A Study on the Impact of Global Replacement of Fossil Fuel Based Electricity Generation, Transportation and Domestic Heating with Nuclear Generated Electricity Using a Modified VENSIM DICE Model

by

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The above committee determined that the thesis is acceptable in form and content and that a satisfactory knowledge of the field covered by the thesis was demonstrated by the candidate during an oral examination. A signed copy of the Certificate of Approval is available from the School of Graduate and Postdoctoral Studies.

ABSTRACT

While much debated across current media, electricity generation using nuclear energy is proposed as one of the means of addressing the global negative impacts of climate change – notably ongoing accumulation of CO_2 in the atmosphere by burning fossil fuels (FF). In this thesis, different transition scenarios were investigated in replacement of FF electricity generation, vehicle transport and domestic heating, using the macro-economic Dynamic Integrated Climate Economy (DICE) model. The model was modified by replacing FF sources by nuclear power plants, electric vehicles and heaters, across global scales. Based on declared national target year to attain net-zero carbon status, simulations were carried out based on parametric targets. Simulations results indicate that replacing all FF generation plants, vehicles and heaters would reduce CO_2 emissions roughly 25%. For a net zero target of 2060, CO_2 concentration will reduce by 82 ppm. This result predicts a reduction in global warming of 0.3°C by 2100.

Keywords: climate change; fossil fuel; nuclear; DICE model; electric vehicles

AUTHOR'S DECLARATION

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____ Huan Shen

STATEMENT OF CONTRIBUTIONS

I hereby certify that I am the sole author of this thesis. A modified Dynamic Integrated Climate Economy (DICE) model was developed in order to analyze the impact of the carbon footprint from replacing world fossil-fuel power plants, vehicles and heaters with nuclear power plants, electric vehicles and electric heaters. This contribution was presented at the 40^{th} Annual Conference of CNS in June 2021. Furthermore, I hereby certify that I am the sole source of the creative works and/or inventive knowledge described in this thesis.

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DISCLAIMER

The results contained in this thesis as product of the modified DICE model, look at some key aspects of climate change but do not consider all possibilities, variables or issues effectively present in such complex problem. The authors and Ontario Tech University do not assume any responsibility for the possible misuse of the content or its results out of the research contest they were carried out and obtained in this work. The authors caution anyone in taking any given results to advocate a position, belief advantageous or not relative to all possible stakeholders in such matter nor assume any liability of any kind for their use.

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LIST OF ABBREVIATIONS

CPP	Coal Power Plant
EH	Electric Heater
EV	Electric Vehicle
FFH	Fossil Fuel Heater
FFPP	Fossil Fuel Power Plant
NGPP	Natural Gas Power Plant
NPP	Nuclear Power Plant
PPP	Petroleum Power Plant
TV	Traditional Vehicle

Chapter 1 Introduction

Global climate change characterized by global warming continues to attract attention in the world as there are potential catastrophic consequences for humanity. According to the Fifth Assessment Report published by the Intergovernmental Panel on Climate Change in 2014 (IPCC), CO_2 emission is the main contributor to climate change. Since 2014 and subsequent years, the daily concentration of CO_2 in the atmosphere has hit record levels [Yan, et al., 2018]. Human activities are responsible for almost all the excess greenhouse gas emissions over the last 150 years; among these activities, burning fossil fuels for electricity production, heat and transportation are among the largest sources of greenhouse gas emissions [EPA, 2020]. Data show that the amount of CO_2 emissions and levels in the atmosphere have risen at a relatively high rate since the beginning of the industrial revolution and continue to grow as energy demand continues to grow [Nordhaus, 1993].

Under these circumstances, seeking possible solutions to reduce CO_2 emissions and control global warming is necessary. With this motivation, this study was initiated to investigate reduction of CO_2 emissions from fossil-fuel based power generation, heating and transportation using nuclear power plants to mitigate climate change effects.

Global warming potential (GWP) is related to the total quantity of gas emitted, the mean lifetime of the gas and the expected effect from the addition of a unit of gas on the radiation balance of the earth [Johnson, et al., 2007]. Carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are long lived in atmosphere and are the major contributors to positive increases in radiative forces [IPCC, 1996]. Changes to earth's radiative equilibrium that cause temperatures to rise or fall over decadal periods are indicated as climate forcing

[Lindsey, 2009]. These three gases are responsible for the potential greenhouse effect: among these gases, CO_2 has the greatest climate forcing potential (57%), while CH_4 and N_2O account for 27% and 16% respectively [CAST, 1992].

As one of the low-carbon energy sources, nuclear power is a potential solution to reduce CO_2 emissions. Recent studies show that nuclear power plants produce during their operational existence only 6% of the CO_2 emissions per Megawatt (MW) produced, in contrast from fossil fuel power plants [Colpetzer, 2014]. According to the World Nuclear Association, there are 440 operable and operating power reactors in the world producing about 10% of the world electricity. In addition, there are 55 reactors under construction and 109 reactors planned at this time. There is thus a clear need for nuclear power plants (NPPs) that are able to meet the increased demand for electricity in specific regions of the world and to replace fossil fuel power plants which are large net contributor to GHG emissions.

In addition to power generation, transportation is also a big contributor of CO_2 emission. The International Energy Agency (IEA) estimates that the transportation sector accounts for approximately 19% of global energy consumption and 23% of energy-related CO_2 emissions [Brand, 2012]. In fact, the fast technological and economic development of nations like India and China have made automobile ownership and use grow rapidly, worsening the situation with respect to emissions. Electric Vehicle (EV) are increasingly becoming popular in recent years, due to relative low running costs and lower environmental, CO_2 (and emissions) footprint during their operational lifetime [Hausfather, 2019]. The increasing number of EVs indicates society's awareness of climate change is increasing accordingly.

Besides power generation and transportation, domestic (home) heating is also a contributor to CO_2 emissions. As the use of fossil fuel (like oil, kerosene, propane and similar) for residential heating is still a common practice in many places in the world, even if electrification reaches high level, this practice is still a significant problem [Chafe, 2015]. It is estimated that globally there are 1.8 billion fossil fueled heaters in the world. Chapter 4 discusses this aspect in detail. In order to reduce the CO_2 emissions from people's daily life, an electric heater (EH) can be used to replace the fossil fueled heater (FFH). As it uses the electricity to heat indoor spaces, it is much more environment friendly than FFHs. Thus, it's also considered a potential solution to reduce CO_2 emissions.

In order to evaluate the impacts of NPP, EV and EH on the climate change metrics, this study has considered replacing all the Fossil Fuel Power Plants (FFPPs), Traditional Vehicles (TVs) and Fossil Fueled Heaters (FFHs) in the world with NPPs, EVs and EHs with the aim of understanding its effects. A detailed analysis reveals that possible reduction is determined by using appropriate models. Subsequently, the magnitude of the reduction of CO_2 emission is estimated; thus, providing insight on global climate modifications. This estimate is herein investigated by a climate model simulating climate change metrics coupled to economic and environmental models.

There are many integrated assessment models used in the scientific community to analyze the interactions of the primary drivers of climate change. Many predict the future climate variations, emissions impact, damages over the environment as well as average temperature in both the ocean and atmosphere [Mcsweeney, et al., 2018]. Notable integrated assessment models include Integrated Model for the Assessment of the Greenhouse Effect (IMAGE), Global Change Analysis Model (GCAM) and Dynamic Integrated Climate-Economy model (DICE) [Stehfest, 2014]. Among the models, the DICE Model (Dynamic Integrated model of Climate and Economy) is one of the highly cited models. This model was originally developed by William Nordhaus at Yale University in 1992 [Nordhaus, 2014]. The DICE model "integrates in an end-to-end fashion the economics, carbon cycle, climate science, and impacts in a highly aggregated model that allows a weighing of the costs and benefits of taking steps to slow greenhouse warming" [Newbold, 2010]. It has been widely cited by climate economists and policy professionals and in its successive versions, has been influential in climate policy deliberations for several decades [Easton, et al., 2014]. Because the DICE model consists of a set of algebraic equations and empirical relationships, it can be constructed using one of several programming languages or software tools. The Vensim software tool was here used to simulate DICE.

Vensim is a commercial simulation software tool, well suited to perform dynamic system simulations [Vensim, 2009]. System dynamic (SD) was created by J.W. Forrester from MIT in 1950s. The approach is based on the feedback control theory, equipped with computer simulation technology, and used in quantitative research of complicated phenomena including socioeconomics [Wang, 1998]. The methods of SD are realized by involving feedback loops, variables, and equations. The feedback loop is defined as a closed chain of causes and effects. The variables include (i) level variable, the one that accumulates a flow over continuous time periods; (ii) rate variable, the one that represents a flow during a time period; (iii) auxiliary variable, the one that identifies rate variables. The three kinds of variables are linked by equations taking the form of integral, differential, or other types [Wang, 2008]. The total process of system dynamics covers the gathering of information, from which important variables are selected and causal relations defined in a causal loop diagram. Once the validation of these causal relations is finished, a second stock and flow model can be constructed including the dynamics (time included) of the situation [Bongard, 2011].

In order to do simulations, the DICE model (equations and relationships) has been recreated with Vensim software. Although it can do climate change simulations, the impacts of NPPs, EVs and EHs cannot be evaluated with the original DICE model. Hence in this study, the DICE model was modified so that it can be used to analyze the impacts of the replacement of FFPPs, TVs and FFHs. The modification to be described simulates and estimates the reduction of CO_2 emission due to the postulated decommissioning of FFPPs, TVs and FFHs.

The modified portion contains three sub-models that correspond to the NPP sub-model, transportation sub-model and heating sub-model. In the NPP sub-model, the Coal Power Plants (CPPs), Natural Gas Power Plants (NGPPs) and Petroleum Power Plants (PPPs) are replaced by NPPs. The decommission rates of these FFPPs vary based on the electrical generating output produced compared to NPPs. In the transportation sub-model, the fossil fuel burning vehicles are replaced by electric vehicles. The rate of increase in EVs is calculated based on the requisite rate of decrease of TVs and increasing rate of people's demand of new vehicles. The heating sub-model is quite similar to the transportation model. It considers the increasing demand of heaters due to the growth of the world's population as well as replacements. Ultimately, EHs are used to replace the FFHs in order to decrease CO_2 emissions. All these sub-models are described later in Chapter 3.

The original DICE model is also modified in order to predict the change in CO_2 concentration in the atmosphere in parts per million (PPM).

As global attention is now focusing more and more on issues related to "the climate change crisis", a growing number of governments are seeking targets to mitigate and manage their contribution to global warming, primarily via CO_2 emission reductions. More than 100 countries have pledged carbon neutrality by 2050. For example, China is the world's biggest CO_2 emitter and has pledged to reach net zero carbon before 2060 [Darby et al., 2019]. In this thesis work, "net zero carbon" is defined as a balance between the CO_2 put into the atmosphere and those taken out. For this reason, one of the introduced input parameters of the modified portion of the model, is the preferred or target year to reach zero CO_2 emissions. This creates several possible scenarios with different level of mitigation. Subsequently, this impacts significantly the year in which all the FFPPs, TVs and FFHs will be decommissioned. After the period over which the replacement is determined, the increase rate of NPPs, EVs and EHs can be calculated based on the existing total number and generating capacity of FFPPs, TVs and FFHs currently operating in the world.

After this transition is simulated, the reduction in CO_2 emissions can be calculated per decommissioning of FFPPs, TVs and FFHs, and then, the reduction in CO_2 from power generation, transportation and domestic heating are added together. Finally, the total reduction of CO_2 is fed into the DICE model's parameter "CO_2 emissions". As the CO_2 emission changes, the variables characterizing climate change will also change. This study describes these variables and parameters relative to historical simulations referenced based on the DICE model.

The different targeted years (or scenarios) to reach net zero CO_2 emissions impact the endpoint scenarios. The climate related results for different scenarios can be compared in order to provide stakeholders a basis to make better decisions. Furthermore, it helps to determine whether NPPs, EVs and EHs are a possible solution to mitigate the postulated (negative) impacts of global warming and/or to understand to what extent. This is then the main target of this research: to provide a reference data to stakeholders (such as policy makers) in order to understand how to reach net zero carbon targets and when different approaches might produce this effect.

We have taken the target year to reach zero CO_2 emissions as follows: 2025, 2030, 2040, 2050, 2060, 2070, 2080, 2090 and 2100. These target years are relative to the start of this research, in 2019. This provides time-based reference relative to the current debate on institutional commitment to zero CO_2 emission. The results produced from each scenario are different as the decommission rates of FFPPs, TVs and FFHs are vary due to the different durations of time left to replace fossil-fueled devices, relative to the declared, target year. We have observed that the climate change can be mitigated in all scenarios. In some scenarios, however, the rate increase of NPPs, EVs and EHs are quite aggressive. In fact, some scenarios maybe impractical, as suggested by Colpetzer, and thus only serve as reference and indicate the impacts of the replacement, relative to the state of CO_2 accumulated.

Overall, the objective of this investigation are as follows:

- Consider the simulations generated impact of various replacement and net-zero target years to the macro-impact metrics describing the negative impacts of climate change such as CO_2 concentration level, spatio-temporally averaged atmospheric, ocean surface and deep ocean temperatures, and finally, the gross economic damage estimates proposed by Nordhaus. Furthermore, from the simulation results and parametric study, identify and suggest the issues and challenges in transition rates with respect to the current status quo.

- Consider per modified DICE model simulation, the broad impact of various scenarios, relative to net zero target year. Comparing results from different scenarios in order to assess the outcome, as influenced by declaration of different net zero target year.

Chapter 2. Literature review

2.1 Climate change

Climate change refers to the long-term change in the average weather patterns that have come to define Earth's local, regional and global climate [NASA, 2021]. Both natural factors and human activities are drivers of climate change [IPCC, 2014]. Greenhouse gases are thought to be the main contributor to climate change, as they are highly efficient at trapping heat within the atmosphere which has been termed as the greenhouse effect [Kaddo, 2016]. Increasing concentrations of these gases in the Earth's atmosphere cause average global temperatures to rise over time, which can lead to catastrophic disasters. [NASA, 2020].

According to Holli Riebeek, who is the author of "global warming", nature contributes to climate change by emitting CO_2, for example from volcanos [Kaddo, 2016]. However, the amount of CO_2 from volcanos is relatively small compared to the CO_2 emission from human activities. The data from NASA show that CO_2 emissions from humans is more than 100 times than that from volcanos [Riebeek, 2010]. Besides volcanos, forest fires and oceans are also sources of CO_2 emissions [Yue et al., 2018]. The largest source of CO_2 emissions from human activities are the burning of fossil fuels for heating, electricity, and transportation [EPA, 2018]. This study analyzes the impacts of the CO_2 emissions from these three areas.

The impacts of the accumulation of CO_2 emissions in the atmosphere on climate appear several decades later than the emissions themselves, means the effects of the increasing level of CO_2 in the atmosphere will not be known until sometime in the future [Colpetzer, 2014]. For this reason, it is of great importance to control and predict CO_2 emissions as early and accurately as possible.

Earth's climate has changed may times over the planet's history. Most of these changes have been due to the small variations of the Earth's orbit, which changes the solar energy received by Earth [NASA, 2021]. While it has been proven that our planet has undergone different climate cycles [Petit et al, 1999], the current climate change is of particular significance as most of it is caused by human activities and the changes are proceeding at a rate that is unprecedented [Santer et al., 1996]. The rate of CO_2 emissions from human activities is more than 250 times faster than those experienced from natural sources after the last Ice Age [Gaffney et al., 2017].

Impacts related to climate change are evident across many regions and sectors which are important to society, such as human health, agriculture and ecosystems. 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 the possible extinction of entire species [Schneider, 2004].

The most obvious evidence for rapid climate change is rising global temperatures. The earth's temperature has increased by about 1.2 °C since the late 19th century [Shaftel, 2021]. The main reason for this increase is the accumulation of carbon dioxide in the atmosphere which has been driven by human activities [Shaftel, 2021]. Most of the warming has occurred in the last 40 years, and data shows that 2016 was the warmest year on record [Northon, 2017]. The continual increase in global temperatures has attracted attention worldwide, as scientists attempt to quantify the lasting effects which this climate change will have.

Besides global temperature rise, the warming of ocean is also evidential of climate change and its effects. Oceans absorb a large amount of the energy that the Earth receives from the sun. According to data, more than 90% of the heat gained by the earth is absorbed by the oceans [Cooper, 2019]. The heat absorbed by the oceans is moved, via currents, around the planet influencing the climate as it travels [Dahlman et al., 2020]. Since 1969, the top 100 meters of the ocean's surface has increased in temperature by 0.33°C [Levitue, et al., 2017].

Global warming has affected many aspects of the planet. One aspect which is of particular importance is the effect which warming has had upon weather. Due to the climate change, it's predicted that the extreme weather events such as large storms and hurricanes are likely to become more frequent or more intense [EPA, 2020]. These events can lead to substantial impacts, including damage to buildings and longer-term economic effects. As predicted by climate models, global warming will cause climate patterns worldwide to experience significant changes which include major shifts in wind patterns, annual precipitation, and seasonal temperature variations [Bradford, 2017].

What's more, global warming can also produce serious effects on human health. According to the research from the American Medical Association, many mosquito-borne diseases such as malaria and dengue fever, as well as the increasing cases of chronic conditions like asthma, most likely are a direct result of global warming [Bradford, 2017]. Additionally, global warming can reduce availability of water, shrink arable land, and increase pollution which will then reduce agriculture resources which will then threaten the survival of human beings [Rossati, 2017].

In addition to the impacts mentioned above, increasing global temperatures also have serious economic consequences. The effect of global warming on economic growth will most likely be increasingly negative as time progresses [Wade, 2016]. For example, the damage to property and infrastructure due to the sea level rise and floods [Serreze, et al., 2009] is predicted to be significant. According to the Swiss Re Institute's stress test, the world economy is set to lose up to 18% GDP from climate change if no actions are taken [Swiss Re Institute, 2021].

For these reasons, there have been many debates and discussions on how to mitigate climate change and its effects: primarily, mitigating climate change means reducing the greenhouse gas emissions which cause the global warming. There have been many solutions proposed to accomplish this, however, there are many factors which influence whether or not these solutions are economically viable [Kaddo, 2016]. In order to mitigate and predict climate change, many climate models have been built which can be used to analyze climate related factors [Buis, 2020].

Climate mitigation is a long-term measure aiming to reduce Greenhouse Gas emissions [Mukhopadhyay, et al., 2018]. Such reduction can be achieved by adopting renewable energy sources, and through the electrification of industrial and other processes. In addition, carbon capture and storage (CCS), or carbon capture and sequestration, is also a method to decrease the atmospheric CO_2 concentration. This is the process of capturing emitted CO_2, transporting it to a storage site, and depositing it in specified locations so that it will not enter the atmosphere [Fanchi, 2016]. Climate change mitigation will continue to be a major concern for humanity in the forthcoming decades [Ernst et al., 2019].

2.2 Greenhouse gas emissions

Greenhouse gas refers to any gas that absorbs and releases infrared radiation, which exists in the atmosphere. Greenhouse gases cause the greenhouse effect. According to the Kyoto Protocol, six kinds of greenhouse gases should be controlled and mitigated: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF_6) [UNFCCC, 2009]. Among them, the latter three have the strongest ability to cause the greenhouse effect; however, CO_2 contributes the most to global warming. Thus, controlling the amount of CO_2 emissions helps controlling global warming ultimate effects.

Without greenhouse gases, the average temperature of the Earth's surface would be about -18°C (0°F) [Ma, 1998]. Human activities are the main cause of the excessive CO_2 emissions present in the atmosphere, and since the Industrial Revolution, the atmospheric concentration of carbon dioxide has increased 45%, from 280 ppm measured in 1750 to 415 ppm measured in 2019 [Jonathan, 2019]. Human activities such as farming, burning of fossil fuels, and deforestation are the main sources of greenhouse gas production. Based on the data from United States Environmental Protection Agency, Figure 2.1 shows the global manmade greenhouse gas emissions by gas in 2014.

