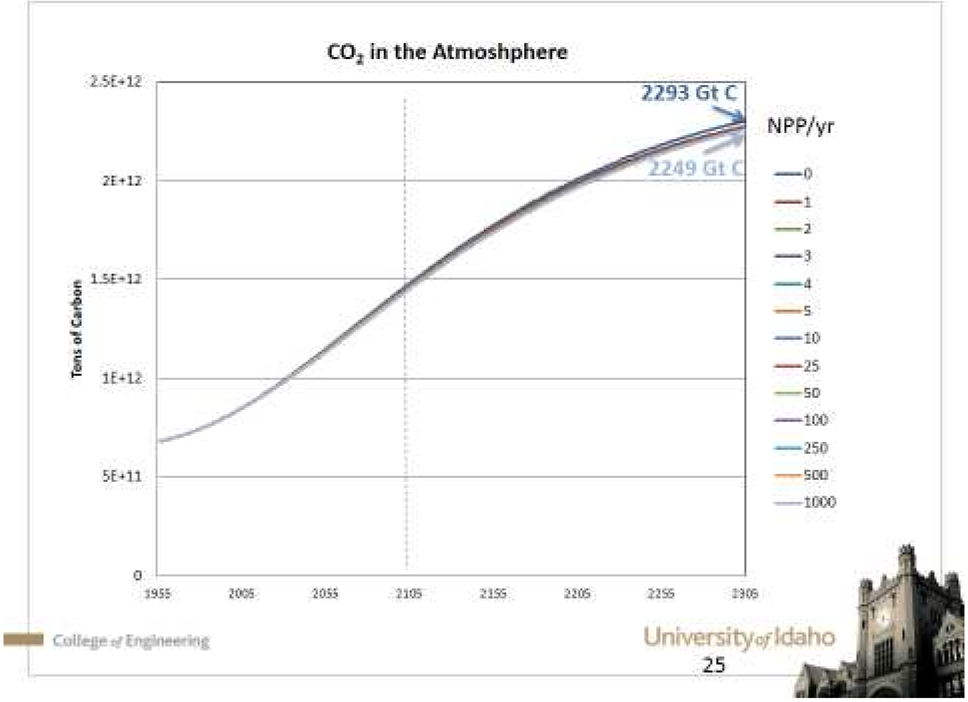


CO$_2$ Emissions Vs. Time

College of Engineering

University of Idaho

24

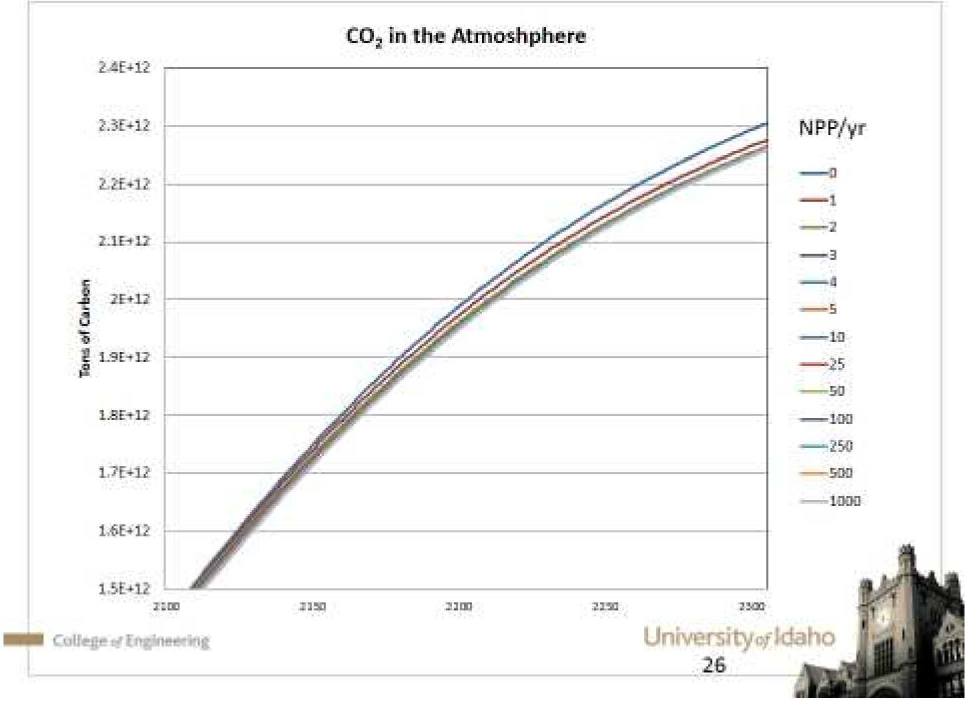


CO$_2$ in the Atmoshphere

College of Engineering

University of Idaho

25

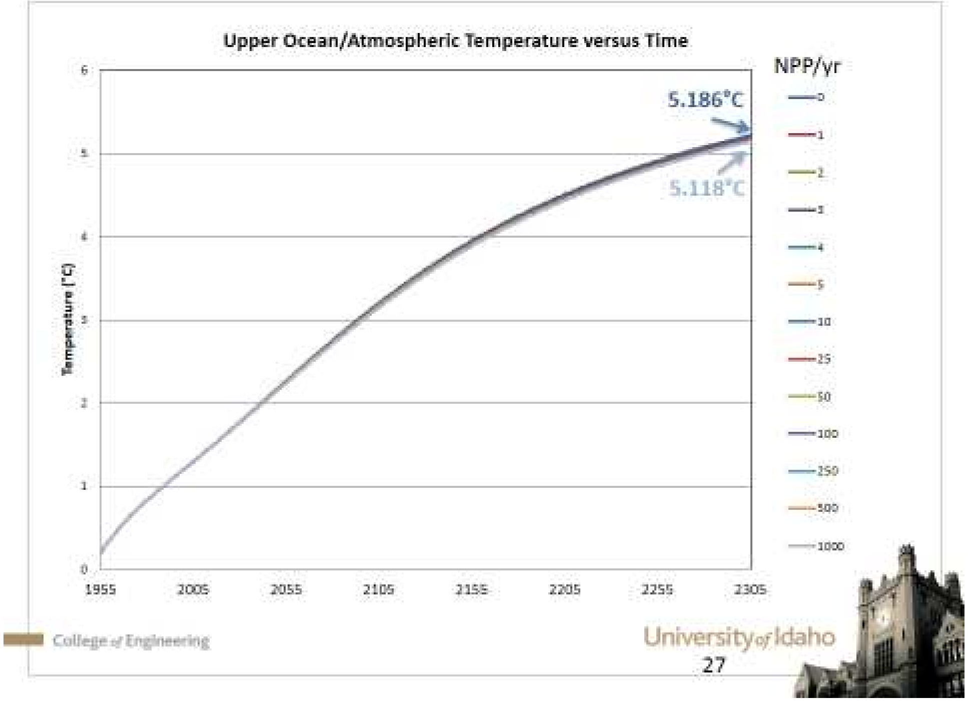


CO$_2$ in the Atmoshphere

College of Engineering