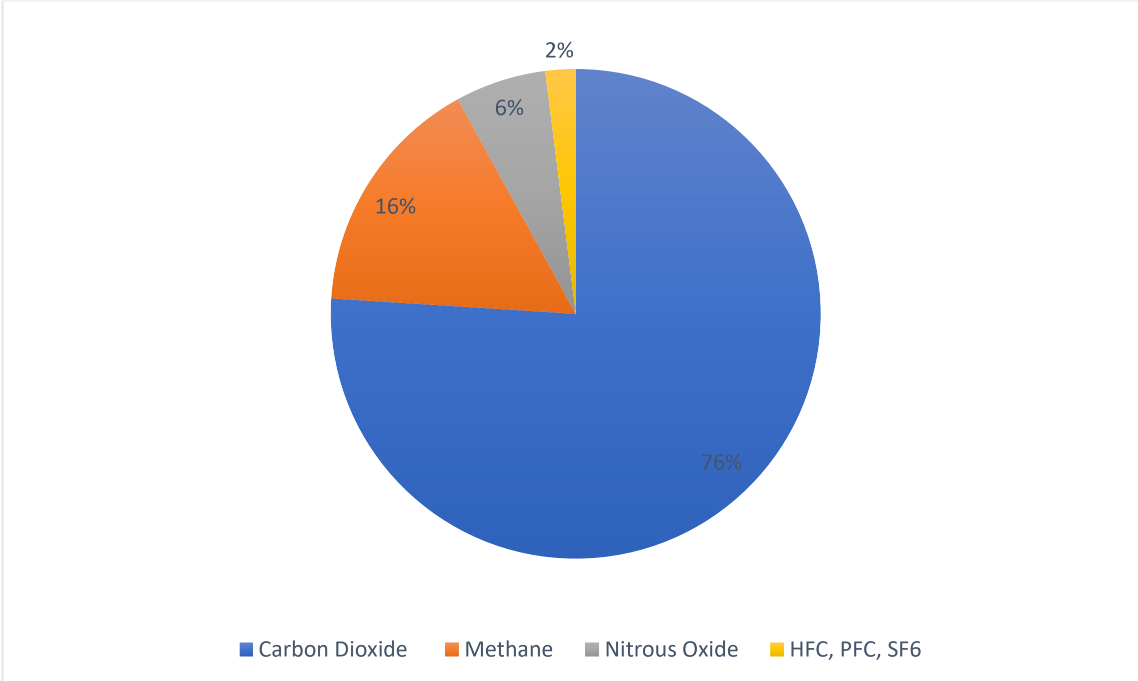


Figure 2.1 global manmade greenhouse gas emissions by gas (Own elaboration based on data from [EPA, 2017])

Global carbon emissions from fossil fuels have significantly increased since 1900 [EPA, 2020]. Since 1970, CO_2 emissions have increased of about 90%, with emissions from fossil fuel combustion and industrial processes contributing about 78% of the total greenhouse gas emissions increase from 1970 to 2011 [IPCC, 2014]. Based on the data from the World Resource Institute, Figure 2.2 shows the manmade greenhouse gas emissions by sector in 2013.

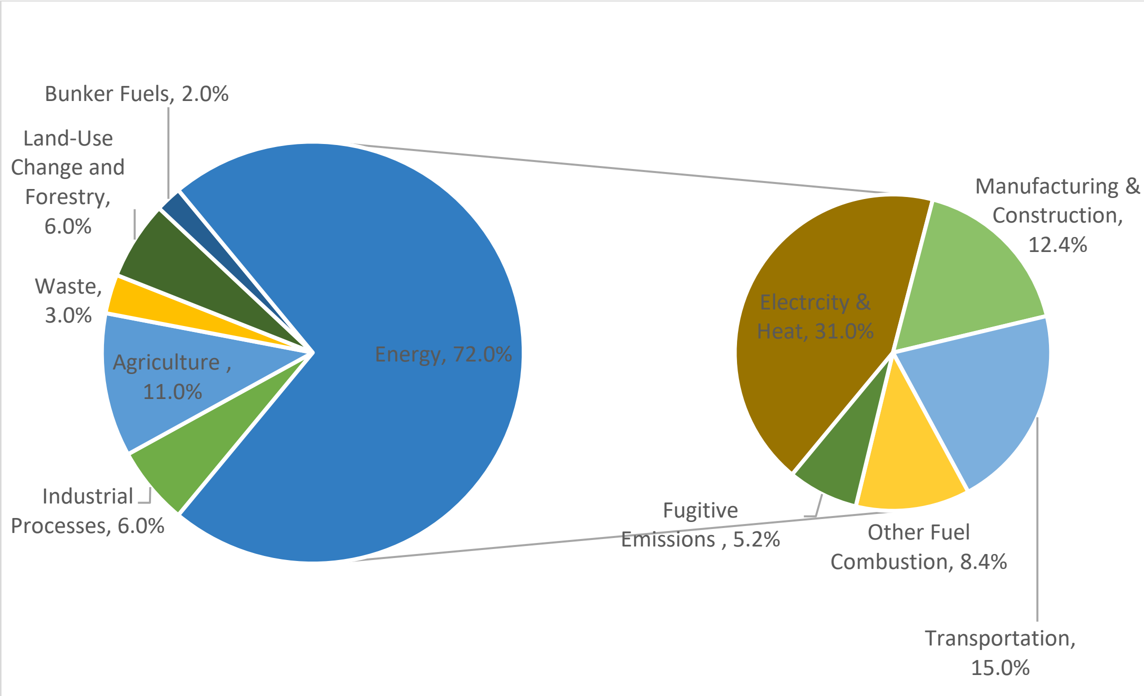


Figure 2.2 manmade greenhouse gas emissions by sector gas (Own elaboration based on data from [World Resource Institute, 2017])

Fossil fuels still supplies 84% of world energy as of 2019 [Ritchie, et al., 2017]. The biggest share of energy consumption came from oil, 33%, while other sources were distributed as follows: 27% from coal, 24% from natural gas, 6% from hydropower, 5% from renewable energy while nuclear power accounts only for 4% [Robert, 2020]. Global CO_2 emissions from fuel combustion reached a historical high of 33.5 $GtCO_2$ in 2018 [IEA, 2020]. Although planet Earth can absorb part of the CO_2 present in the atmosphere, humans should drastically decrease emissions of CO_2 in order to gain back control over global warming.

According to the data from the Global Monitoring Laboratory, the CO_2 level in the atmosphere for the month of February 2021 is 416.75 ppm [NOAA, 2021]. This measurement is from the Mauna Loa Observatory in Hawaii which has the longest record of direct measurements of CO_2 in the atmosphere. Based on the data from the Mauna Loa Observatory, Figure 3.3 shows the CO_2 concentration in the atmosphere from 1985 to 2020.

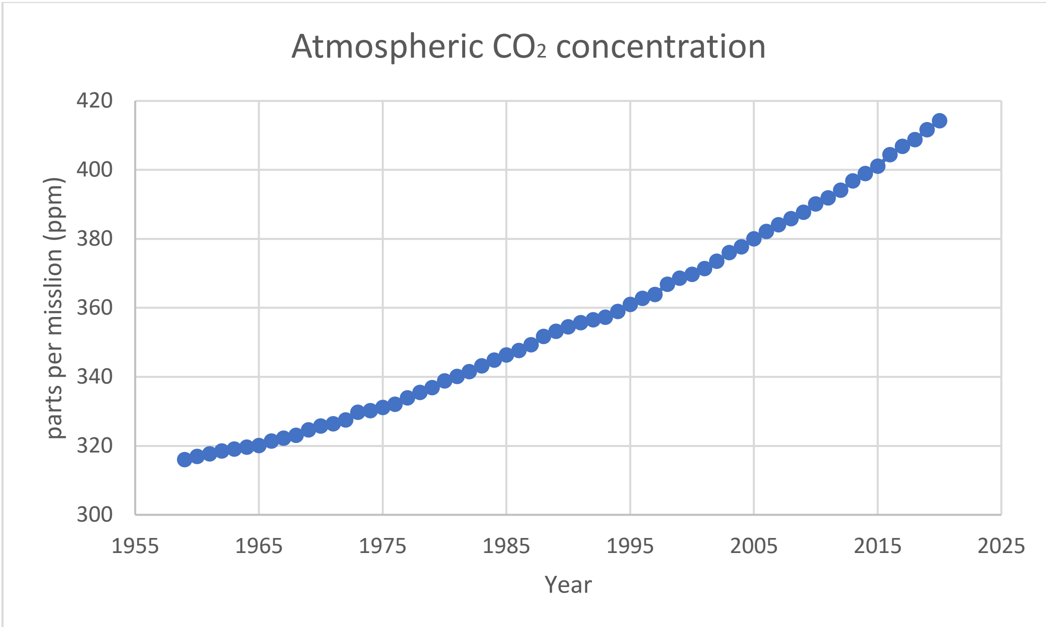


Figure 2.3 Monthly mean carbon dioxide (Own elaboration based on data from [NOAA, 2021])

The increasing level of CO_2 in the atmosphere causes climate change. After many years of study, it is estimated that the global temperature will increase about 1.5°C to 4.5°C for a doubling of pre-industry CO_2 levels [Hausfather, 2018]. Doubling atmospheric CO_2 concentration is sure to cause significant warming of the climate [Fingerprinter, 2010]. Thus, it is important to control the carbon dioxide level to prevent severe climate change related damages.

There are varieties of things can be done by individuals and human societies in order to control GHG emissions. For individuals, the following actions can be taken:

1. Reducing CO_2 emissions on the road by driving less, carpooling and checking cars regularly in order to keep it more efficient [Albeck-Ripka, 2021].
2. Reducing CO_2 emissions by choosing local food sources and reducing the amount of wasted food which as individual is producing [Albeck-Ripka, 2021].
3. Reducing CO_2 emissions in homes by turning off heaters, lights and other appliances when you are not at home [Albeck-Ripka, 2021].
4. Taking a reusable bag to the store and reducing use of single-use plastics [Albeck-Ripka, 2021].

For human societies, the following possible actions can be taken:

1. Afforestation and reforestation

   Worldwide, forests currently sequester on the order of 2 Gt of CO_2 per year. If performed at a high enough rate or volume, afforestation and reforesting could increase this by a gigaton or more [ENSIA 2017].
2. Carbon farming

   This practice uses plants to trap CO_2, then strategically uses practices such as reducing tilling, planting longer-rooted crops and incorporating organic material into the soil to encourage the trapped carbon to move into and stay in the soil [ENSIA 2017].
3. Bioenergy with carbon capture and storage (BECCS)

   BECCS is the process of extracting energy from biomasses and subsequently capturing and storing the emissions to keep them from entering the atmosphere [ENSIA 2017].
4. Direct air capture and storage

This approach uses chemicals or solids to capture greenhouse gases from thin air, then, stores them for extended periods either underground or in long lasting materials [ENSIA 2017].

2.3 Fossil fuel power plants

Fossil fuel power plant are a type of thermal power plant which burns fossil fuels to produce heat which can be used to create steam, and then through use of a turbine, electricity. Fossil fuels include coal, petroleum, oil shales, natural gas, bitumen, tar sand and heavy oils. They all contain carbon and formed as a result of geologic processes acting on organic matter [Kopp, 2020]. According to the World Nuclear Association, fossil fuel generated 63.3% of worldwide electricity in 2020 [World Nuclear Association, 2021]. Of all fossil fuels, coal burning power plants produced most the most electricity in the world. Based on the data from World Nuclear Association, Figure 2.4 presents the global electricity production by source.

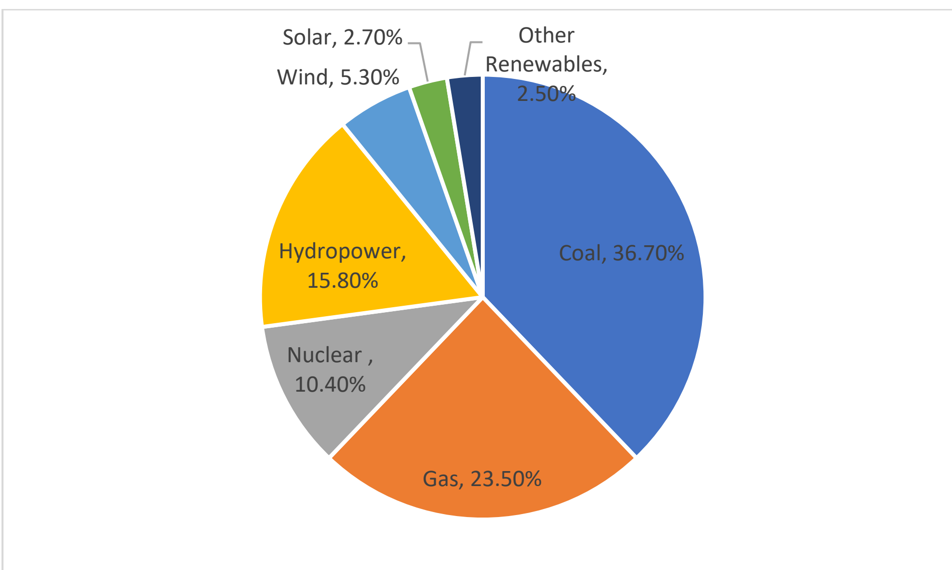


Figure 2.4 World electricity generation by sources (Own elaboration based on data from [World Nuclear Association, 2021])

From this figure, we can see that coal power plants produced 36.7% of the world's total electricity, natural gas power plants produced 23.5% and petroleum power plants produced 3.1% of the total. This data also indicated that fossil fuel power plants play an important role in power generation despite the huge amount of CO_2 they emitted every year.

The average efficiencies of power generation are 35% for coal, 45% for natural gas and 38% for oil-fired power generation [Zeiss, 2010]. Table 2.1 shows the heat values of various fossil fuels in terms of the amount of heat released during their combustion.

Fuel	Heat Production (KJ/g)
Petrol/ gasoline	44-46
Diesel	42-46
Crude oil	42-47
Liquefied petroleum gas (LPG)	46-51
Natural Gas	42-55
Hard black coal (IEA definition)	>23.9
Sub-bituminous coal (IEA definition)	17.4-23.9
Lignite/brown coal (IEA definition)	<17.4

Table 2.1 Heat value of various fossil fuels (Own elaboration based on data from [World Nuclear Association, 2021])

Table 2.1 indicates that the heat values for different fossil fuels varies. Among these fossil fuels, coal produces the least amount of heat by mass when compared to other fossil fuels. This translates into lower efficiencies in terms of power production. Besides the heat value, the CO_2 emissions, per unit energy, varies significantly between the different fossil fuels Table 2.2 shows the amount of CO_2 different fossil fuel produce when they are burned.

Fuel	Pounds of CO_2 emitted per million British thermal units (Btu) of energy
Coal (anthracite)	228.6
Coal (Bituminous)	205.7
Coal (Lignite)	215.4
Coal (Subbituminous)	214.3
Diesel fuel and heating oil	161.3
Gasoline (without ethanol)	157.2
Natural gas	117.0

Table 2.2 Pounds of CO_2 emitted per million British thermal units (Btu) of energy for various fuels (Own elaboration based on data from [EIA, 2021])

From Table 2.2, it can be seen that, per unit of energy, coal will emit the most CO_2 and natural gas emit the least. As previously mentioned, coal power plant produced the most power in world, and also produced the most CO_2 emissions. However, the capacity of coal power plants continues to increase worldwide particularly due to China. Figure 2.5 shows the global coal power capacity operating in 2010 through 2019.

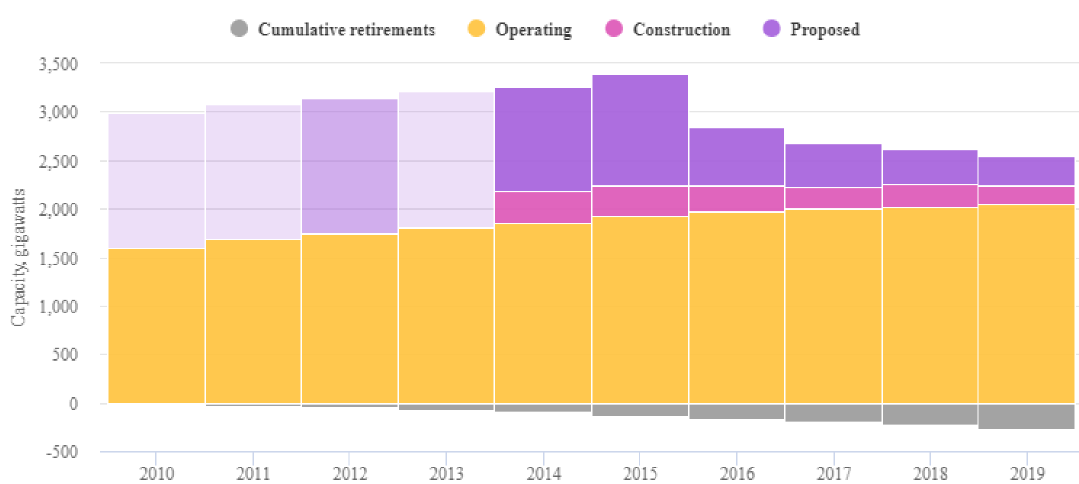


Figure 2.5 Global coal power capacity operating in 2010 through 2019 (Cited from [CarbonBrief, 2020])

Figure 2.5 indicates that the global coal power capacity is still rising: however, the proposition of new coal power plants construction has decreased strongly in the last years. It also reveals that the world's coal capacity will reach a peak and then start to fall [CarbonBrief, 2020].

Due to the huge quantity of CO_2 emissions from fossil fuel power plants, the reduction of CO_2 emissions must be achieved by decommission the FFPPs as fast as possible to mitigate the effects they have on global warming.

2.4 Nuclear power plants

Nuclear power plants use a nuclear reaction to produce steam which can then be used to create electricity. There are no GHGs produced during the fission process, and it does not contribute to air pollution. [World Nuclear Association, 2021]. Nuclear power provided 10% of the world's electricity in 2018 and the use of nuclear power has already reduced CO_2 emissions by 60 gigatons over the past 50 years [IEA, 2019].

It is estimated that the GHG emissions from both Light Water Reactors (LWR) and Heavy Water Reactors (HWR) is between 10 and 130g of CO_2 per KWh of electricity they produce [Lenzen, 2008]. LWRs and HWRs, therefore produce only a fraction of the emissions that can are produced by FFPPs. Additionally, the heat produced by 1 gram of nuclear fuel is much larger than that from equivalent amounts of fossil fuels. Table 2.3 shows the heat value of nuclear fuels.

Fuel	Heat Production (KJ/g)
Natural uranium, in LWR (normal reactor)	500,000
Natural uranium, in LWR with U & Pu recycle	650,000
Natural uranium, in FNR	28,000,000
Uranium enriched to 3.5%, in LWR	3,900,000

Table 2.3 Heat value of various nuclear fuels (Own elaboration based on data from [World Nuclear Association, 2021])

One NPP only produces about 7.2% the amount of GHGs compared to a FFPP [Colpetzer, 2014]. The table below show the data of current existing CPPs, PPPs, NGPPs and NPPs in the world. It shows that NPPs are much more environment friendly than FFPPs at least from the GHG emission point of view.

Plant	Operating units in 2019	MWh/unit	Ton CO_2/MWh	% of CPP
Coal Power Plant (CPP)	7,813	1,300,000	1.05	100%
Petroleum Power Plant (PPP)	31,136	24,896	0.78	74%
Natural Gas Power Plant (NGPP)	32,439	189,522	0.44	42%
Nuclear Power Plant (NPP)	440	7,250,000	0.012	1%

Table 2.4 Power output and CO_2 emissions from each type of power plants (Own elaboration based on data from [IEA, 2020] and [World Nuclear Association, 2021])

From the table, it can be seen that NPPs only produce 1% of CO_2 emissions as that from a CPP [World Nuclear Association, 2021]. This is estimated based on a life cycle assessment, and the majority of CO_2 emissions are from cement and steel production, and component manufacturing during construction [World Nuclear Association, 2021]. This study analyzes the effects of the replacement of FFPPs by NPPs. The FFPPs gradual decommissioning is based on different target year to reach zero CO_2 emissions: at the same time new NPPs will go into operation in order to meet global power demands.

2.5 Electric vehicles

According to the IEA, transportation is responsible for 24% of direct CO_2 emissions from fuel combustion [IEA, 2021]. Although the number of Electric vehicles (EV) has been rapidly increasing in recent years, traditional fossil fuel consuming vehicles are still the main transportation tool around the world. In most countries, EVs account for less than 1% of the total passenger vehicles. Table 2.5 shows the number of traditional vehicles and electric vehicles in some countries.

Country	Number of Traditional Vehicles	Number of Electrical Vehicles	EV Percentage
China	207,000,000	3,100,000	1.498%
US	118,520,440	1,126,000	0.950%
Japan	61,770,573	296,215	0.480%
Brazil	39,507,050	11,858	0.030%
Germany	46,475,000	196,750	0.423%
France	32,006,000	204,617	0.639%
UK	32,201,000	197,000	0.612%

Table 2.5 Number of passenger vehicles in some countries in 2019 (Own elaboration based on data from [Nation Master, 2021])

According to the IEA, the stock of electric vehicles expanded by an annual average of 60% from 2014 to 2019 [IEA, 2020]. Figure 2.6 shows the stock of EVs from 2010 to 2019 which indicates that the demand for EVs has been increasing rapidly.