University of Idaho

26



Upper Ocean/Atmospheric Temperature versus Time

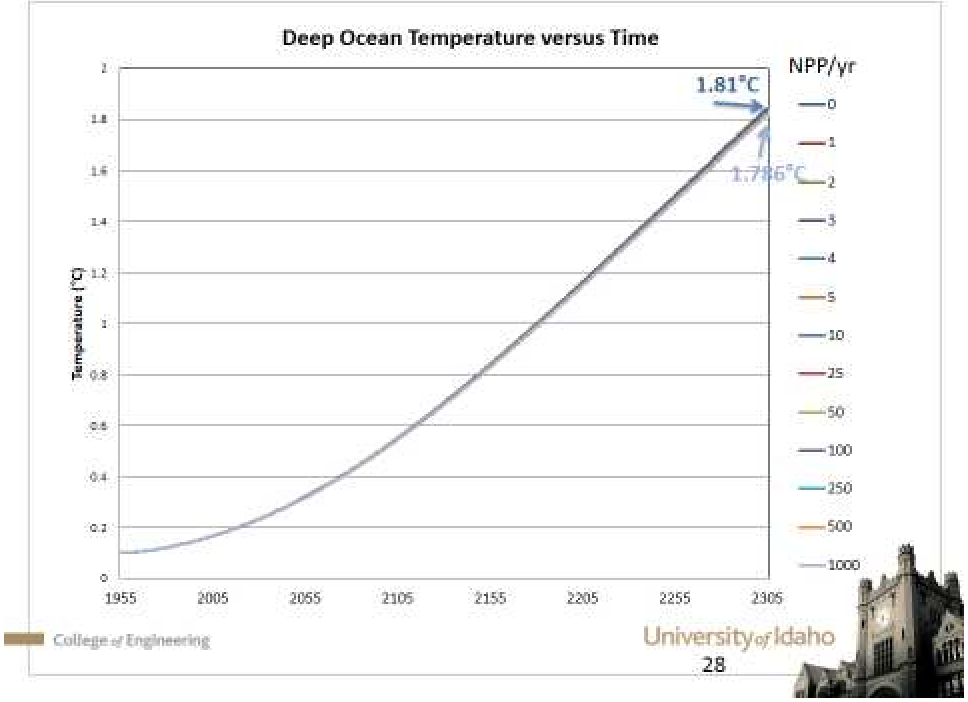
5.186°C

5.118°C

College of Engineering

University of Idaho

27



Deep Ocean Temperature versus Time

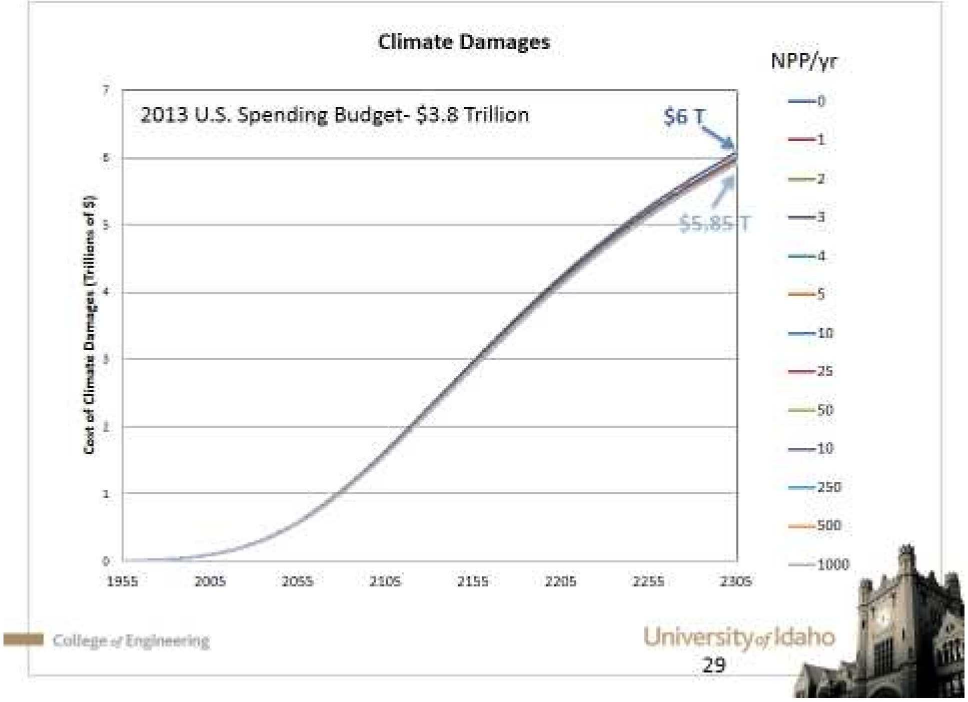
1.81°C

1.786°C

College of Engineering

University of Idaho