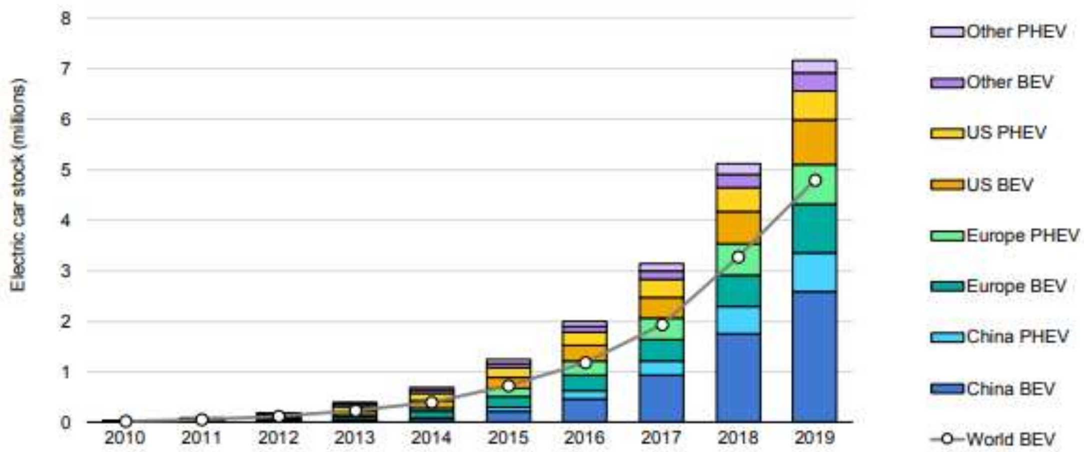


Figure 2.6 Global electric car stock, 2010-2019 (Cited from [IEA, 2020])

EVs can consume twice as much energy during the manufacturing process as TVs, which increases the overall CO2 emissions associated with EVs. However, over their years of usage, EVs generate far lower CO_2 emissions particularly if electricity is produced via low carbon emission methods [Poovanna, 2018]. Thus, over longer periods of time, EVs are considered more environmentally friendly. Although EVs produce lower emissions, there is a barrier, in the form of cost, which may be preventing larger portions of the population from buying them. Due to this, there are many policies whose aim is to promote the purchase and use of electric vehicles through monetary incentives such as rebates, and other tax incentives. [IEA, 2021].

There are many reasons why EVs have become more and more popular: they are more efficient than gas-powered cars, require less maintenance and are environmentally friendly [EnergySage, 2019]. Since EVs help to decrease CO_2 emissions, increasing the number of EVs, while decreasing the number of traditional vehicles, may help to combat climate change. This study estimates the effects which replacing TVs with EVs would have upon global CO2 emissions. Furthermore, the impacts of EV on global climate will be predicted by using appropriate simulation models.

2.6 Electric heaters

The majority of North American households depend on a central furnace to produce heat which can be powered by electricity, natural gas or fuel oil [Smart House, 2021]. Globally, heating accounts for 40% of energy-related CO_2 emissions [Cole, 2020]. In recent years, the market of electric heaters has increased steadily, statistic indicate that the global electric heater market reached 8.57 billion USD, and it is predicted that the EH market will continue to increase [Statista, 2018]. Based on the data from Statista, Figure 2.7 shows the EH market value worldwide from 2017 to 2025.

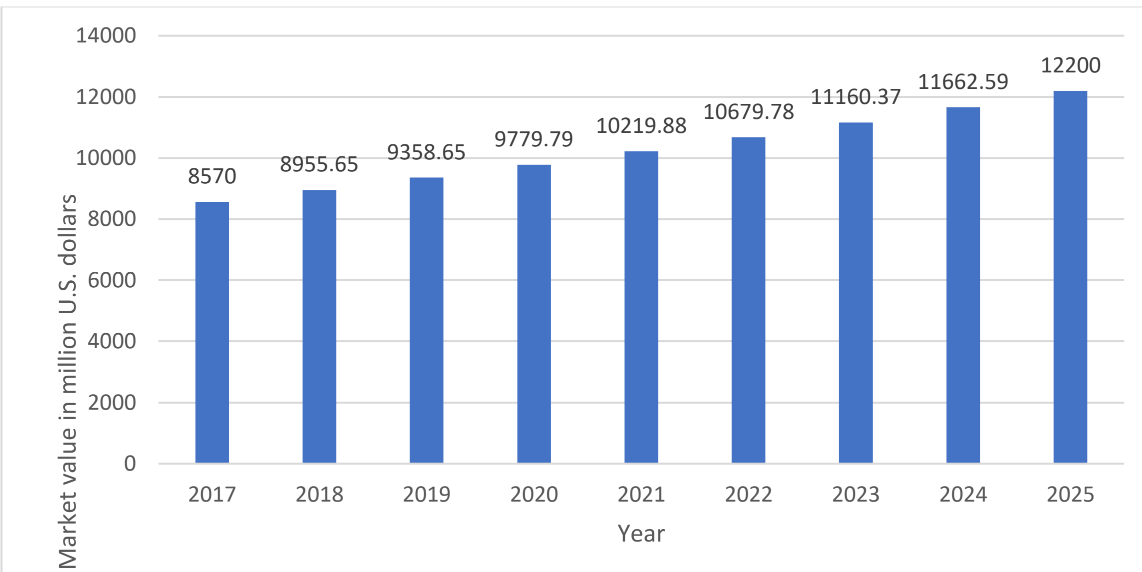


Figure 2.7 Electric heater market value worldwide from 2017 to 2025 (Own elaboration based on data from [Statista, 2018])

The increasing use of electric heaters can reduce global CO_2 emissions by eliminating the need to use fossil fuel-based heating in residential and commercial buildings. In this research, all the Fossil Fuel Heaters are replaced by EHs in order to reduce CO_2 emissions. In this study, convection heaters which use electricity to provide heat are considered in terms of domestic electric heaters. The effects of the reduction of CO_2 emissions from heating will be measured in order to analyze whether EHs are a viable part of the solution to climate change.

Chapter 3. DICE model and modification

3.1 DICE model

In the disciplines of natural and social sciences, there are multiple factors and relationships that link together and form a complex system. Integrated assessment models (IAMs) are one approach to deal with such complex systems, integrating knowledge from several domains into a single framework [Nordhaus, 2018]. These models are widely used in climate change research because of their simplicity and ease of use [Ward, 2019]. Research lead by Hausefather, which conducted a systematic evaluation of the performance of 17 climate models, showed no evidence that the climate models evaluated either systematically overestimated or underestimated warming over the period of their projections [Buis, 2020].

There are many research centers and thousands of climate scientists creating and fine-tuning computerized climate models worldwide [Climate Atlas of Canada, 2021]. Climate models are typically generated from mathematical equations that uses thousands of data points to simulate the climate system [Blogger, 2018].

The Dynamic Integrated Climate Change (DICE) model is one of the earliest IAMs for climate change. The DICE model is a simplified analytical and empirical model that represents the economic, policy, and scientific aspects of climate change [Nordhaus, 2013]. It was first been developed by William Nordhaus in 1992 and, has received continued attention as an early contribution to climate change modeling and simulation research.

Figure 3.1 shows a schematic flow chart of the major modules and logical structure of the DICE model [Nordhaus, 2013]. This is a closed loop: the CO_2 emissions have influence on the carbon cycle which will then affect the climate system by changing the radiative warming, sea level rise and so on. Due to climate change, the ecosystem, agriculture, and other biological related areas will be affected. Then, people will seek possible measures to control emissions in order to mitigate climate change. As the CO_2 emissions change, it will then influence other parameters in the model. The following schematics represents this closed loop (Fig. 3.1).

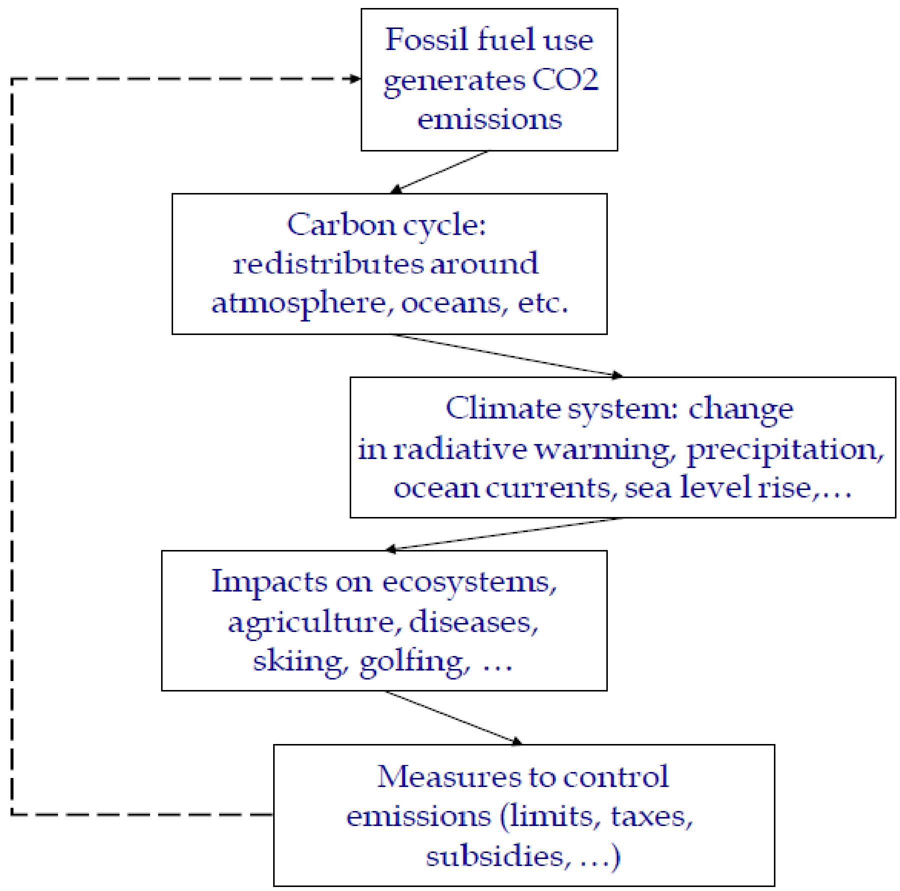


Figure 3.1 Schematic flow chart of the logical structure of the DICE model (Cited from [Nordhaus, 2013])

The DICE model is an integrated economic model able to estimate the global impacts of climate change on the economy. The model relies on cost minimization and economic welfare (or utility) maximization. The DICE model combines labor and capital assuming a constant return rate; the model precludes economic collapse either in the form of mass unemployment or financial crisis as fundamental assumptions. It is important to stress that the DICE model deals with problems related to climate change using a macroeconomics approach, primarily looking at historical decisions made by countries or governments as a whole.

Economics, in the research context here, is divided into two categories which are microeconomics and macroeconomics. Microeconomics is the study of individual and business decisions, it focuses on supply and demand and other forces that determine price levels in the economy, making it a bottom-up approach [Staff, 2021]. Macroeconomics, looking at the decisions of countries and governments and takes a top-down approach and looks at economy across large domains [Staff, 2021]. For this reason, the DICE model adopts a classical top to bottom approach, estimating the impact of policies on a global scale, primarily looking at economies of industries, gross domestic product (GDP) variations, rates of growth (including population) and price levels.

The DICE model consists of algebraic equations describing macro econometric correlations without considering, as typically done in microeconomics, problems related to the demand and supply chain, labor economics and cost of production. The DICE model does not deal with human choices, local decisions or allocation of resources but rather seeks the least-cost emission pathway, thus providing an evaluation of the "social cost of carbon."

The algebraic equations integrated in DICE define one variable in terms of others that are casually connected. DICE does not set or solve partial differential or integral differential equations if posed in a microeconomic approach and as such assumes that the cost of reducing emissions for a given period is substantially unrelated to the previous determined pathway nor influences in any way subsequent evaluations or future prospects. This temporal independence can be seen as one of the major limitations of its applicability in climate change related research studies [Nordhaus, 2013].

In this model, the atmospheric CO_2 concentration is assumed as the "natural capital" and it has a negative effect on economic output because of its influence on global average surface temperature. DICE is an optimal control model which was designed to help stakeholders make informed decisions (or scenario-based decisions) on balancing the cost and benefit when considering CO_2 emissions. Figure 3.2 shows the DICE model used in this thesis with key variables in GUI-based representation.

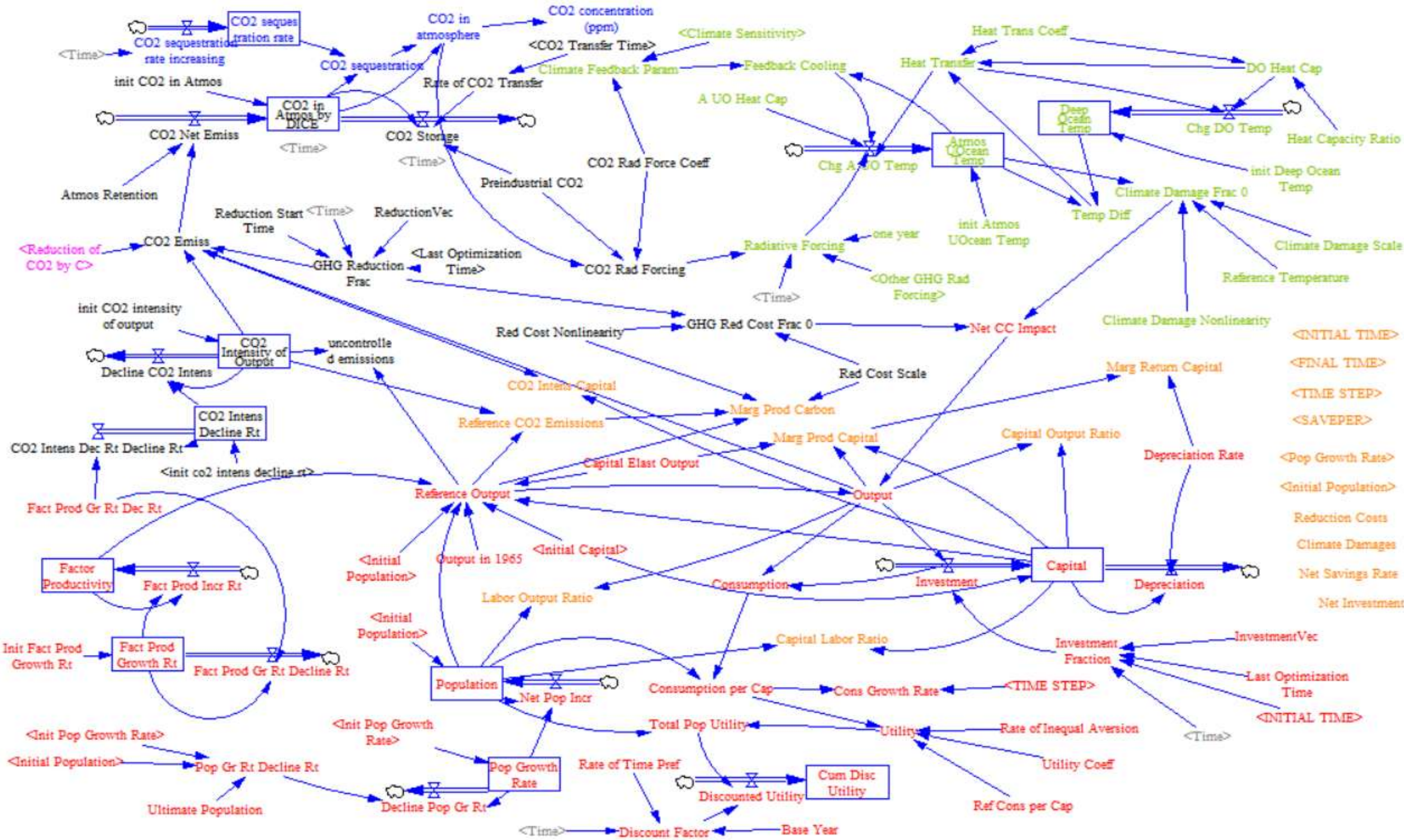


Figure 3.2. DICE model

There are various versions of the model, widely cited by climate economists and policy professionals. For example, it has been used by the US government to estimate the social cost of carbon. From this, the government has set policies in order to mitigate and adapt actions [Easton, et al., 2014].

This model is divided into four major sections. The black colored region (Figure 3.2) represents aspects connected to carbon production or emission; the green colored region represents the climate model; the red colored region represents a model connected to economy while the orange-colored region presents indices. In this research, we sought DICE climate change variables as follows: CO_2 in atmosphere, atmospheric and ocean temperature, climate damage etc. as per definition into the DICE original model. These variables are chosen as they show the main consequences resulting from the effects of climate change which are predicted by DICE model.

The original DICE model only predicts the amount of CO_2 concentration in atmosphere. In this work the atmospheric CO_2 concentration level is expressed via parts per million (ppm) as this measure is widely used globally. For this reason, the original DICE model was modified accordingly (blue region in Figure 3.2). Furthermore, the atmospheric CO_2 concentration calculated by the original DICE model is higher than the actual measured level: for this reason, a new parameter labelled "CO_2 sequestration" is introduced. The CO_2 concentration from 1992 to 2011 calculated by the original DICE model was then compared with the actual level of CO_2 concentration which was observed by the Mauna Loa Observatory in Hawaii. The difference was then adjusted through the CO_2 sequestration. The detailed methods used to reduce such amount of CO_2 are not considered.

After the calibration, the CO_2 concentration calculated by the modified DICE model is much more consistent with the actual level.

3.2 NPP (Nuclear Power Plant) sub-model

In order to understand the impact of the replacement capacity of nuclear power plants and electrical vehicles on the reduction of CO_2 emissions, the DICE model has been modified accordingly. Three new sub-models have been added: the nuclear power plant model which is used to address the replacement of fossil fuel power plants (FFPPs) with NPPs is addressed in this section. This, in simple terms, is to replace existing FFPP generating capacity. The number of FFPPs that are assumed in shut down mode when one NPP is constructed is determined by the ratio of the power produced by one NPP compared to that of the FFPP. The orange, black and blue colored regions show the replacement process (Figure 3.2). We assume that if FFPPs are being replaced fully by NPPs: as a consequence, greenhouse gas (GHG) emissions will decrease as the CO_2 emissions from FFPPs are far greater than those produced by an NPP.

In this study, different target years to reach zero CO_2 emission are studied alongside the time to calculate NPP construction rates to predict the CO_2 emissions, in addition to CO_2 concentrations, atmospheric and deep ocean temperature changes and climate damage. The parameter "target year to reach CO_2 emission" is introduced in this contest as more and more countries are committed to moving to net zero CO_2 emissions by 2050. Achieving net zero emissions means either emitting no greenhouse gases or offsetting the existing emissions [Government of Canada, 2021]. Figure 3.3 shows the proposed nuclear power plant sub-model.

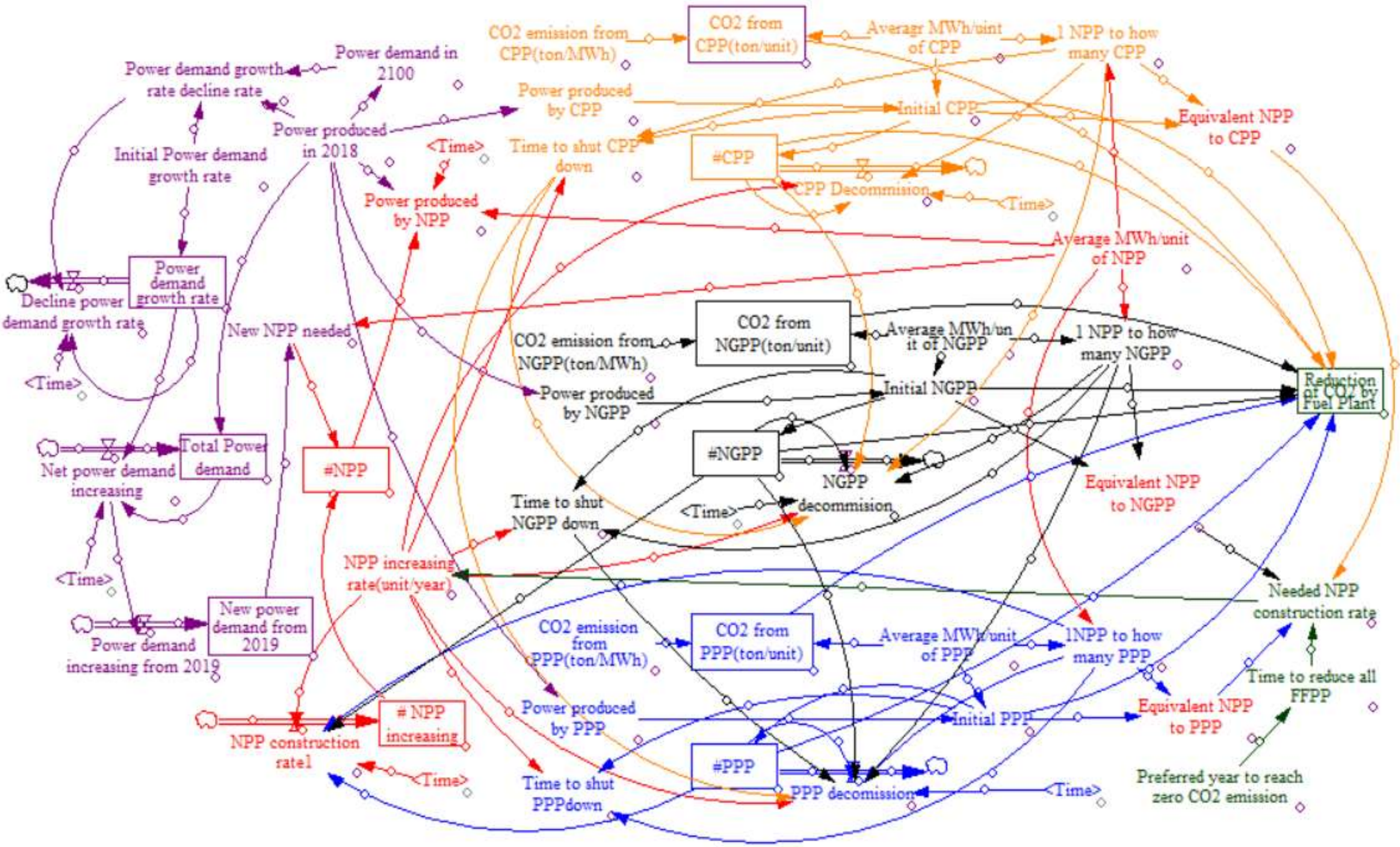


Figure 3.3. Nuclear power plant model

In Figure 3.3, the orange color represents all the variables related to Coal Power Plants. Firstly, a simulation of CO_2 emissions from CPPs in order to produce one megawatt-hour (MWh) electricity and the average capacity of one CPP unit is used to calculate the average CO_2 emission per unit CPP. The calculation process can be expressed by the following equations:

- CO_2 emissions from CPP = 1.05 tons/MWh (3.1)
- Average MWh/unit of CPP = $1.3*10^6$ MWh/unit (3.2)
- CO_2 emission from CPP = CO_2 emissions from CPP* Average MWh/unit of CPP = $1.05*1.3*10^6 = 1.365*10^6$ tons/unit (3.3)

Secondly, the average capacity of one unit of CPP and NPP is compared in order to find out the equivalent number of CPP units to one NPP unit. The calculation process can be expressed as follows:

- Average MWh/unit of CPP = $1.3*10^6$ MWh/unit (3.4)
- Average MWh/unit of NPP = $7.25*10^6$ MWh/unit (3.5)
- 1 NPP to how many CPP = Average MWh/unit of NPP/ Average MWh/unit of CPP = 5.58 (3.6)

Thirdly, based on the number of FFPPs currently operating in the world which was estimated based on the power produced in 2018 and the average capacity of a CPP, NGPP and PPP, and the time left to reach zero CO_2 emissions, the construction rate of NPP is calculated. The calculation process can be expressed as follows:

- Power produced in 2018 = $2.67*10^{10}$ MWh (3.7)

- Power Produced by CPP = Power produced in 2018 * 0.38 (3.8)
- Initial CPP = Power Produced by CPP/ Average MWh/unit of CPP (3.9)
- Equivalent NPP to CPP = Initial CPP/1 NPP to how many CPP (3.10)
- Power Produced by NGPP = Power produced in 2018 * 0.23 (3.11)
- Initial NGPP = Power Produced by NGPP/ Average MWh/unit of NGPP (3.12)
- Equivalent NPP to NGPP = Initial NGPP/1 NPP to how many NGPP (3.13)
- Power Produced by PPP = Power produced in 2018 * 0.029 (3.14)
- Initial PPP = Power Produced by PPP/ Average MWh/unit of PPP (3.15)
- Equivalent NPP to PPP = Initial PPP/1 NPP to how many PPP (3.16)
- Time to reduce all FFPP = Preferred year to reach zero CO_2 emission – 2019 (3.17)
- Needed NPP construction rate = (Equivalent NPP to CPP+ Equivalent NPP to NGPP+ Equivalent NPP to PPP)/ Time to reduce all FFPP (3.18)

In equation 3.8, 3.11 and 3.14, 0.38 presents the percentage of power produced by CPP in 2018, NGPP produced 23% of the total power and PPPs produced 2.9% of the total power.