28



Climate Damages

2013 U.S. Spending Budget- $3.8 Trillion

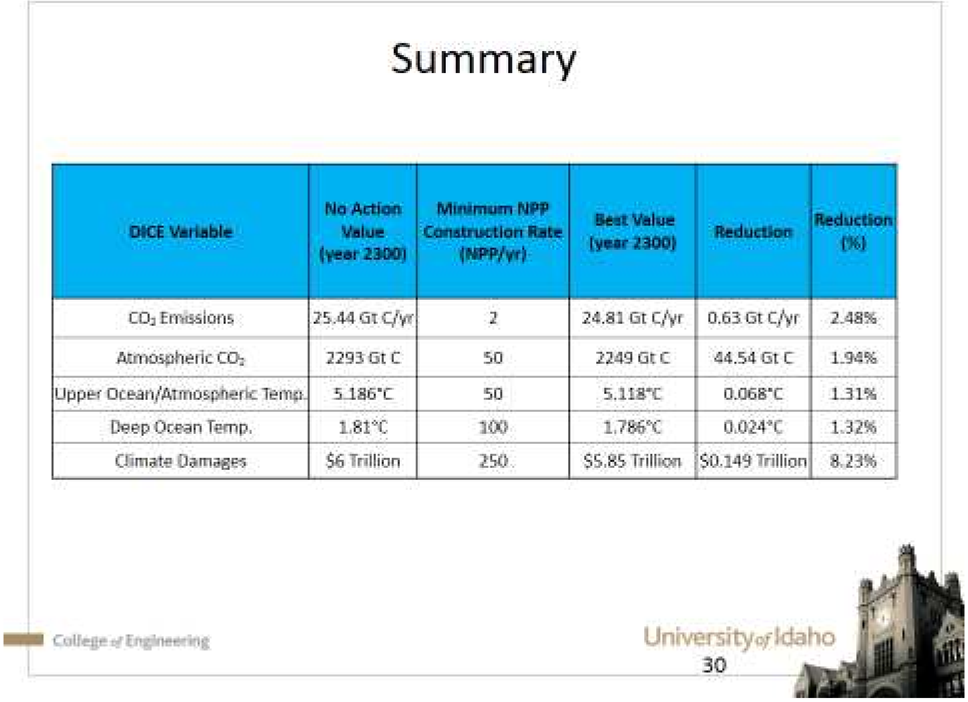
$6 T

$5.85 T

College of Engineering

University of Idaho

29



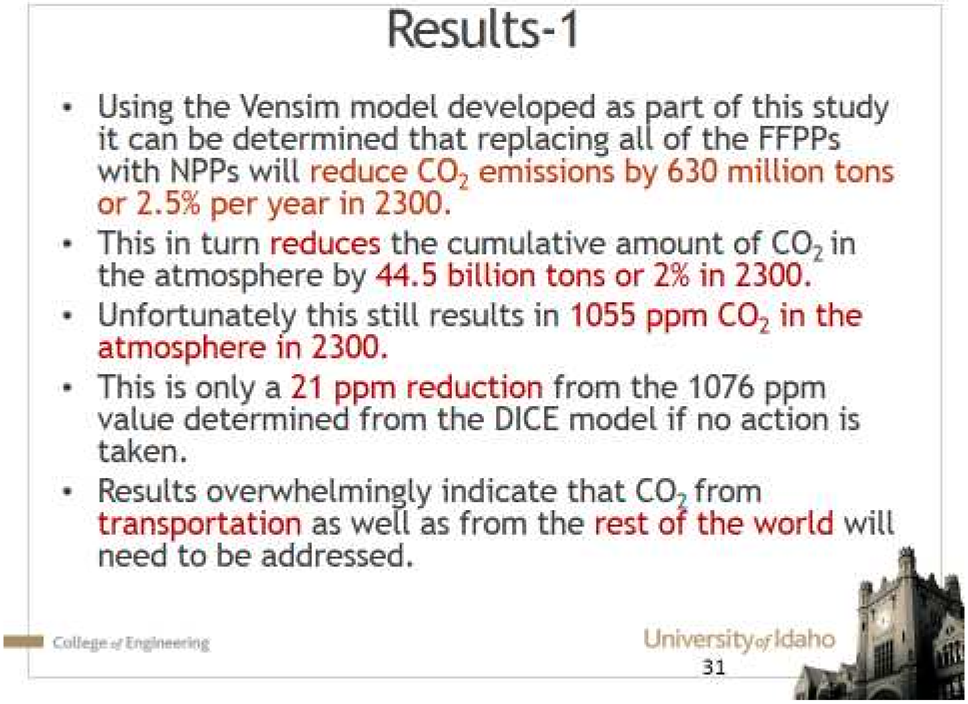
Summary

DICE Variable	No Action Value (year 2300)	Minimum NPP Construction Rate (NPP/yr)	Best Value (year 2300)	Reduction	Reduction (%)
CO_2 Emissions	25.44 Gt C/yr	2	24.81 Gt C/yr	0.63 Gt C/yr	2.48%
Atmospheric CO_2	2293 Gt C	50	2249 Gt C	44.54 Gt C	1.94%
Upper Ocean/Atmospheric Temp.	5.186°C	50	5.118°C	0.068°C	1.31%
Deep Ocean Temp.	1.81°C	100	1.786°C	0.024°C	1.32%
Climate Damages	$6 Trillion	250	$5.85 Trillion	$0.149 Trillion	8.23%