Then, the decommissioning rate of CPPs is estimated as the construction of NPPs. The decommissioning process of CPPs can be expressed as follows:

(1) If the simulation time reached 2019 and the number of CPP is more than the equivalent NPP to CPP, then:

- CPP decommission = 1 NPP to how many CPP *NPP increasing rate (3.19)

(2) If the simulation time reached 2019, there are still CPP but the number of CPP is less than the equivalent NPP to CPP, then:

- CPP decommission = #CPP (3.20)

(3) If the simulation time hasn't reached 2019 or no CPPs exist, then:

- CPP decommission = 0 (3.21)

For the equation "CPP decommission", it will start to decommission CPPs in 2019, the decommissioning rate is calculated based on the variable "1 NPP to how many CPP" and "NPP increasing rate (unit/year)". As the decommissioning rate of CPPs was calculated, the number of CPPs will then be calculated.

Finally, due to the decommissioning of CPPs, the CO_2 emissions avoided is estimated. The calculation process can be expressed as follows:

- Reduction of CO_2 emissions from CPP = CO_2 from CPP (ton/unit) * (Initial CPP-#CPP) (3.22)

However, as the target year to reach zero CO_2 emissions is different in each scenario, the reduction of CO_2 emissions is also different. Figure 3.4 shows the global number of CPP units versus time under eight scenarios of the CPP decommissioning rate based on the target net zero CO_2 year. In this study, it's assumed that there are no new CPP that go into operation after 2019 and the time to decommission a CPP is essentially ignored. Because decommissioning a CPP is a complex process and the time required to physically decommission a CPP varies, thus, the time is not considered in this work as also proposed by other researchers [Johnson, et al., 2019].

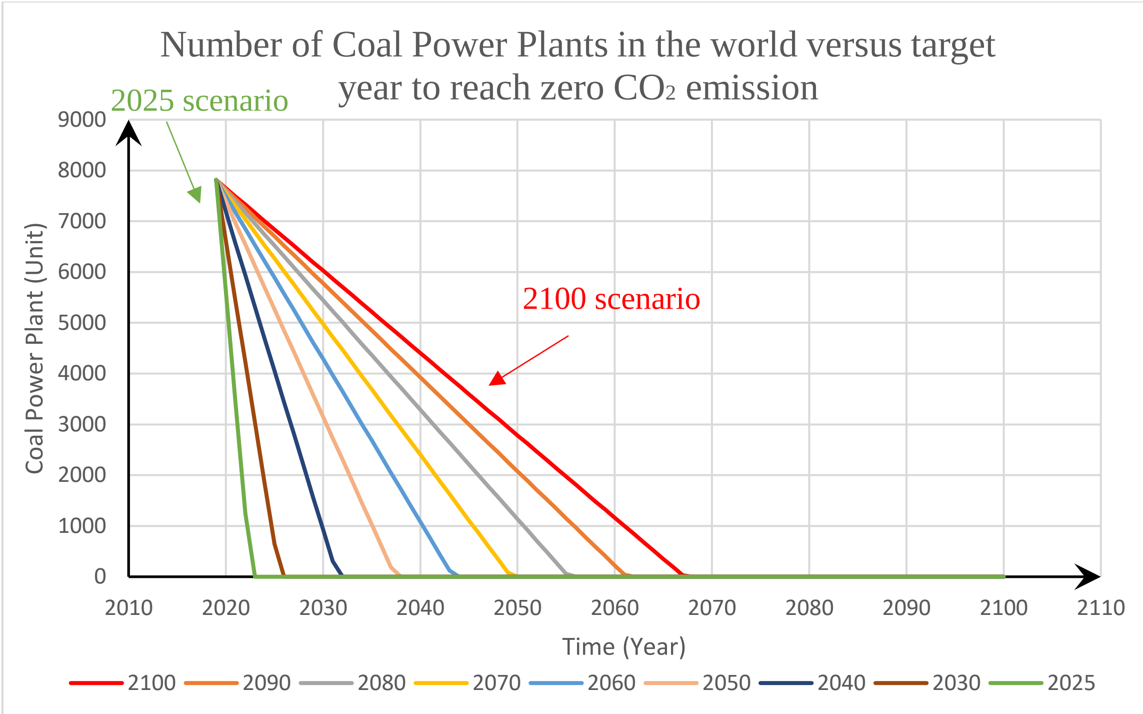


Figure 3.4. Number of Coal Power Plants in the world with different target year to reach net zero CO_2 emission

In this figure, the green curve represents the 2025 scenario. In this scenario, about 2,200 CPPs must be decommissioned every year: this rate of decommissioning and replacement with NPPs is impractical and not feasible. Although that it is known to be impractical, the 2025 scenario has been presented as an extreme case for means of comparison, not as a practical solution to climate change. The red curve represents the reduction of CPPs under a 2100 target scenario. Here, the global decommissioning rate of CPPs is about 162 units per year. Between the extreme and year 2100 reduction trends, other trends (curves) are shown and correspond to other possible intermediate scenarios. Throughout the thesis, results from simulations such as Figure 3.4 are consistently shown with representative "immediate" (2025), "long-term" (2100) and "intermediate" curves in between. The per unit CPP decommissioning rate is given in Table 3.1. From this table, as the target year to reach net zero CO_2 emission is postponed, the decommission rate of CPP will decrease. This will lead to an increasing in the annual CO_2 emissions.

Target year to reach zero CO_2 emission	CPP decommission rate (unit/year)
2025	2,190
2030	1,194
2040	626
2050	424
2060	320
2070	258
2080	215
2090	185
2100	162

Table 3.1. Coal Power Plant decommission rate in different scenarios

In the NPP model, the coal-powered plants were replaced first as those are the larger CO_2 emitters compared to other types of FFPPs (natural gas and petroleum) [IEA, 2018]. After all the CPP are decommissioned, natural gas plants are then replaced by NPPs.

The black region in Figure 3.3 shows the variables related to NGPPs, in a manner similar to the CPP replacement model. They have the same calculation process, however, the data for them is different. The calculation process of NGPP sub-model can be expressed as follows:

- CO_2 emission from NGPPs (ton/MWh) = 0.44 tons/MWh (3.23)
- Average MWh/unit of NGPP = 189,522 MWh/unit (3.24)
- CO2 from NGPP (ton/unit) = CO_2 emission from NGPPs (ton/MWh) * Average MWh/unit of NGPP = 83,390 tons/unit (3.25)

- 1 NPP to how many NGPP = Average MWh/unit of NPP/ Average MWh/unit of NGPP (3.26)

The decommission rate of NGPPs can be calculated as follows:

(1) If the simulation time reached 2019 plus the time to shut down CPP minus 1 and the time reached 2019 plus time to shutdown CPPs, then:

- NGPP decommission = [NPP increasing rate(unit/year) - #CPP / 1 NPP to how many CPP")] * 1 NPP to how many NGPP (3.27)

Under this situation, the CPP and NGPP are both decommissioned in the same year, because there are not enough CPPs remaining to be decommissioned in that year. Thus, NGPPs start to be decommissioned.

(2) If simulation time reached 2019 plus time to shutdown CPP and number of NGPP is more than equivalent NPP to NGPP times NPP increasing rate, then:

- NGPP decommission = 1 NPP to how many NGPP * NPP increasing rate (3.28)

(3) If simulation time reached 2019 plus time to shutdown CPP and there has NGPP but number of NGPP is less than equivalent NPP to NGPP times NPP increasing rate, then:

- NGPP decommission = #NGPP (3.29)

Under this situation, there’s not enough NGPP to be decommissioned as and replaced with NPPs. Thus, PPPs start to be decommissioned which is introduced later in the PPP sub-model.

(4) If the simulation time has not reached 2019 and there’s no NGPP, then:

- NGPP decommission = 0 (3.30)

As the decommission rate of NGPPs was calculated, the existing number of NGPPs can be calculated. Due to the decommission of NGPPs, reduction of CO_2 emission from NGPPs can be calculated as:

- Reduction of CO_2 emission from NGPP = CO2 from NGPP (ton/unit) * (Initial NGPP - #NGPP) (3.31)

Among those variables, the variable "NGPP decommission" is the most important one: in fact, it indicates when NGPPs start to be decommissioned in different scenarios, which can only be started once all of the CPPs have been decommissioned.

Although there are more NGPPs than CPPs, the total CO_2 emission from NGPPs is less than that from CPPs. Figure 3.5 depicts the decommission rate of NGPPs in the world. It has been estimated that there are about 32,500 NGPPs currently operation in the world, as of 2019 [IEA, 2018]. This estimate is based on the data of the world's annual electricity generation from NGPPs and the average capacity of one NGPPs. Also, the assumption that there are no new NGPPs going into operation after 2019 was made here and the decommissioning time of NGPPs is not considered.

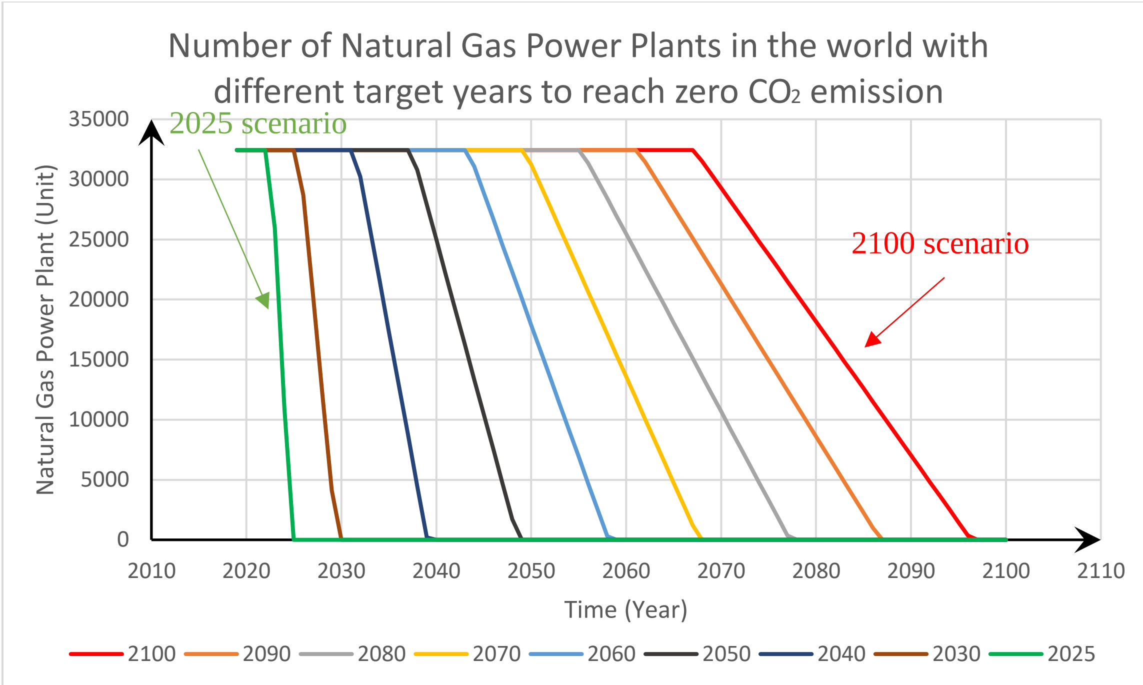


Figure 3.5. Number of Natural Gas Power Plants in the world with different target years to reach zero CO_2 emission

In the Figure 3.5, the green curve shows the most immediate scenario in which there would be about 15,000 NGPP units decommissioned per year. In this bounding scenario, NGPPs are decommissioned starting in 2022 and though unlikely, in less than three years all NGPPs are shut down. The red curve represents the 2100 scenario which coincides with the longest time for the decommissioning of FFPPs: the reduction rate of NGPP is about 1,100 units per year in this case. In this scenario, the shutdown of NGPPs starts in 2067. The remaining curves correspond to scenarios, 2030 to 2090, and are shown from left to right in the figure. The tabulated NGPPs decommissioning rate under these different scenarios is also shown in Table 3.2.

Target years to reach zero CO_2 emission	NGPP decommission rate (unit/year)
2025	15,021
2030	8,193
2040	4,292
2050	2,907
2060	2,198
2070	1,767
2080	1,477
2090	1,269
2100	1,113

Table 3.2. Natural Gas Power Plant decommission rate in different scenarios

The decommission rate of NGPPs varies from 1113 units/year to 15021 units/year. This range exists due to the varying rates of CPP decommissioning rates of the scenarios postulated, which must be completed before the NGPPs start to be decommissioned. Some of the decommissioning rates are indeed quite aggressive and highly unlikely to be realized.

Finally, after all CPPs and NGPPs in the world are decommissioned, the PPPs are replaced as shown in blue color in Figure 3.2. In contrast to CPPs and NGPPs, PPPs contribute least to CO_2 emissions. This is why the decommissioning of PPPs is selected as last. Currently, there are about 31,000 PPPs operating in the world, and the average capacity of a PPP is much smaller than a nominal NPP. As such the decommissioning rate of PPPs is rapid even under the 2100 scenario. The decommission process of PPPs can be expressed as follows:

- CO_2 emission from PPPs (ton/MWh) = 0.78 tons/MWh (3.32)
- Average MWh/unit of PPP = 24,896 MWh/unit (3.33)
- CO2 from NGPP (ton/unit) = CO_2 emission from PPPs (ton/MWh) * Average MWh/unit of PPP = 19,419 tons/unit (3.34)

- 1 NPP to how many NGPP = Average MWh/unit of NPP/ Average MWh/unit of NGPP (3.35)

Similar to the CPP and NGPP sub-model, the decommission rate of PPPs can be determined as follows:

(1) If the simulation time reached 2019 plus time to shutdown CPPs plus time to shutdown NGPP minus 1 but has not reached 2019 plus time to shutdown CPP plus time to shutdown NGPP, also,

- ("NPP increasing rate(unit/year) - #NGPP / 1 NPP to how many NGPP) * 1NPP to how many PPP > #PPP (3.36)

Under this situation, PPPs can't be decommissioned in the year when all the remaining NGPP have been decommissioned. However, some of them should be able to be decommissioned, hence:

- PPP decommission = #PPP (3.37)

(2) If the simulation time reached 2019 plus time to shutdown CPPs plus time to shutdown NGPP minus 1 but has not reached 2019 plus time to shutdown CPP plus time to shutdown NGPP, also,

- ("NPP increasing rate(unit/year) - #NGPP / 1 NPP to how many NGPP) * 1NPP to how many PPP < #PPP (3.38)

Under this situation, PPPs cannot be decommissioned in the year when all NGPPs decommissioned, but some PPPs was decommissioned in that year, then:

- PPP decommission = (NPP increasing rate(unit/year) - #NGPP / 1 NPP to how many NGPP") * 1NPP to how many PPP (3.39)

(3) If simulation time reached 2019 plus time to shutdown CPPs plus time to shutdown NGPP and number of PPPs is more than equivalent NPP to PPP times NPP increasing rate, then:

- PPP decommission = 1NPP to how many PPP * NPP increasing rate (3.40)

(4) If simulation time reached 2019 plus time to shutdown CPPs plus time to shutdown NGPPs, also, there has PPPs, but the number of PPPs is less than equivalent NPP to PPP times NPP increasing rate, then:

- PPP decommission = #PPP (3.41)

Under this situation, after several years of decommissioning processes, the existing PPPs need less than one year to be decommissioned.

(5) If there are no PPPs or the simulation time has not reached 2019, then:

- PPP decommission = 0 (3.42)

Once the decommission rate of PPPs was determined, the existing number of PPPs can be calculated. Based on the existing number of PPPs and the initial number of PPPs, reduction of CO_2 emissions from PPP can be calculated as:

- Reduction of CO_2 emissions from PPP = Average MWh / unit of PPP * (Initial PPP - #PPP) (3.43)

Similar to the NGPP sub-model, the variable “PPP decommission” is the most important one in the PPP sub-model because PPPs need to be decommissioned after there’s no CPPs or NGPPs remaining. Thus, this variable checks whether there are still CPPs or NGPPs, when it find there's no CPPs and NGPPs, the decommission of PPPs start.

Figure 3.6 shows the decommissioning curves for each scenario. In the 2025 scenario, shown in green color below, the hypothetical scenario takes less than one year to decommission all PPPs. This could, in theory, be possible as the commissioning of one nuclear reactor can potentially offset the replacement power need for about 291 PPPs. Next, the red curve shows the number of PPPs versus time under the 2100 scenario. Although it is the scenario that spans the most years, it only takes about 4 years to shut down all global PPPs under this scenario. Thus, visually all the curves, for all scenarios, practically look vertical.

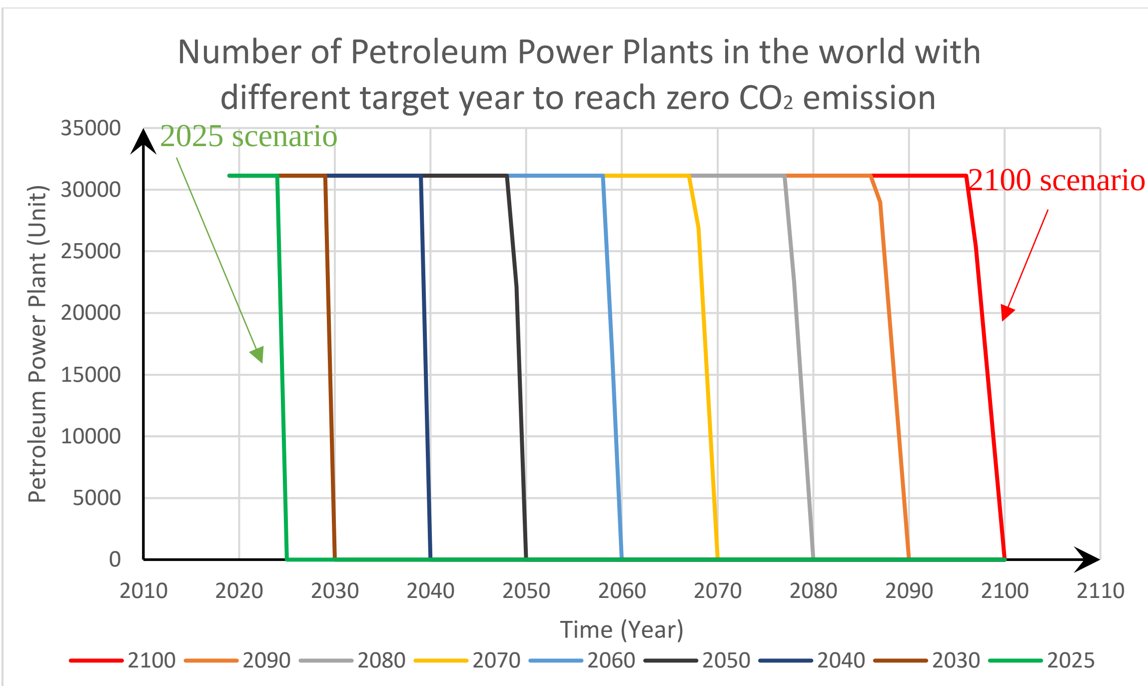


Figure 3.6. Number of Petroleum Power Plants in the world with different target year to reach zero CO_2 emission

Table 3.3 is given to show in tabular form the PPP decommissioning rate for each colored scenario. For scenarios labelled as 2025, 2030 and 2040, the PPP decommission rate is approximately the same, because there are about 31,136 PPPs in the world [IEA, 2018]. Under these three scenarios, all the PPPs are decommissioned within a hypothetical one-year period.