College of Engineering

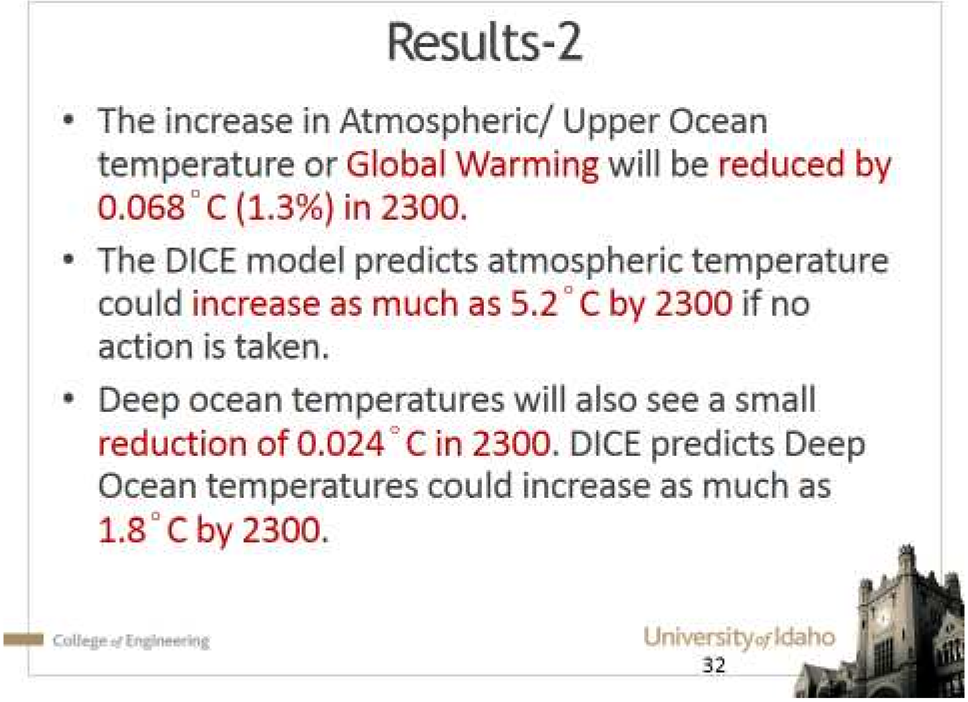
University of Idaho

30



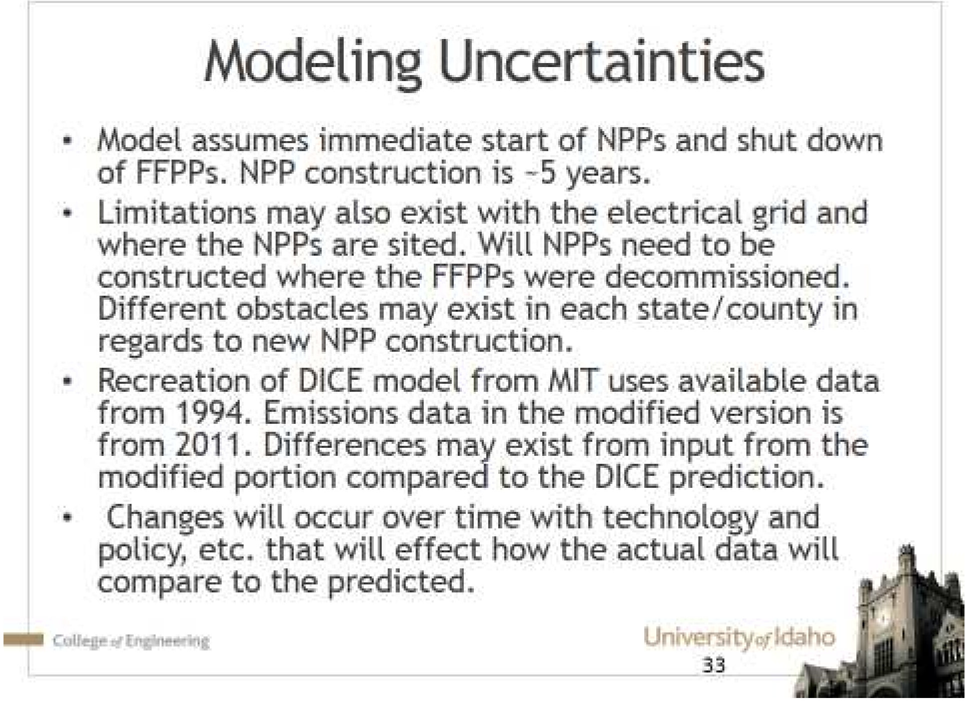
Results-1

- Using the Vensim model developed as part of this study it can be determined that replacing all of the FFPPs with NPPs will reduce CO_2 emissions by 630 million tons or 2.5% per year in 2300.
- This in turn reduces the cumulative amount of CO_2 in the atmosphere by 44.5 billion tons or 2% in 2300.
- Unfortunately this still results in 1055 ppm CO_2 in the atmosphere in 2300.
- This is only a 21 ppm reduction from the 1076 ppm value determined from the DICE model if no action is taken.
- Results overwhelmingly indicate that CO_2 from transportation as well as from the rest of the world will need to be addressed.



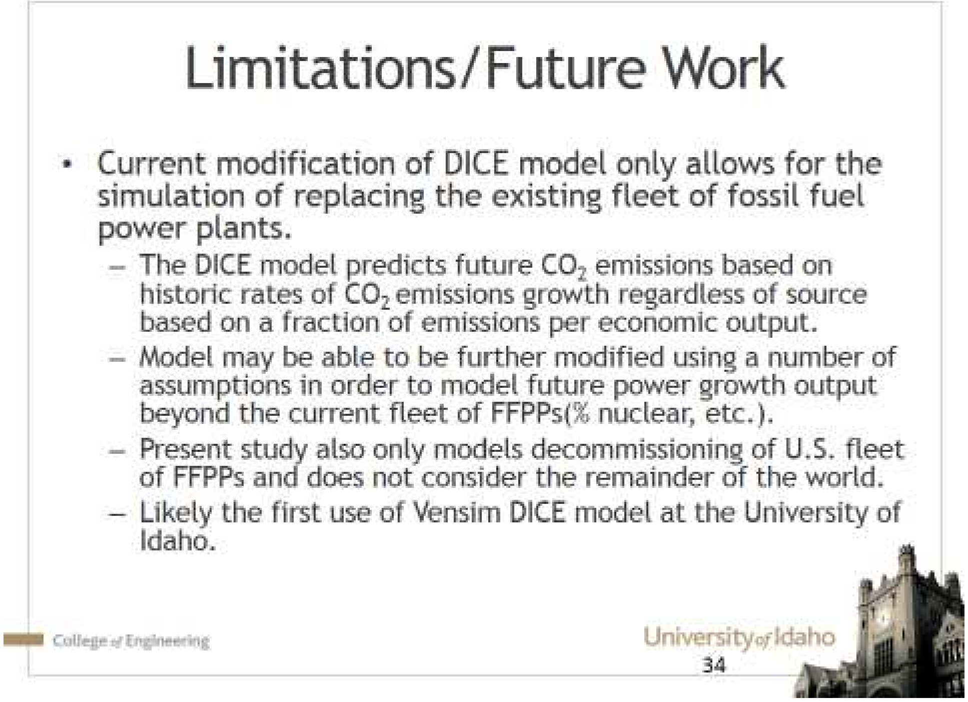
Results-2

- The increase in Atmospheric/ Upper Ocean temperature or Global Warming will be reduced by 0.068°C (1.3%) in 2300.
- The DICE model predicts atmospheric temperature could increase as much as 5.2°C by 2300 if no action is taken.
- Deep ocean temperatures will also see a small reduction of 0.024°C in 2300. DICE predicts Deep Ocean temperatures could increase as much as 1.8°C by 2300.



Modeling Uncertainties

- Model assumes immediate start of NPPs and shut down of FFPPs. NPP construction is ~5 years.
- Limitations may also exist with the electrical grid and where the NPPs are sited. Will NPPs need to be constructed where the FFPPs were decommissioned. Different obstacles may exist in each state/county in regards to new NPP construction.
- Recreation of DICE model from MIT uses available data from 1994. Emissions data in the modified version is from 2011. Differences may exist from input from the modified portion compared to the DICE prediction.
- Changes will occur over time with technology and policy, etc. that will effect how the actual data will compare to the predicted.



Limitations/Future Work

- Current modification of DICE model only allows for the simulation of replacing the existing fleet of fossil fuel power plants.
  - The DICE model predicts future CO_2 emissions based on historic rates of CO_2 emissions growth regardless of source based on a fraction of emissions per economic output.
  - Model may be able to be further modified using a number of assumptions in order to model future power growth output beyond the current fleet of FFPPs(% nuclear, etc.).
  - Present study also only models decommissioning of U.S. fleet of FFPPs and does not consider the remainder of the world.
  - Likely the first use of Vensim DICE model at the University of Idaho.