Target years to reach zero CO_2 emission	PPP decommission rate (unit/year)
2025	31,136
2030	31,136
2040	31,136
2050	22,131
2060	16,733
2070	13,452
2080	11,247
2090	9,663
2100	8,470

Table 3.3. Petroleum Power Plant decommission rate in different scenarios

These figures and tables shown so far indicate that the decommission rate of CPPs, NGPPs and PPPs can vary drastically in different scenarios. Based on the different power output from CPPs, NGPPs and PPPs, the annual decommissioning rates are different even though the construction rate of NPPs is held constant. According to the postulated scenarios of this research, CPPs require the most time to decommission due to CPPs having such a large electrical generating capacity, which requires the construction of more NPPs to compensate for their decommissioning. The time to decommission all PPPs is only one to four years because it accounts for the lowest generating capacity, and can therefore be replaced with fewer NPPs, thus requiring less time for the replacements to occur.

As the decommissioning of CPPs, NGPPs and PPPs takes place, the annual CO_2 emissions will decrease. The decrease of CO_2 emission is calculated by the NPP sub-model. The CO_2 emissions decrease attributed to CPPs, NGPPs and PPPs are calculated separately and then, added together to calculate the total CO_2 emissions avoided through the commissioning of NPPs. The equation to calculate the reduction of CO_2 emissions by FFPPs is:

(1) If only CPPs was decommissioned, then:

- reduction of CO_2 by fuel plant = CO_2 from CPP (ton / unit) * (Initial CPP - #CPP) … . (3.44)

(2) If all CPPs were decommissioned and NGPPs started to be decommissioned, then:

- reduction of CO_2 by fuel plant = CO_2 from CPP (ton / unit) * Initial CPP + CO_2 from NGPP (ton / unit) * (Initial NGPP - #NGPP) (3.45)

(3) If all CPPs and NGPPs were decommissioned, and PPPs started to be decommissioned, then:

- reduction of CO_2 by fuel plant = CO_2 from CPP (ton/unit) * Initial CPP + CO_2 from NGPP (ton / unit) * Initial NGPP + CO_2 from PPP (ton / unit) * (Initial PPP - #PPP) … (3.46)

Per equation 3.44, 3.45 and 3.46, the reduction of CO_2 emissions varies as the CPPs, NGPPs and PPPs are decommissioned in this order. Thus, the curve for each scenario has three segments (parts) that correspond to the three main periods of the decommissioning process. This is reflected in Figure 3.7.

The total reduction of CO_2 emissions from CPPs, NGPPs and PPPs is calculated in the variable "reduction of CO_2 by fuel plant" as is shown in Figure 3.7 below. It is then fed into the DICE model CO_2 emission variable to evaluate the impact of FFPPs on the climate.

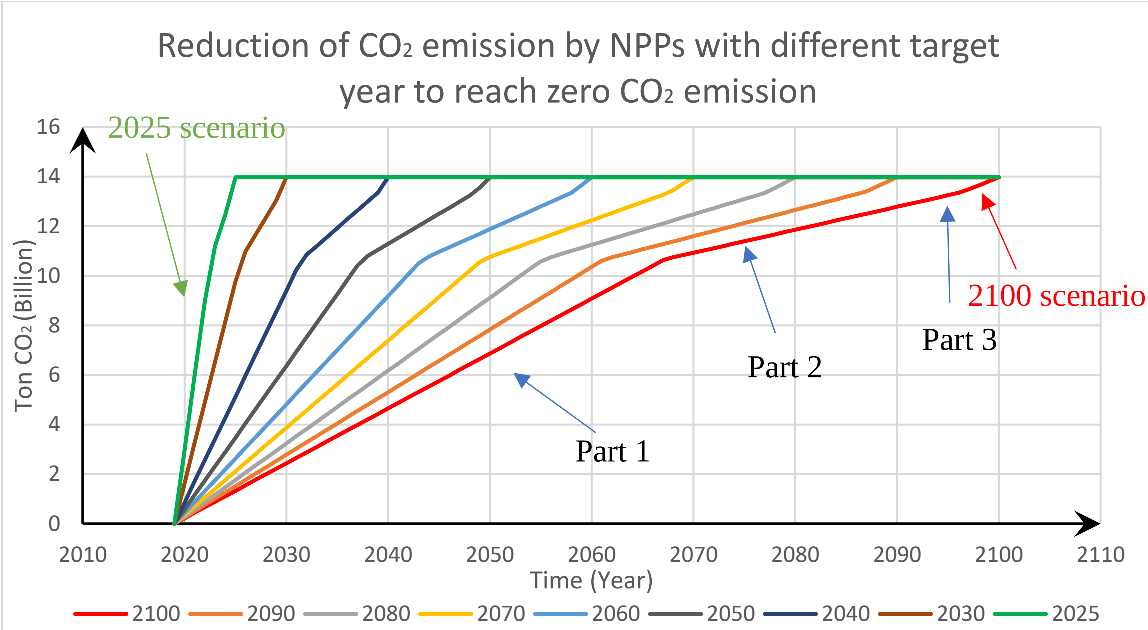


Figure 3.7. Reduction of CO_2 emission by NPPs with different target year to reach zero CO_2 emission

In Figure 3.7, the green curve has the highest rate of increase; this is the 2025 scenario. Because the NPP construction rate in this scenario is much faster than in other scenarios, the FFPPs decommissioning rate is also faster than in any other scenario. Consequently, this will result in the highest rate of CO2 emissions reduction each year. The composite trends of the curves are influenced by three factors, thus reflected in three parts, of which the last one (Part 3) is barely visible. These three segments can be explained as follows; initially the emissions are reduced rapidly. Only as decommissioning of NGPP takes place, the slope of the curve starts decreasing (Part 2). The last part of each curve is where the increasing rate of CO_2 emission reduction changes again due to the shutdown of PPPs being initiated; this last segment is not immediately obvious from the curves of Figure 3.7 due to the smaller capacity of PPPs compared to NPPs. When the PPPs start shutting down, the slope increases as the CO_2 emissions from PPPs to generate 1 MWh electricity, are higher than that from NGPPs. However, the slope is still smaller than in the CPPs portion as the average CO_2 emission from CPPs is larger than that from PPPs.

Finally, the trend becomes a horizontal line as the amount of CO_2 emission become a constant when no more FFPPs can be replaced. After all the FFPPs are decommissioned, a decrease of about 14 billion tons of CO_2 annually can be attained according to the simulations done.

With respect to, the NPP sub-model that is integrated into the modified DICE, the FFPPs are replaced starting from 2019. However, the entire model simulates all data from 1965, as the start time of the original DICE model is set in 1965. Therefore, between year 1965 and 2019, there's no CO_2 emission reduction. Once the FFPPs have been replaced, CO_2 emissions decrease, and this value is directly used in the DICE model such that the outputs metrics change correspondingly. These output metrics will be discussed in chapter 4 and 5.

3.3 Transportation model

Due to the high CO_2 emissions contribution from transportation, a specific model has also been proposed and designed to replace all traditional vehicles in the world. In this study, different scenarios looking at different zero CO_2 emission targets are considered and consequently different EV increasing replacing rates are evaluated. It is also assumed that EV world producers can always meet the demand for EVs by consumers: this is in fact consistent with the general DICE macro-economy settings. There are more than 1 billion traditional vehicles and 4 million electrical vehicles in the world as of early 2019 [Saja, 2020]. All internal combustion engines vehicles are assumed to be replaced gradually with time. The replacement is assumed to start in 2019. As previously done, the output of this model is feed into the DICE model. Figure 3.8 shows the proposed and implemented transportation model.

The model can be separated into two parts: one is dedicated to calculating the increasing vehicles demand and the other one is used to calculate the reduction of CO_2 emissions through the replacement of traditional vehicles by electric vehicles. These two parts are combined to calculate the number of electric vehicles in the world with a significant contribution to CO_2 emission reduction by EVs.

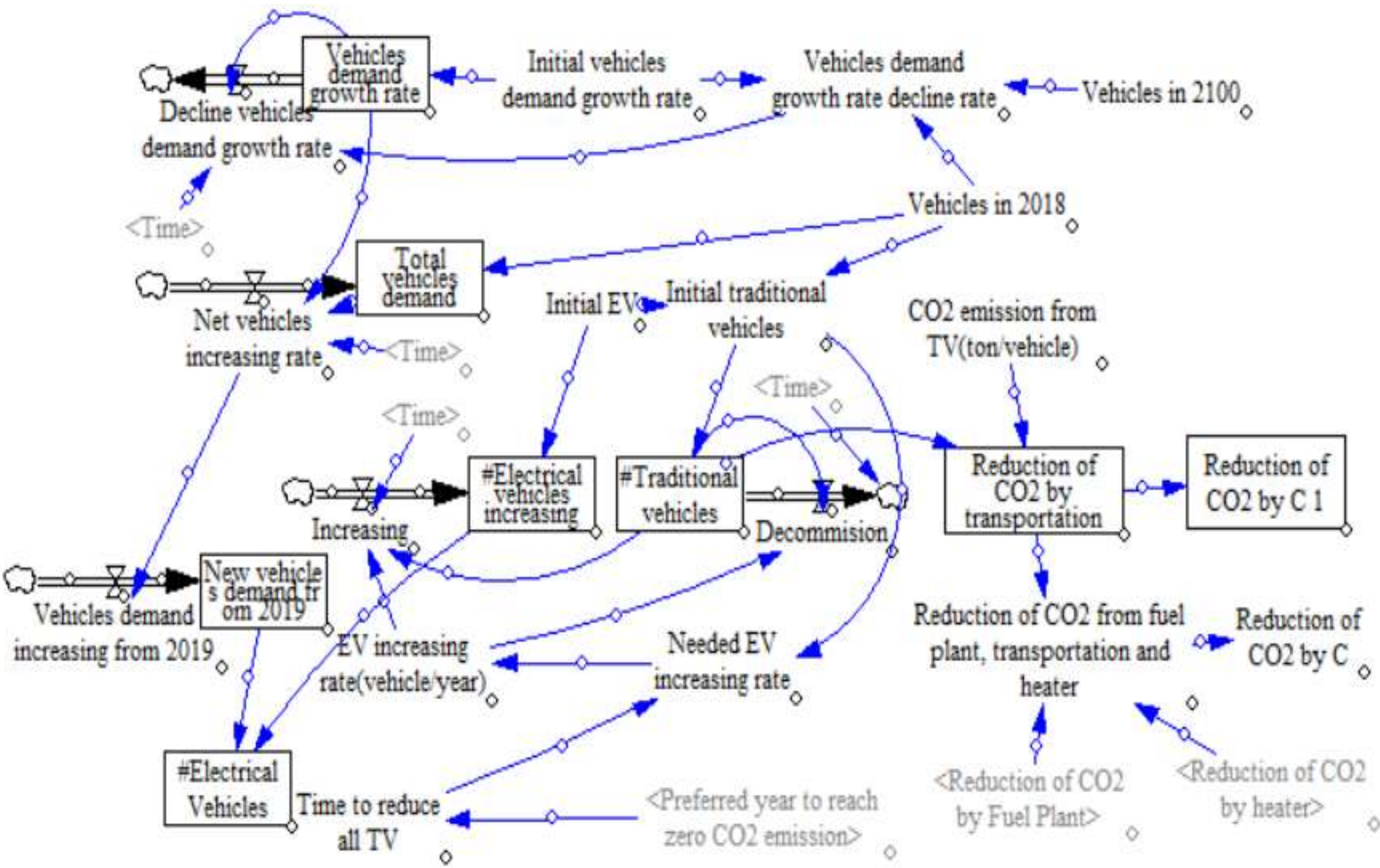


Figure 3.8 Transportation model

In the transportation model, the new EVs put into use are not only to replace the traditional vehicles but also to meet the increasing demand of vehicles as the growth of population in the world. The new demand of vehicles is calculated using the same population growth model used in the original DICE model: under the assumption that there are no more fossil fuel powered vehicles being produced. This appears to be a reasonable assumption, given the fact that the EV demand should be considered proportional to the amount of people predicted to be populating our planet. Thus, the increasing demand of vehicles can be calculated through the following process:

- Vehicles in 2018 = 1.2*10^9 autos (3.47)
- Vehicles in 2100 = 3.06 *10^9 autos (3.48)
- Initial vehicles demand growth rate = 0.04436 auto / year (3.49)
- Vehicles demand growth rate decline rate = Initial vehicles demand growth rate / LN (Vehicles in 2100/Vehicles in 2018) (3.50)

If the simulation time reached 2019, then the decline vehicles demand growth rate and net vehicles increasing rate can be calculated as:

- Decline vehicles demand growth rate = Vehicles demand growth rate*Vehicles demand growth rate decline rate (3.51)
- Vehicle demand growth rate = INTEG (-Decline vehicles demand growth rate) …… (3.52)
- Net vehicles increasing rate = Total vehicles demand*Vehicles demand growth rate … (3.53)
- Total vehicles demand = $\int(\text{Net vehicles increasing rate})$ (3.54)

- Vehicles demand increasing from 2019 = Net vehicles increasing rate. (3.55)
- New vehicles demand from 2019 = $\int$(Vehicles demand increasing from 2019) ….. (3.56)

In the transportation model, it is assumed that EVs emit zero CO_2 during their operational lifespan. The CO_2 emissions during the construction and transportation of EVs, although not negligible, are not considered. Thus, the reduction of CO_2 emissions from one EV is identical to the amount of CO_2 emission emitted by one TVs. When there's no TVs in the world, the new increasing numbers of EVs will have no more influence over the climate. Figure 3.9 shows the number of TVs in the world in different scenarios.

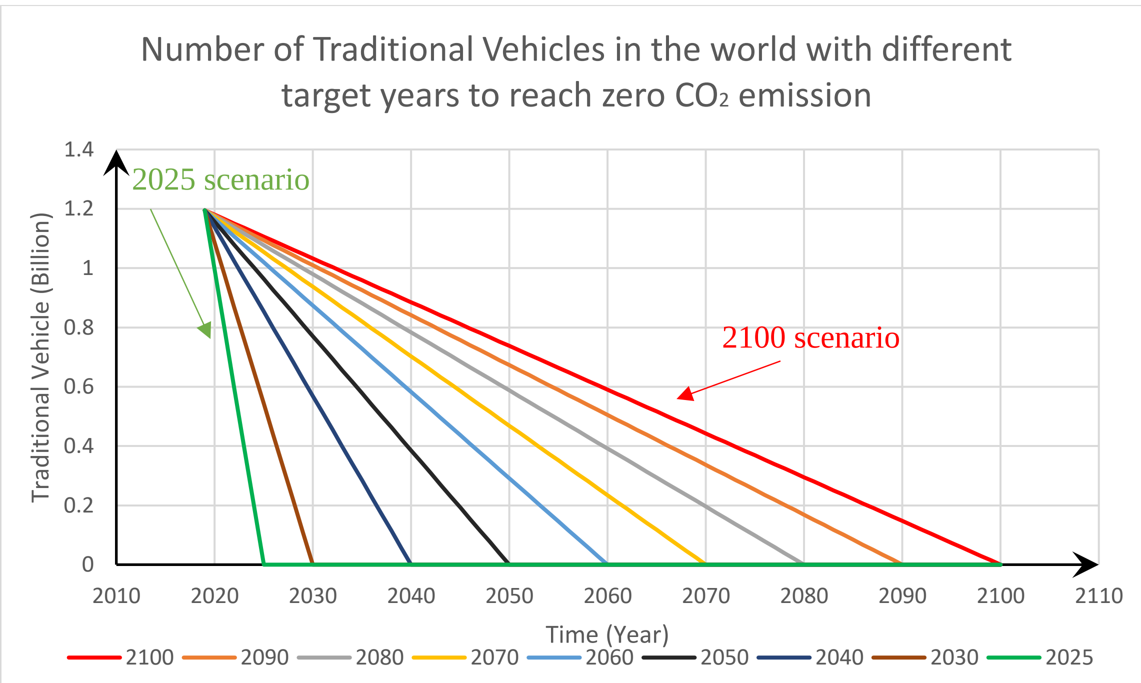


Figure 3.9. Number of Traditional Vehicles in the world with different target years to reach zero CO_2 emission

In Figure 3.9, the green curve shows how the number of TVs decreases in the 2025 scenario. In order to replace all TVs within 6 years, there would need to be about 200 million TVs decommissioned annually: this makes the slope of the curve very steep in this scenario. The slope of the red curve is much smaller due to the longest time to do the replacement (2100 scenario). In this scenario, the decreasing rate of TVs is about 9 million vehicles per year which would seems quite possible given the actual production capacity of existing automotive manufacturing companies [Statista, 2021]. Between these two curves other scenarios is also shown. The scenarios for 2025 to 2100 are shown from left to right.

As the decommission of TVs progresses, there will be a subsequent reduction of CO_2 emission which can be calculated as follows:

- Time to reduce all TV = Preferred year to reach zero CO_2 emission-2019 (3.57)
- Initial EV = $5.2*10^6$ autos (3.58)
- Initial traditional vehicles = Vehicles in 2018-Initial EV (3.59)

When the simulation time reached 2019, the decommission rate of traditional vehicles can be calculated as follows:

(1) If the existing number of TV is more than the increasing rate of EV, then:

- TV decommission = EV increasing rate(vehicle/year) (3.60)

(2) If the existing number of TV is less than the increasing rate of EV, then:

- TV decommission = #Traditional vehicles (3.61)

(3) If there are no TVs still operating, then:

- TV decommission = 0 (3.62)

Based on the TV decommission rate and the initial number of TVs, the existing number of TVs can be calculated. Then, the reduction of CO_2 by transportation can be estimated as follows:

- CO_2 emission from TV (ton/vehicle) = 4.6 tons / vehicle (3.63)
- Reduction of CO_2 by transportation = (Initial traditional vehicles - #Traditional vehicles) * CO_2 emission from TV (ton / vehicle) (3.64)

When there are no TVs in the world, all passenger vehicles must be powered by electricity: this would contribute to a reduction of world's annual CO_2 emission of about 5.5 billion tons. Figure 3.10 shows the reduction of CO_2 emission by EV implementation in different scenarios.

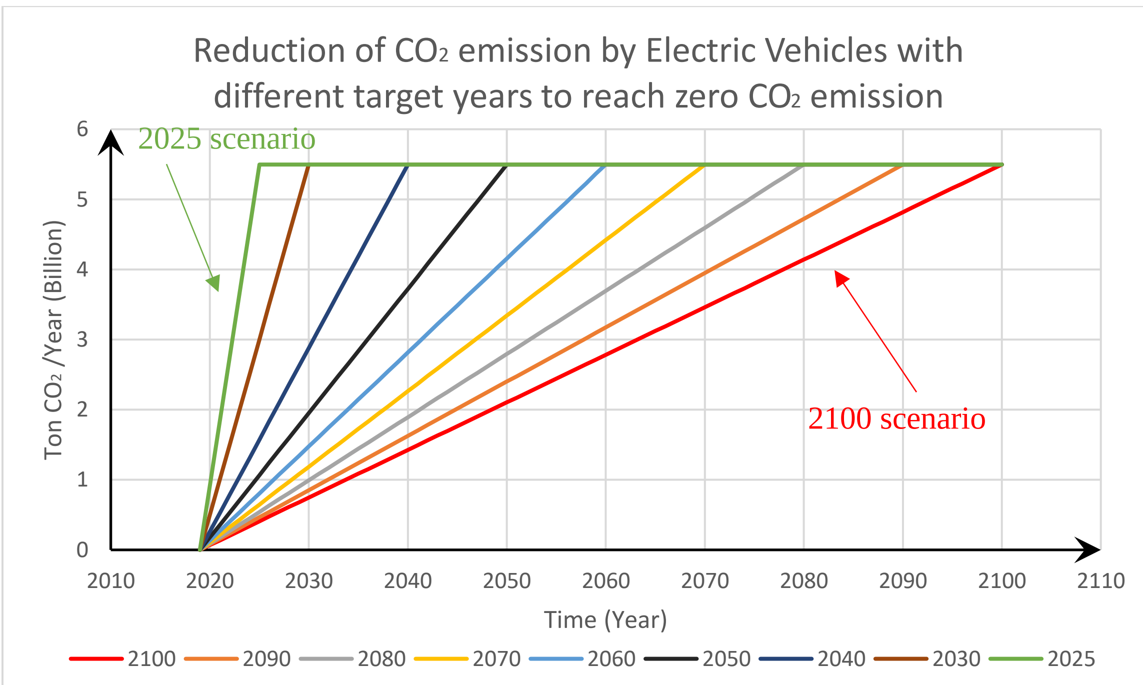


Figure 3.10. Reduction of CO_2 emission by Electric Vehicles with different target years to reach zero CO_2 emission

In the Figure 3.10, the green curve shows the reduction of CO_2 emissions by EVs in the 2025 scenario. In this scenario, all TVs will be replaced within 6 years (from 2019), thus the rate of CO2 reduction is higher than in any other scenario. The red curve indicates the 2100 scenario. All other scenarios' curves are shown between these two as seen previously.