The Inconvenient Truth

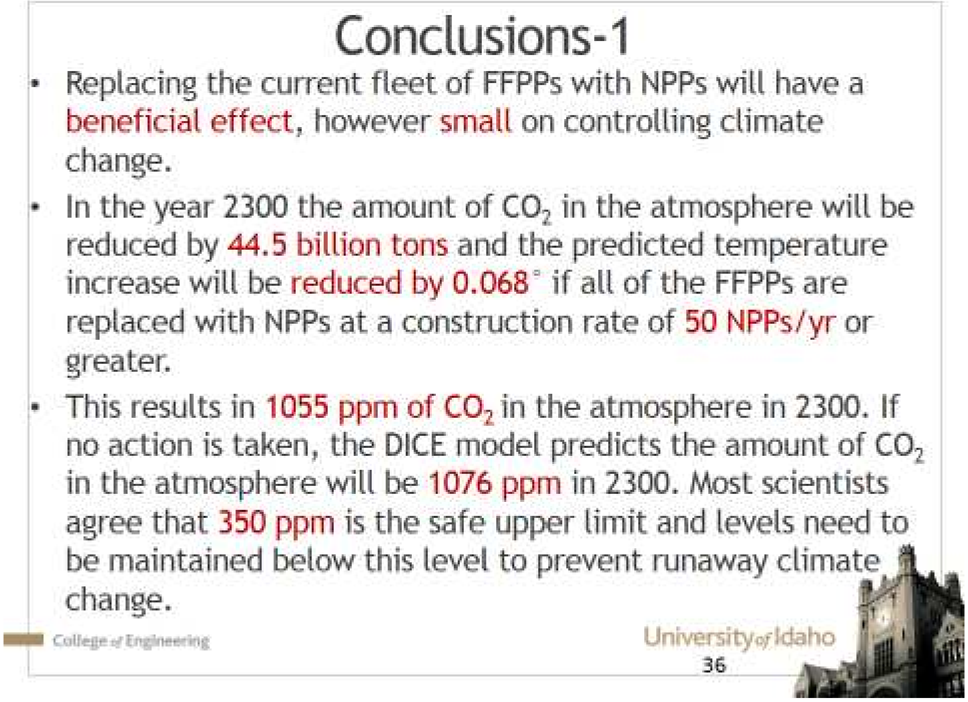
(of Nuclear Power)

- The United States is in no position to increase construction of NPPs anytime in the near future.
- Following a 30-year period in which few new reactors were built, it is expected that 4-6 new units “may” come on line by 2020?
- The U.S. currently has not identified a location for permanent disposal of spent nuclear fuel.
- Even if Yucca Mountain was approved for use, the 104 operating nuclear reactors in the U.S. are expected to produce enough spent fuel to consume the entire capacity of waste storage by 2014.
- Availability of nuclear fuel is limited. Reprocessing of spent nuclear fuel does not occur in the U.S. due to nuclear proliferation concerns.
- Management of radioactive waste is not considered. With high production rates, these will present significant challenges.
- Nuclear power alone will not do much to control climate change.