3.4 Heating sub-model

Besides power generation and transportation, residential heating is also an area that has to be analyzed in order to ascertain CO_2 reduction. In this study, a heating model has also been proposed and developed in order to analyze the impact of emissions under the assumption that all households convert to use of electric heaters. According to OECD, the average family size is 2.63 person [OECD, 2011]; combining the market of fossil fueled heaters (FFH) and electric heaters (EH), the number of EHs and FFHs can be estimated. According to the year set to reach zero CO_2 emissions from heating, the rates to replace FFHs might be different. In this way different scenarios can be evaluated. Figure 3.11 shows the heating model.

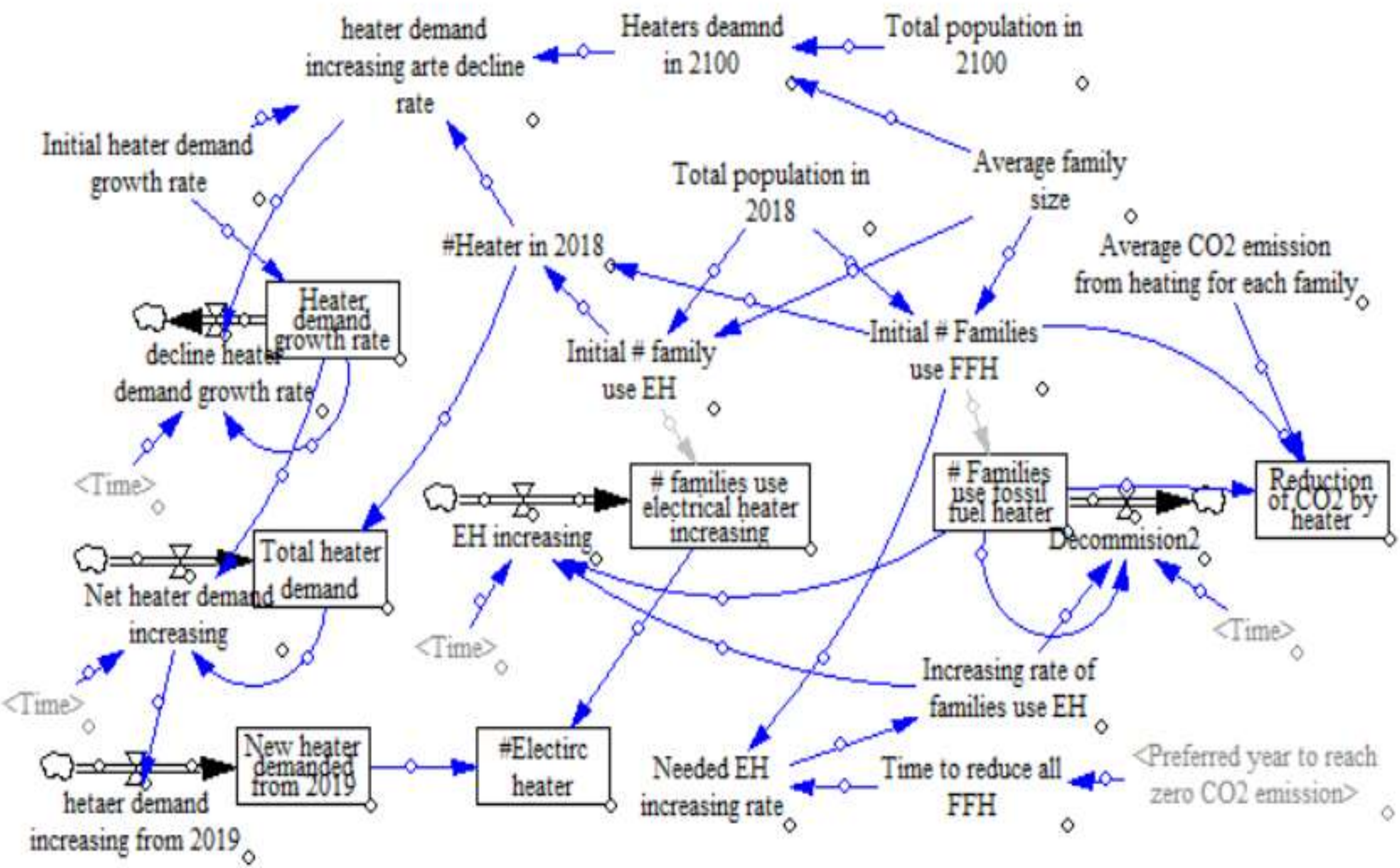


Figure 3.11 Heating model

This model also consists of two main parts. The left part calculates the demand of heaters according to the rise of population. The right part does the calculation related to the replacement of FFHs by EHs and the subsequent reduction of CO_2 emissions.

This model is quite similar to the transportation model. At first, the needed EH increasing rate in order to replace all FFHs was calculated based on the number of FFHs in the world in 2019 and the target year to reach zero CO_2 emissions. Next, the increasing demand of heaters has also been evaluated using the same increasing model just like the population model. Then, the total annual EH rate of replacement has been calculated using the results from the previous two calculations. Finally, the amount of CO_2 emission that can be reduced annually by the EHs has been calculated as the decreasing number of FFHs. This data has then been fed into the DICE model to predict the impacts on climate. Figure 3.12 shows the number of Fossil Fuel Heaters in the world with different target year to reach zero CO_2 emissions.

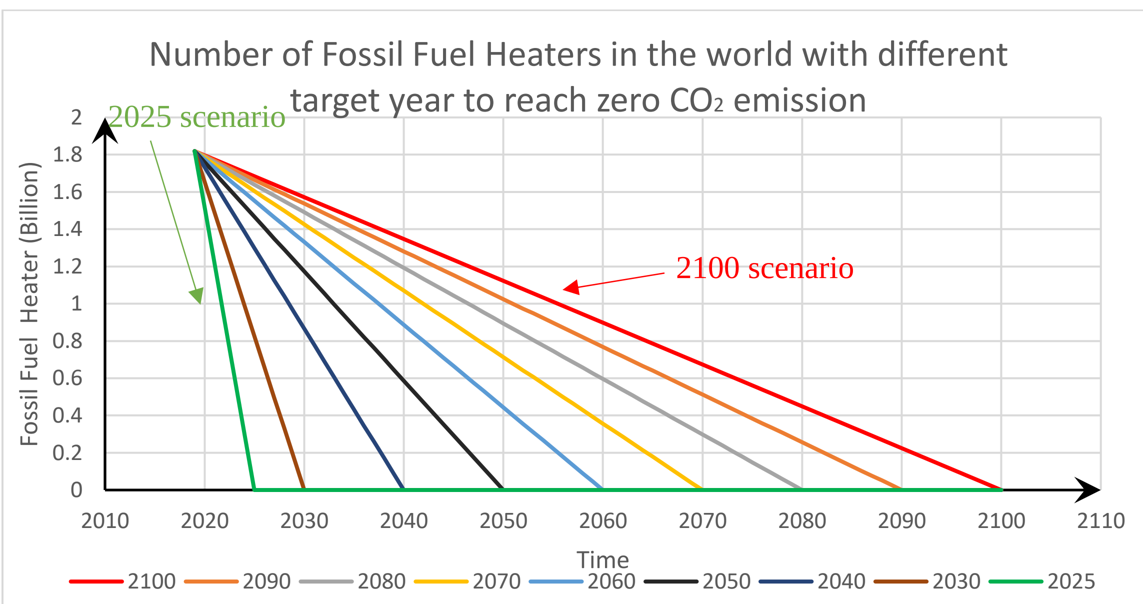


Figure 3.12. Number of Fossil Fuel Heaters in the world with different target year to reach zero CO_2 emission

This figure shows different decreasing rate of FFHs in different scenarios. The curves for scenarios 2025 to 2100 are indicated from the left to the right. In the 2025 scenario, there's a need of about 303 million FFHs to be decommissioned each year. However, in the 2100 scenario which is shown in the red curve, the reduction rate is about 22 million heaters per year (roughly 15 times less aggressive than 2025 scenario). In some scenarios, the decommission rate of FFHs is quite a huge number and is not practicable. For this reason, it is assumed that the supply of the EHs is always sufficient.

If all the 1.8 billion FFHs are being decommissioned, a reduction of 5.2 billion tons of CO_2 can be reached. Figure 3.13 shows the reduction of CO_2 emission by EH.

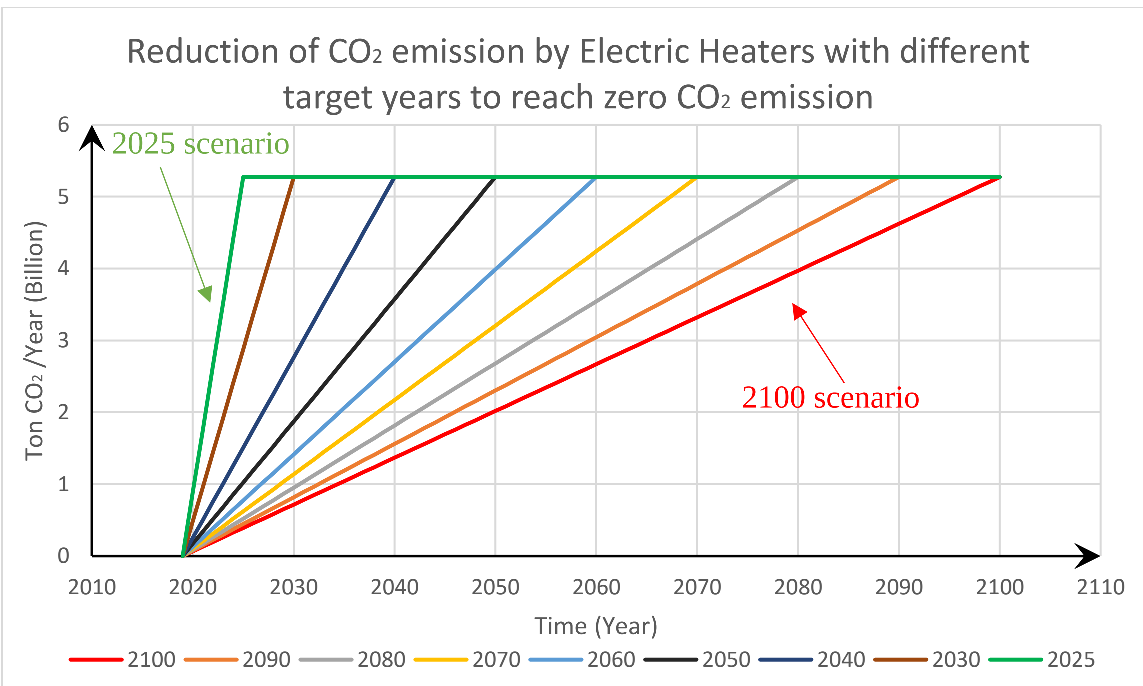


Figure 3.13. Reduction of CO_2 emission by Electric Heaters with different target years to reach zero CO_2 emission

In Figure 3.13, as the target year to reach zero CO_2 emissions is postponed, the slopes of the curves decrease. In the 2025 scenario, 0.879 billion tons of CO_2 can be reduced annually as 303 million FFHs are hypothetically being replaced every year. In the 2100 scenario, only 22 million FFHs need to be replaced, therefore, the CO_2 emission can be reduced by 0.065 billion tons annually assuming reductions are distributed for each year. From this figure, it can be predicted that the replacement of FFHs with EHs will have some benefit in terms of mitigating climate change.

3.5 Modified DICE model simulation

With the addition of the afore-mentioned systems, the reduction of CO_2 emissions from each sub-model can be calculated. The total reduction of CO_2 emissions through the deployment of NPPs, EVs and EHs, has been estimated: Figure 3.14 shows the total reduction of CO_2 emissions in different scenarios. The simulation results show that if all the FFPPs, TVs and FFHs currently in operation in the world are decommissioned, world's annual CO_2 emissions can be reduced by about 25 billion tons. As different scenarios have different substitution rates and different impacts over the final emissions, the trends look quite similar to Figure 3.7.

Figure 3.14, on the following page, indicates that the decommissioning of FFPPs, TVs and FFHs, helps in reducing global CO_2 emissions. Therefore, it becomes important to consider implementing such replacements to help mitigate impending climate changes. The next chapter will discuss these impending changes, based on CO_2 emissions impact on climate factors.

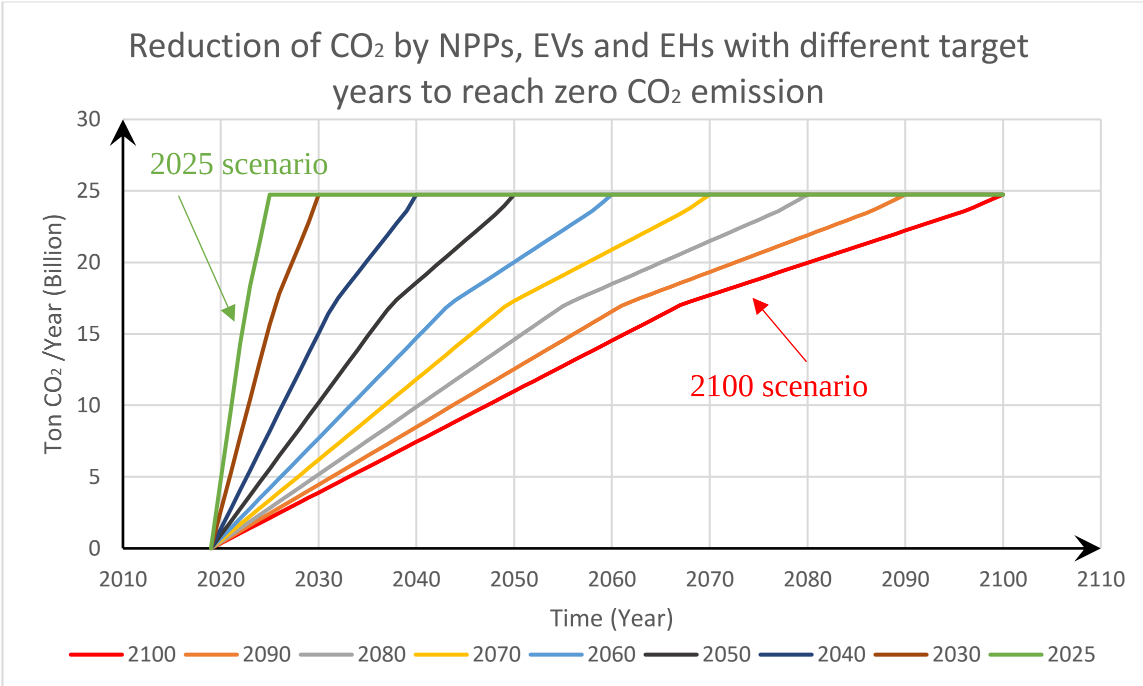


Figure 3.14. Reduction of CO_2 emission by NPPs, EVs and EHs with different target years to reach zero CO_2 emission

Chapter 4. Simulation and Results

Once the NPP sub-model, transportation sub-model and heating sub-model were integrated into the DICE model, a series of simulations were carried out. Results have been studied using a net-zero CO_2 emissions target year of 2025, 2030, 2040, 2050, 2060, 2070, 2080, 2090 and 2100, as one of the key parameters. For these different scenarios, construction rates of NPPs, EVs and EHs were varied and tested. The results from these scenarios are compared with the results from a “business as usual scenario” (BAUS) in which nothing is done to decrease global CO_2 emissions. In this scenario, emissions are sustained under today’s policies and practices. Results using the BAUS scenario are predicted with no modification to the Nordhaus DICE model.

The original DICE model considers a time frame of possible simulations ranging from the year 1965 to the year 2300. However, the modified portion of the model considered in this work simulates the evolution of climate change from 2019; that is, the FFPPs, TVs and FFHs are all replaced starting 2019. This is simply to be consistent with this research started in 2019 and the “time stamp” of reference data used. Also, the modified DICE model was set up to produce results until the year 2100. Between year 2019 to 2100, different scenarios are considered with various replacement rates, resulting in different numbers of Nuclear Power Plants, Electric Vehicles and Electric Heaters deployed in the world. Finally, the impact of NPPs, EVs and EHs on the short-term climate effects are evaluated.

This model has been designed to replace all the FFPPs, TVs and FFHs currently operating in the world. As the FFPPs, TVs and FFHs contribute CO_2 emissions, as each unit is replaced, the world’s annual, cumulative CO_2 emission is expected to decrease. As the human development factor increases, global demand of electricity, vehicles and heaters generally increase. Thus, a fundamental assumption is that from the year 2019, no new FFPPs, TVs and FFHs, are put into operation. With the increase of demand, new NPPs, EVs and EHs will go into operations. Thus, beyond a point in time when all the FFPPs, TVs and FFHs are decommissioned, the NPPs, EVs and EHs that are put into operations beyond this point in time will have no further effect on global climate.

At the end of this century, it is predicted that as many as 4,500 nuclear reactors in the world will be needed to replace all the FFPPs currently in operation and to meet the increasing power demand due to population growth. Figure 4.1 shows the number of nuclear reactors in the world under different scenarios.

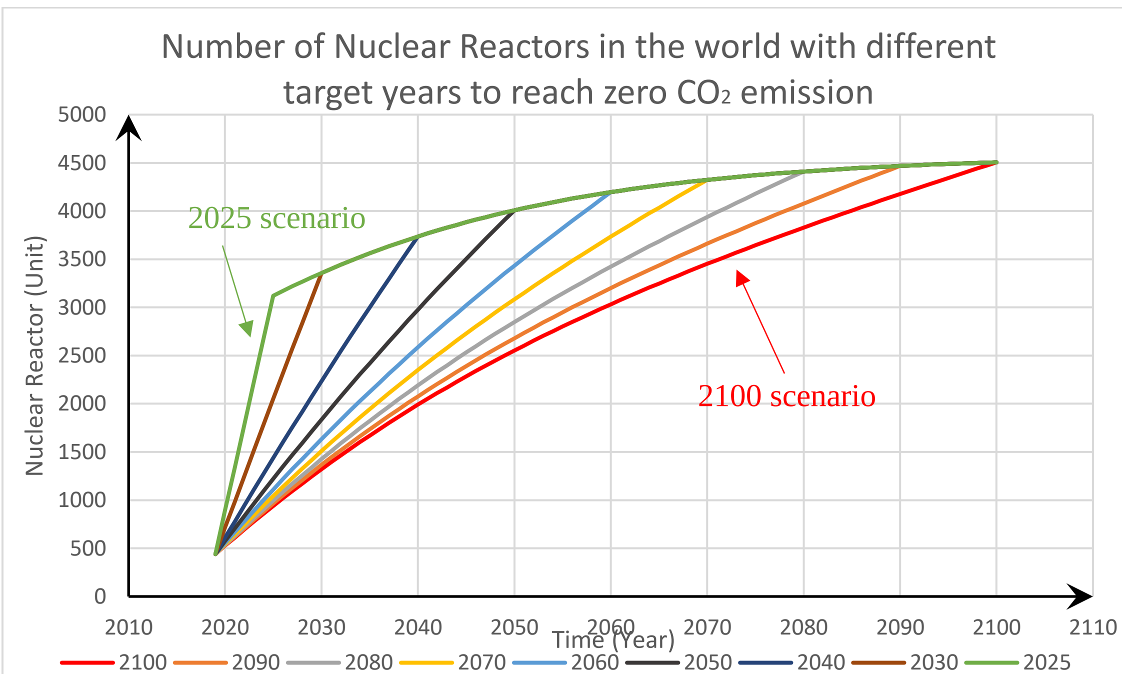


Figure 4.1. Number of Nuclear Reactors in the world with different target years to reach zero CO_2 emission

From 2019, as the FFPPs are replaced by NPPs, the number of nuclear reactors starts to rise. The green curve (left-most) shows the number of nuclear reactors in the 2025 scenario in which all the FFPPs are decommissioned by 2025. As there's only 6 years (from 2019) to replace all FFPPs, the construction rate of NPP is very high and unrealistic, 393 (~400) nuclear units per year. This is nearly 90% of the total number of nuclear power plant operating (~450) currently in the world. As the 2025 scenario has the highest NPP construction rate, the curve has the highest rate of increase. In contrast, the red curve indicates the 2100 scenario. In this case, about 80 years are available to decommission FFPPs. Thus, the NPP construction rate is relatively slower, about 29 nuclear unit per year. By current practice, this construction rate is still large but comparable to some of the higher construction periods in the global nuclear era. The curves for different scenarios converge after all the FFPPs have been decommissioned in each scenario, because the world's total power demand is the same, under all different scenarios. Table 4.1 indicates the different NPP construction rates in the world with different target years to reach zero CO_2 emissions. This table serves as a reference, and for the largest NPP construction rates noted, it seems self-evident that such scenarios are impractical.

Target Year to Reach Zero CO_2 Emissions	**Nuclear Power Plant Construction Rate (Units/year)**
2100	29
2090	33
2080	39
2070	46
2060	58
2050	76
2040	112
2030	214
2025	393

Table 4.1. Increasing rate of Nuclear Power Plant with different target years to reach zero CO_2 emissions

This sub-model also predicts the number of electric vehicles which would be required in order to replace all traditional vehicles. In 2019, there were about 5 million electric vehicles in the world. When traditional vehicles start to be replaced (by assumption of this research work in 2019), the number of electric vehicles increases rapidly. However, each scenario has a different EV deployment rate. Figure 4.2 shows the total number of EVs in the world under different scenarios. Finally, in 2100, there will be about 3 billion EVs in the world.

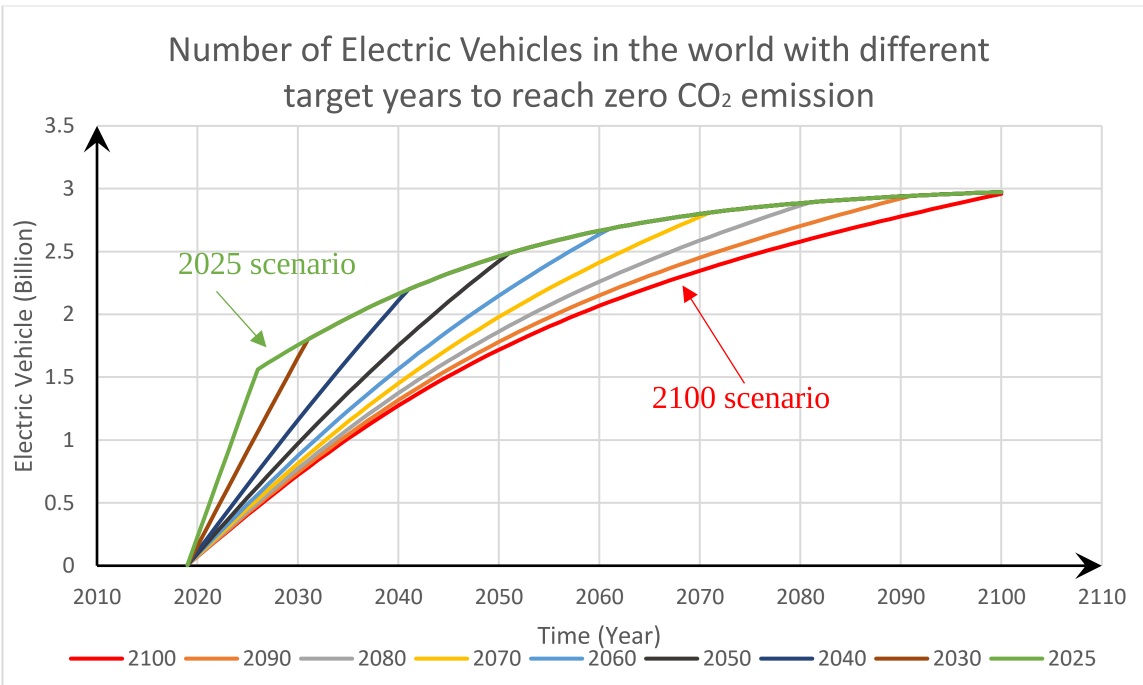


Figure 4.2. Number of Electric Vehicles in the world with different target years to reach zero CO_2 emission

From Figure 4.2, it can be observed that in the 2025 scenario, shown by the green line, the rate of increase of EVs is much higher than in other scenarios due to the fact that this scenario simulates the fast replacement of TVs. If the target year to reach zero CO_2 emissions is chosen as 2025, the required EVs deployment rate is about 200 million vehicles per year. Here again, the substitution rate is surprisingly high as it not only replaces all TVs present, but also adds units to meet the projected demand. The lowest curve shows the number of EVs versus time in 2100 scenario. This provides the longest time to replace all TVs so that the EV increasing rate is about 15 million vehicles per year which is more practical compared to 200 million vehicles per year. Other scenarios curves are between the green curve and red curve according to Figure 4.2. As the time to reach zero CO_2 emissions is postponed, the time to replace TVs increases, so that the rate of increase in EVs decreases. After all scenarios reach zero CO_2 emissions, these curves merge into one line because the world's total demand of vehicles will not change. Table 4.2 shows the EVs deployment rate in different scenarios. The rate of increase in EVs varies from 14.75 million vehicles per year to 199.13 million vehicles per year.

Target Year to Reach Zero CO_2 Emissions	**Electric Vehicle Increasing Rate (Million Vehicles/year)**
2100	14.75
2090	16.83
2080	19.59
2070	23.43
2060	29.14
2050	38.54
2040	56.90
2030	108.62
2025	199.13

Table 4.2. Increasing rate of Electric Vehicle with different Target years to reach zero CO_2 emissions

After predicting the number of NPPs and EVs in the world, the number of EHs required to replace FFHs was also predicted in different scenarios. In 2019, there were about 1 billion electric heaters in the world. It is important to note that this value is simply an estimate based on the historical market for electric heaters as an exact value for this data point was not available. With increasing population and economic development in the world, more and more heaters are needed. By the end of this century, this modified sub-model predicts that there will be about 3.9 billion EHs required globally. Figure 4.3 shows the predicted number of EHs in the world with different target years to replace all the fossil fueled heaters.

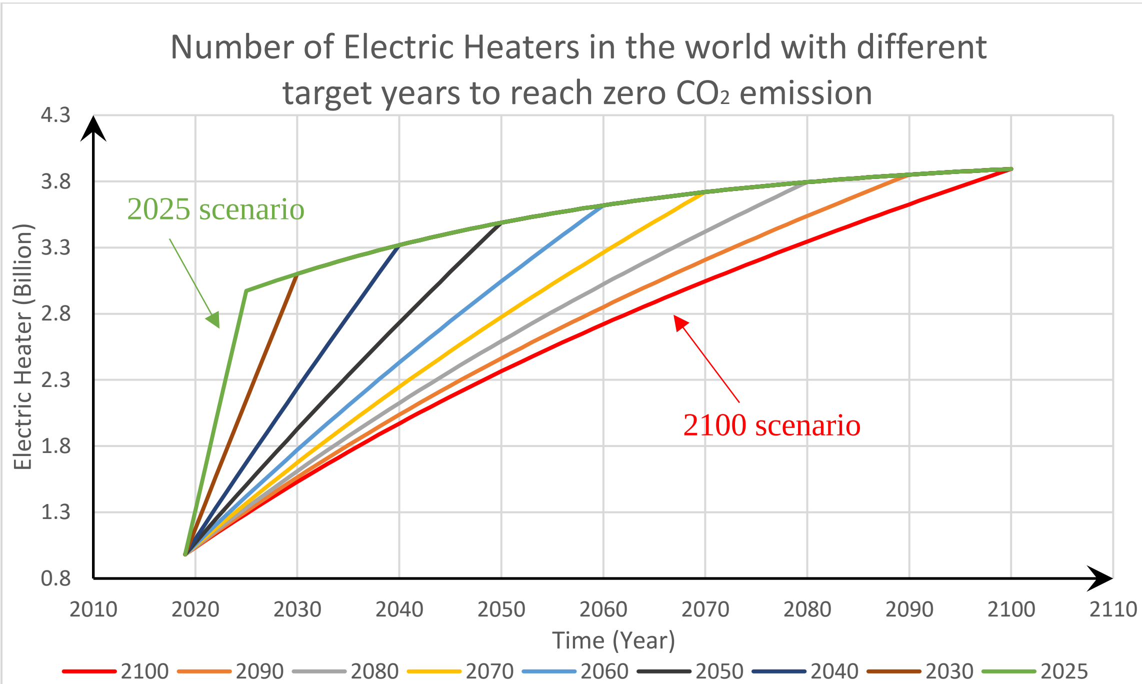


Figure 4.3. Number of Electric Heaters in the world with different target years to reach zero CO_2 emission

Similar to results seen before for NPPs and EVs, in this figure, the highest curve presents the 2025 scenario, and the lowest curve shows the 2100 scenario; one has the highest replacement rate and the other, the lowest rate. At the end, all lines converge when there are no additional FFHs to be replaced; in effect, this is when there has been a complete electrification of domestic heating needs. Table 4.3 shows the different EH deployment rates of increase under different scenarios. From this table, it can be seen that in the most pressing scenario, there is a need to be about 303 million new EVs annually, all over the world. In the 2100 scenario the deployment rate of EHs is greatly reduced, compared to the 2025 scenario, with only 22 million EHs required deployment annually.

Target Years to Reach Zero CO_2 Emission	**Electric Heater Increasing Rate (Million Heaters/Year)**
2100	22.46
2090	25.62
2080	29.82
2070	35.67
2060	44.37
2050	58.68
2040	86.62
2030	165.37
2025	303.18

Table 4.3. Increasing rate of Electric Heater with different target years to reach zero CO_2 emission

After these simulations, the CO_2 emissions under different scenarios were evaluated and shown in Figure 4.4. The results show that the earlier the zero CO_2 emission target year is set, the less CO_2 will be emitted. At minimum, this may justify an aggressive energy policy. The blue line in Figure 4.4 indicated the BAUS (business as usual) scenario, while the other lines show the results for different scenarios corresponding to the year anticipated in reaching zero emissions. The lowest line shows the CO_2 emissions if zero contribution is set by 2025. As the target year to reach zero CO_2 emission increases (postponed), the relative difference in CO_2 emission, relative to BAUS curve decrease. That is, reduction in tons of carbon avoided per year.

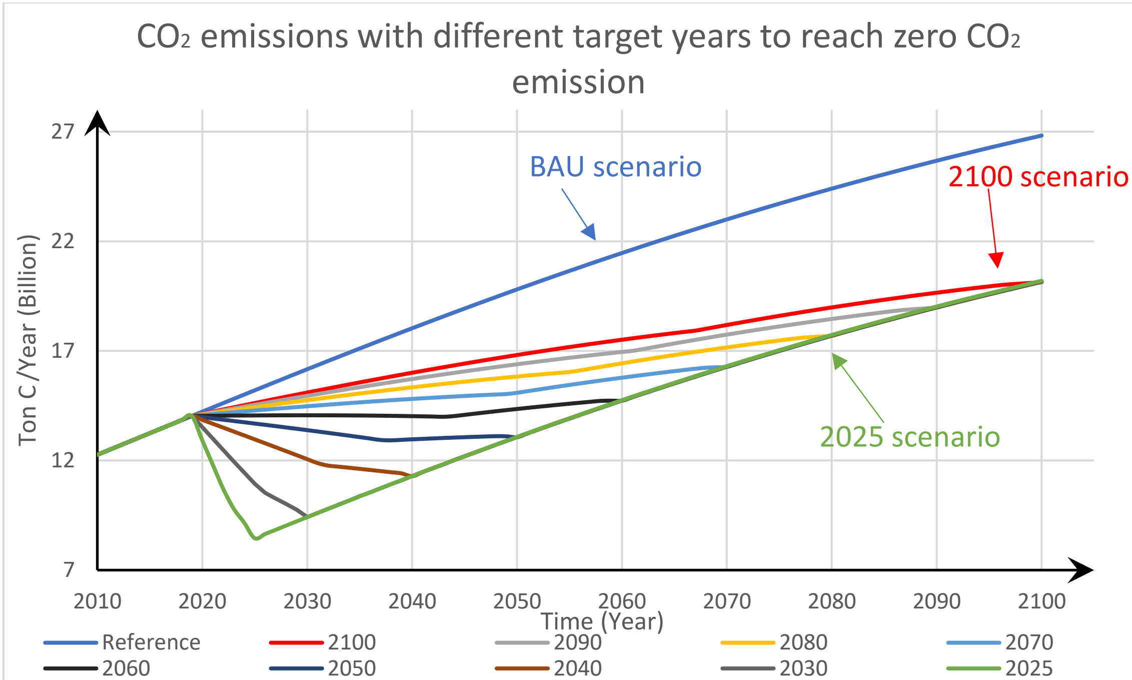


Figure 4.4. CO_2 emission with different target years to reach zero CO_2 emission

The DICE model and replacement of fossil fuel power plants, traditional vehicles and fossil fueled heaters sub-models decrease the generation of CO_2 emission: thus, CO_2 emission drop relative to 2019 under all scenarios. The initial drop is relatively large because the Coal Power Plants are shut down first. CPPs represent the biggest contribution to CO_2 emissions, followed by Natural Gas Power Plants and Petroleum Power Plants. After all the CPPs are shut down, the rate of CO_2 reduction decreases. Finally, as PPPs are shut down, the rate of decline rate further decreases because PPPs emit less CO_2 and are fewer in deployed number. After the target year to reach zero CO_2 emissions for each scenario is realized, CO_2 emissions increase at the rate of the (BAUS) reference curve. Thus, the trends corresponding to each scenario converge and then appear parallel to the reference curve. The difference between the merged trendlines and the reference curve is the difference in tons of CO_2 produced by FFPPs, TVs and FHs.

By 2100, about 6.5 billion tons of carbon per year are predicted to be reduced under the assumption of the replacement of all FFPPs, TVs, and FFHs. This accounts for 24.76% of the cumulative CO2 present in the atmosphere and demonstrates that the combined use NPPs, EVs and EHs can have a significant impact on decreasing annual CO_2 emissions. Comparing the 2025 and 2100 scenarios versus the BAUS-reference, the global savings trend in tons of CO_2 emitted per year is immediately evident as indicated in Table 4.4.

Year	Annual CO_2 reduction in 2025 scenario (Billion tons of CO_2 /Year)	Annual CO_2 reduction in 2100 scenario (Billion tons of CO_2 /Year)
2020	1.3	0.1
2025	6.7	0.6
2030	6.7	1.0
2040	6.7	2.0
2050	6.7	3.0
2060	6.7	4.0
2070	6.7	4.8
2080	6.7	5.4
2090	6.7	6.0
2100	6.7	6.7

Table 4.4 Annual CO_2 reduction in scenario 2025 and 2100

Besides the CO_2 emissions, the total mass of CO_2 accumulated in the atmosphere was also considered. Figure 4.5 shows the amount of CO_2, in tons, in the atmosphere. It is important to remember that not all of the CO_2, which is emitted into the atmosphere will remain there, and some is actively absorbed by plants, oceans, and other sources.

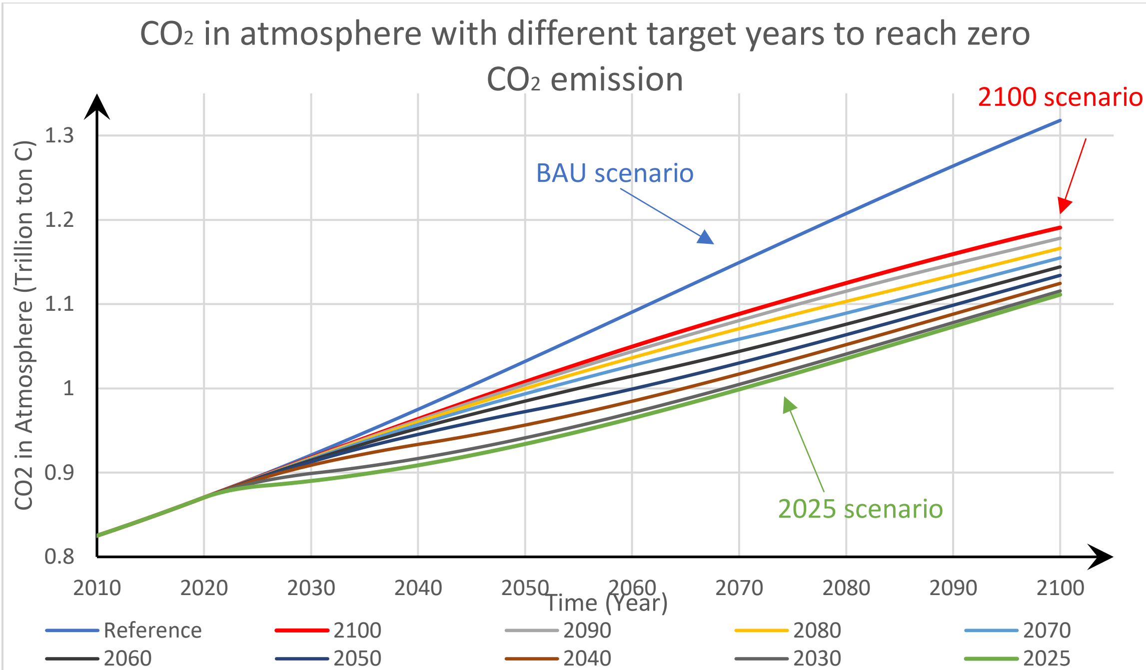


Figure 4.5. CO_2 in atmosphere with different target years to reach zero CO_2 emission

Figure 4.5 shows that as the FFPPs, TVs and FFHs decrease over decades, the CO_2 in atmosphere also decreases. The earlier the FFPPs, TVs and FFHs decommissioning is done, the less CO_2 there will be in the atmosphere. Table 4.5 shows this in a tabulated form. The CO_2 in the atmosphere can be reduced by 0.13 to 0.2 trillion tons per year by the end of this century. Since the fractional tons' reduction is not a large number compared to the total CO_2 in the atmosphere, however, it helps to slow the pace of global warming.

Target Years to Reach Zero CO_2 Emission	CO_2 in Atmosphere in 2100 (Trillion Ton C)	Reduction of CO_2 in Atmosphere in 2100 (Trillion Ton C)	Reduction of CO_2 in Atmosphere in 2100 (%)
Reference	1.32	0	0
2100	1.19	0.13	9.65%
2090	1.18	0.14	10.61%
2080	1.17	0.15	11.52%
2070	1.15	0.16	12.37%
2060	1.14	0.17	13.19%
2050	1.13	0.18	13.95%
2040	1.12	0.19	14.67%
2030	1.12	0.20	15.46%
2025	1.11	0.21	15.69%

Table 4.5. CO_2 in atmosphere in 2100 with different target years to reach zero CO_2 emission

Monitoring the CO_2 concentration in atmosphere is significant not only as the representation of the state of the atmospheric condition, but as a focal point of the climate change debate. Concentrations of CO_2 in the atmosphere were as high as 4,000 parts per million (ppm, on a molar basis) during the Cambrian period about 500 million years ago, and have been as low as 180 ppm during the Quaternary glaciation of the last two million years [Eggleton, 2013]. In this work, the DICE model has been modified in order to predict the atmospheric CO_2 concentration. The results show the CO_2 concentration can be reduced by approximately 60ppm to 97ppm, under different scenarios or 9.6% to 15.7%. Figure 4.6 shows the CO_2 concentration versus time under different scenarios.

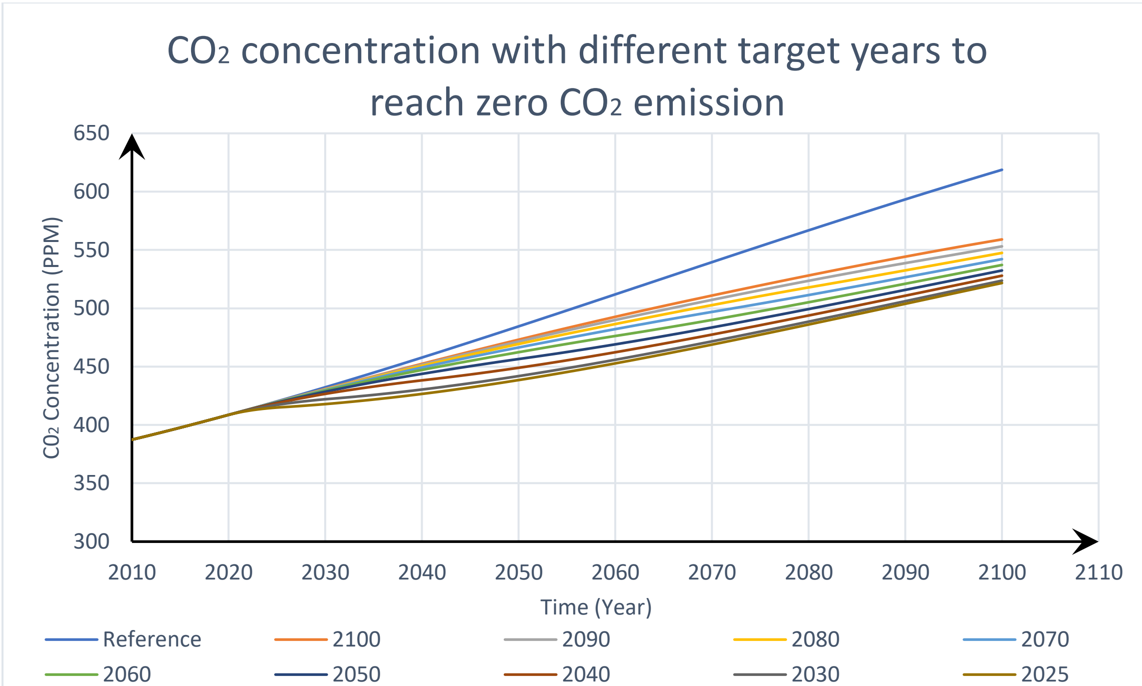


Figure 4.6. CO_2 concentration with different target years to reach zero CO_2 emission

The difference between the curves for each scenario and the reference line shows the ppm reduction of CO_2 in the atmosphere. The blue curve is the reference line (BAUS) which is based on the current and implemented policy. The other curves show the CO_2 concentration under modified conditions. The lowest curve in Figure 4.6 is the prediction for the year 2025. It shows the lowest CO_2 concentration because the rate of decrease of FFPPs, TVs and FHs are the highest of all scenarios. As the target year to reach zero CO_2 emissions is pushed father in time, the installation rate of NPPs, EVs and EHs decreases. Consequently, more CO_2 production is predicted as shown.