College of Engineering

University of Idaho

35



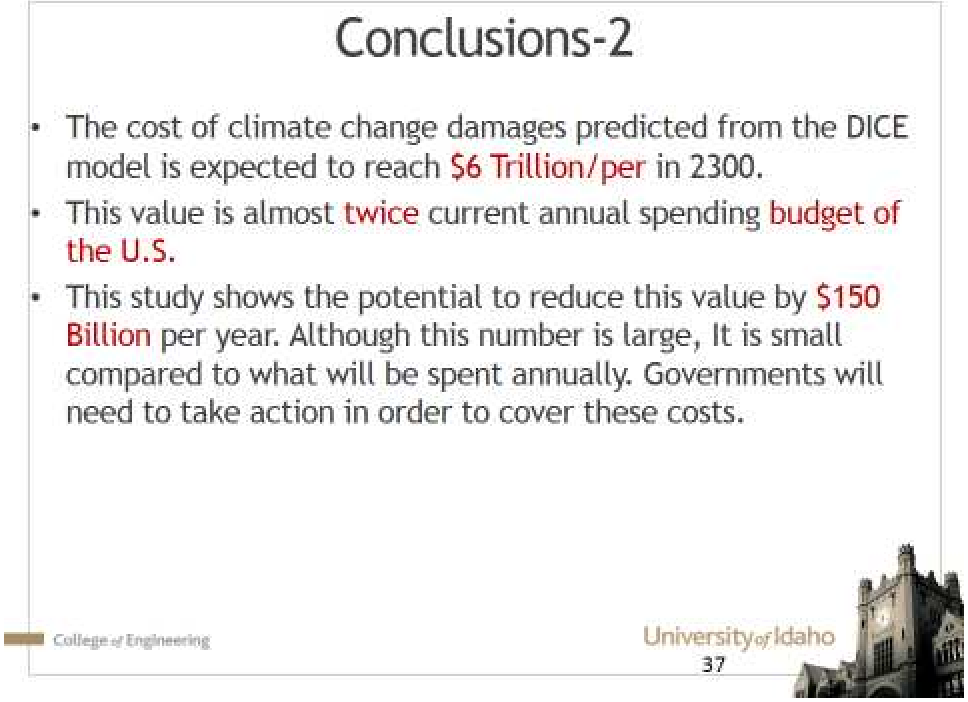
Conclusions-1

- Replacing the current fleet of FFPPs with NPPs will have a beneficial effect, however small on controlling climate change.
- In the year 2300 the amount of CO_2 in the atmosphere will be reduced by 44.5 billion tons and the predicted temperature increase will be reduced by 0.068° if all of the FFPPs are replaced with NPPs at a construction rate of 50 NPPs/yr or greater.
- This results in 1055 ppm of CO_2 in the atmosphere in 2300. If no action is taken, the DICE model predicts the amount of CO_2 in the atmosphere will be 1076 ppm in 2300. Most scientists agree that 350 ppm is the safe upper limit and levels need to be maintained below this level to prevent runaway climate change.

College of Engineering

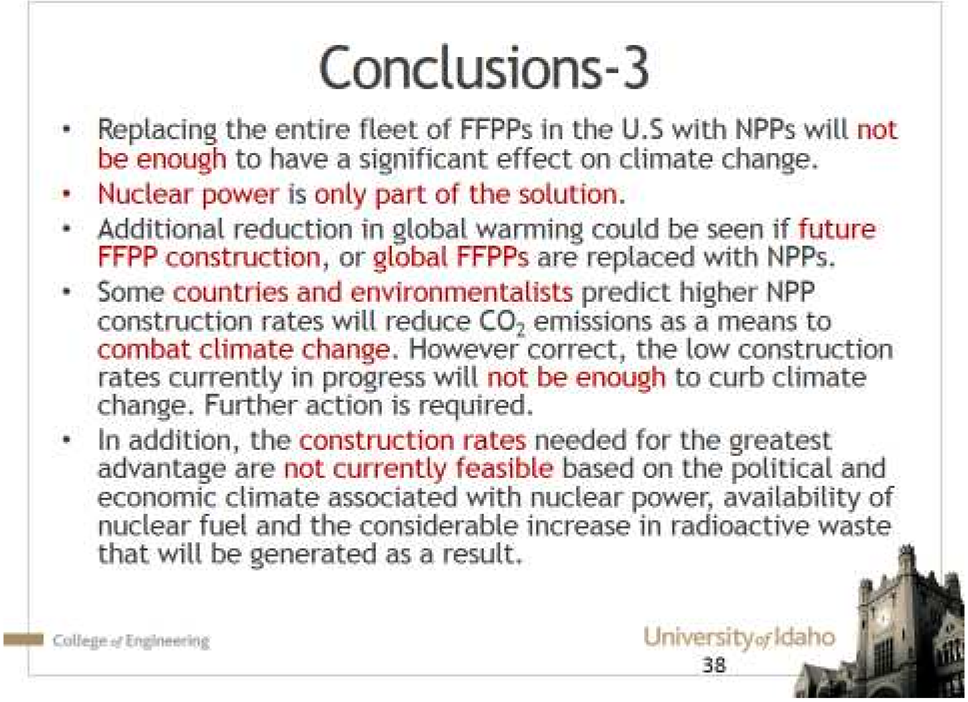
University of Idaho

36



Conclusions-2

- The cost of climate change damages predicted from the DICE model is expected to reach $6 Trillion/per in 2300.
- This value is almost twice current annual spending budget of the U.S.
- This study shows the potential to reduce this value by $150 Billion per year. Although this number is large, It is small compared to what will be spent annually. Governments will need to take action in order to cover these costs.



Conclusions-3

- Replacing the entire fleet of FFPPs in the U.S with NPPs will not be enough to have a significant effect on climate change.
- Nuclear power is only part of the solution.
- Additional reduction in global warming could be seen if future FFPP construction, or global FFPPs are replaced with NPPs.
- Some countries and environmentalists predict higher NPP construction rates will reduce CO_2 emissions as a means to combat climate change. However correct, the low construction rates currently in progress will not be enough to curb climate change. Further action is required.
- In addition, the construction rates needed for the greatest advantage are not currently feasible based on the political and economic climate associated with nuclear power, availability of nuclear fuel and the considerable increase in radioactive waste that will be generated as a result.