To be observed more clearly, Figure 4.7 shows an enlarged portion of the Figure 4.6. In this figure, the differences between each scenario are illustrated more clearly.

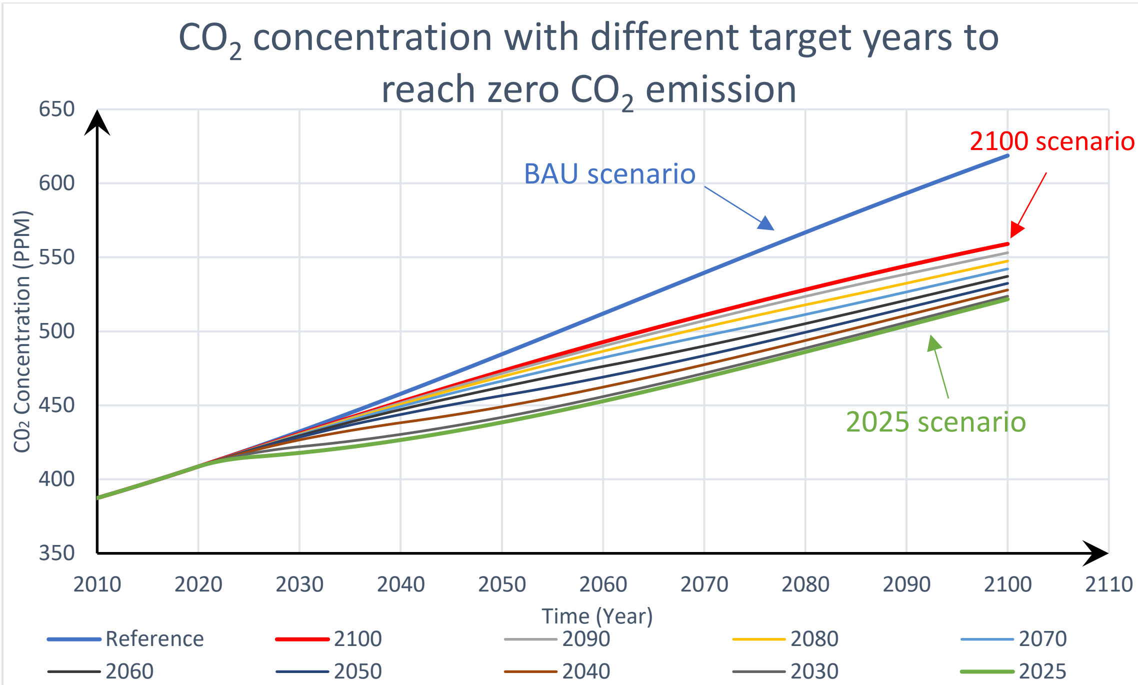


Figure 4.7. Enlarged portion of the plot shows the CO_2 concentration in different scenarios

Table 4.6 shows the data of CO_2 concentration in 2100 for each scenario as well as the reduction in percentage of the world's CO_2 concentration.

Target Years to Reach Zero CO_2 Emission	CO_2 Concentration in 2100 (PPM)	Reduction of CO_2 Concentration in 2100 (PPM)	Reduction of CO_2 Concentration in 2100 (%)
Reference	618.74	0	0
2100	559.05	59.69	9.65%
2090	553.10	65.64	10.61%
2080	547.48	71.26	11.52%
2070	542.17	76.57	12.37%
2060	537.16	81.58	13.19%
2050	532.43	86.32	13.95%
2040	527.95	90.79	14.67%
2030	523.72	95.02	15.46%
2025	521.70	97.05	15.69%

Table 4.6. CO_2 concentration in 2100 with different target years to reach zero CO_2 emission

The increased concentration of CO_2 in atmosphere directly contributes to change and damage of the global ecosystem. In this study, as in previous studies based on the DICE model, the upper and deep ocean temperature are predicted.

According to the US National Oceanic and Atmospheric Administration (NOAA), the upper ocean temperature has increased by approximately 0.13°C per decade over the past 100 years. There are many negative consequences that will be initiated by warming of oceans [Bergman, 2011]; foremost of which is sea level rise and continental ice melting. For these reasons, it's of great importance to study the change in ocean temperature over time. The prediction of atmospheric and upper ocean temperature calculated by the modified DICE models are shown in Figure 4.8.

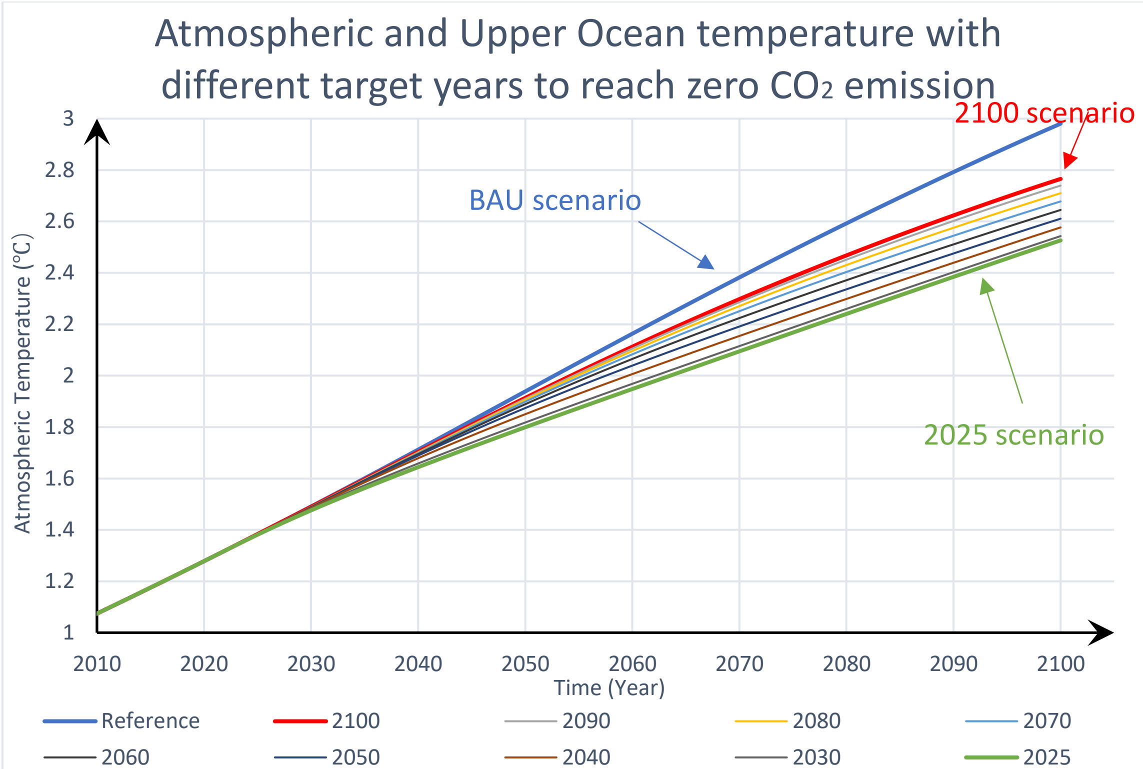


Figure 4.8. Atmospheric and Upper Ocean temperature with different target years to reach zero CO_2 emission

A small reduction of atmospheric temperature can be seen in this simulation result. The atmospheric temperature is increasing continuously, (after 2019) but at slightly different rates according to specific scenarios. At the end of the century, the atmospheric temperature can be reduced by 0.22°C via the 2100 scenario, compared to 0.45°C via the 2025 scenario. This clearly indicates that by replacing the FFPPs, TVs and FFHs with NPPs, EVs and EHs, the ongoing temperature increase can be mitigated but not fully reversed.

Table 4.7 shows more detailed data of the atmospheric and upper ocean temperatures in 2100. From this table, one can see a reduction of 7.2% to 12.4% in the atmospheric and upper ocean temperature, relative to the BAU scenario.

Target Years to Reach Zero CO_2 Emission	**Atmospheric & Upper Ocean Temperature in 2100 (°C)**	**Reduction of Atmospheric & Upper Ocean Temperature in 2100 (°C)**	**Reduction of Atmospheric & Upper Ocean Temperature in 2100 (%)**
Reference	2.98	0	0
2100	2.77	0.22	7.21%
2090	2.74	0.24	8.08%
2080	2.71	0.27	9.08%
2070	2.68	0.30	10.15%
2060	2.65	0.34	11.27%
2050	2.61	0.37	12.40%
2040	2.58	0.40	13.54%
2030	2.54	0.44	14.68%
2025	2.53	0.45	15.24%

Table 4.7. Atmospheric & Upper Ocean temperature in 2100 with different target years to reach zero CO_2 emission

The ocean has been divided (according to DICE) into three parts: the top portion is called the surface layer. This is followed by a boundary layer called the thermocline which separates the surface layer and the deep layer of the ocean [Nordhaus, 2011]. The average deep ocean temperature is also an important factor that should be considered as it takes up energy from sun and helps to moderate the earth's temperature. Similar to the upper ocean temperature, as the implementation rates of NPPs, EVs, and EHs increases, the predicted growth of deep ocean temperatures diminishes. Overall, the increase of the deep ocean temperatures is less than that of the upper ocean temperatures. This is because the high radiative exposure warms the atmospheric, with consequent upper ocean warming, while the warming of the deep ocean is more gradual [Nordhaus, 2013]. The results shown in

Figure 4.9, anticipate that a reduction in temperature increase, from 0.011°C to 0.032 °C, under different scenarios relative to an increase of slightly more than 0.45°C under the BAU scenario.

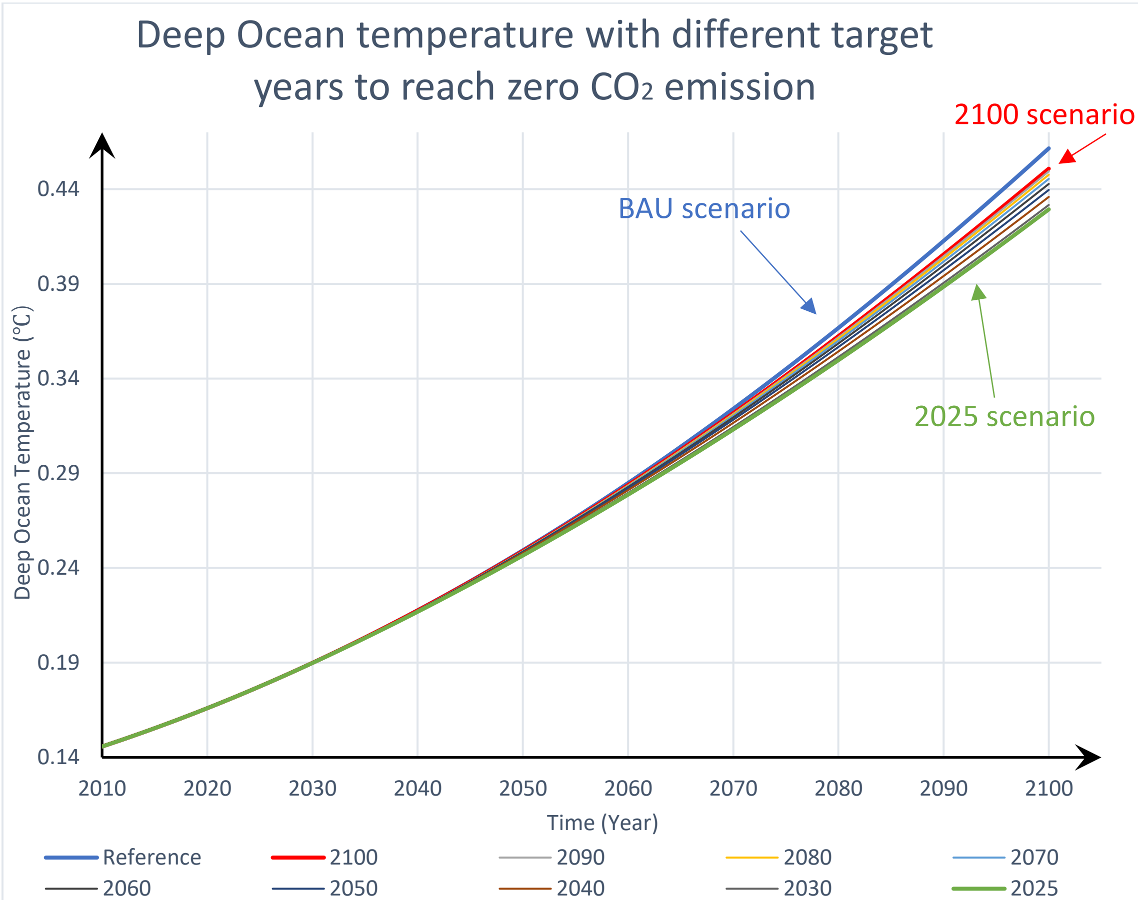


Figure 4.9. Deep Ocean temperature with different target years to reach zero CO_2 emission

Table 4.8 lists the deep ocean temperatures for different target years to reach zero CO_2 emissions. Compared to the upper (surface) ocean temperature, the increase in deep ocean temperature is much smaller, relative to the BAU scenario. The table shows that rise in the deep ocean temperature, relative to the BAU scenario, can be reduced by 2.3% to 6.9%. Although this seems small relative to the ~0.45°C increase seen in the BAU scenario, since buoyancy driven flows scale with the cube of the characteristic length along temperature difference, this can have a large impact on the ocean ecosystem.

Target Years to Reach Zero CO_2 Emissions	**Deep Ocean Temperature in 2100 (°C)**	**Reduction of Deep Ocean Temperature in 2100 (°C)**	**Reduction of Deep Ocean Temperature in 2100 (%)**
Reference	0.462	0	0
2100	0.451	0.011	2.32%
2090	0.449	0.012	2.63%
2080	0.448	0.014	3.01%
2070	0.445	0.016	3.49%
2060	0.443	0.019	4.07%
2050	0.440	0.022	4.75%
2040	0.436	0.026	5.55%
2030	0.432	0.030	6.47%
2025	0.429	0.032	6.88%

Table 4.8. Deep Ocean Temperature in 2100 with different target years to reach zero CO_2 emission

Due to the climate change, outcomes such as warming and extreme weather events, economic losses and burdens may occur annually. In the DICE model, the term "climate damages" is used to estimate economic damage and/or financial impacts of climate change. Estimates of climate damage are indispensable for making sensible decisions about the appropriate balance between costly emissions reductions and climate damages [Nordhaus, 2013]. The impact of climate change is defined as the "monetized estimates of the social welfare" as impacted by climate change [National Academies of Science, 2017]. The impact of climate change can be in terms of water resources, agriculture, human health and associated direct and indirect hazards. In the DICE model, damages are based on quadratic functions of temperature and sea level rise [National Academies of Science, 2017]. Figure 4.10 shows the costs associated with global temperature increase.

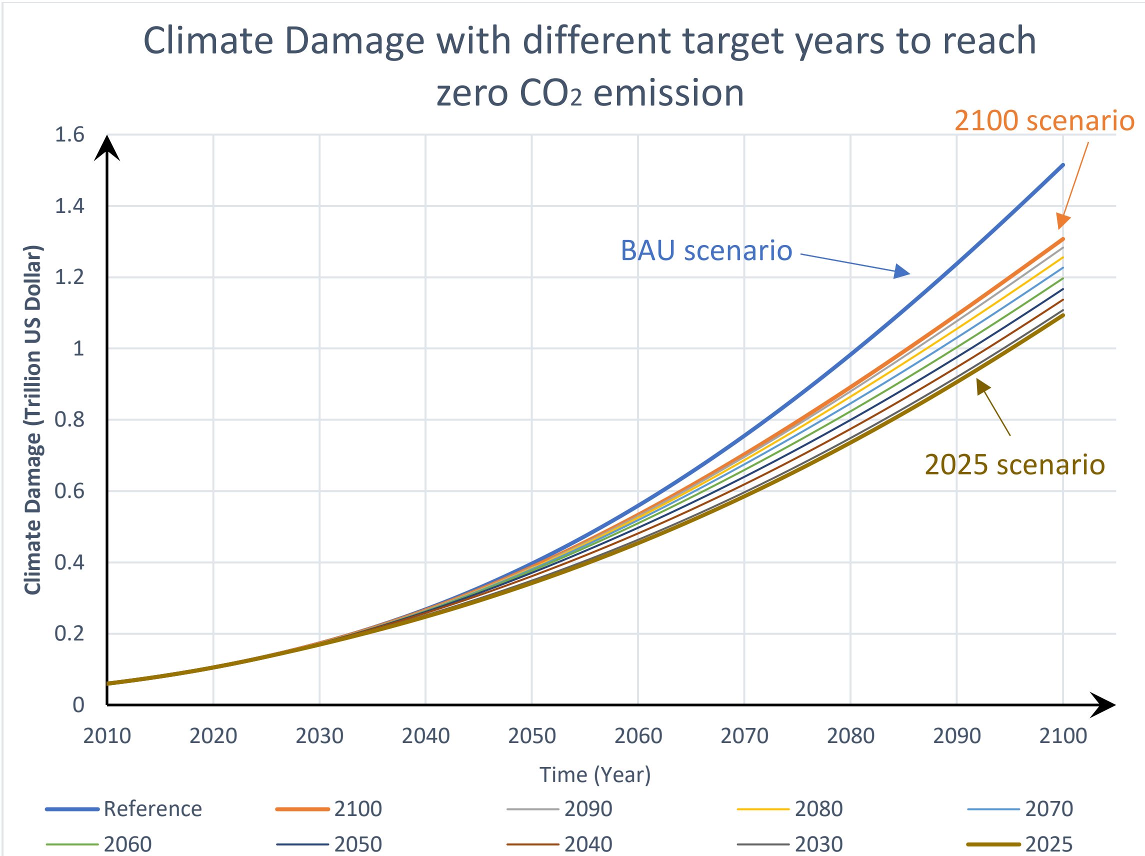


Figure 4.10. Climate Damage with different target years to reach zero CO_2 emission

As can be seen in the Figure 4.10, decrease in fossil fueled power plants, traditional vehicles and fossil fueled heaters can reduce the "damage" costs, although the reduction proportion is small amount compared to the total. It is predicted in this context that between 0.21 trillion to 0.42 trillion dollars can be saved by year 2100. With an earlier target year to reach zero CO_2 emissions (increasingly aggressive target), the damage costs due to global warming decrease relative to the BAU scenario.

Table 4.9 displays the climate damage data. As can be seen, in 2100, more than one trillion dollars may need to be expended in order to mitigate the negative impact of climate change.

However, if actions are being taken earlier, for example, decommissioning FFPPs, TVs and FFHs, a reduction of 13.7% to 27.8% of the total "damage cost" may be possible per this study's modified DICE model.

Target Years to Reach Zero CO_2 Emission	**Climate Damage in 2100 (Trillion Dollar)**	**Reduction of Climate Damage in 2100 (Trillion Dollar)**	**Reduction of Climate Damage in 2100 (%)**
Reference	1.52	0	0
2100	1.31	0.21	13.72%
2090	1.28	0.23	15.31%
2080	1.26	0.26	17.11%
2070	1.23	0.29	19.03%
2060	1.20	0.32	21.00%
2050	1.17	0.35	22.99%
2040	1.14	0.38	24.96%
2030	1.11	0.41	26.89%
2025	1.09	0.42	27.84%

Table 4.9. Climate Damage in 2100 with different target years to reach zero CO_2 emission

The figures and tables shown above are the main results that are being evaluated in this study through the application of the modified DICE model. In the next chapter, these results will be discussed in detail.

Chapter 5. Discussion of results

The potential and emerging negative impacts of climate change are perceived and understood to be a global issue in the current world. In order to mitigate and reduce the impacts caused by CO_2 emissions, more and more actions and conventions are proposed. Among which, the Paris Agreement is one of the most important one. It is a landmark international accord to address climate change and its negative impacts, adopted by 195 counties in 2015 [Denchak, 2021]. It also provided a framework to address significant negative impacts of climate change by limiting global warming to below 2℃ and in fact targeting a limit of 1.5℃ [European Commission, 2021]. Given this, this study was undertaken to predict the near-term climate change.

With the development of technology and continuing increase in global population, demand for electrical power, heat, and transportation means continue. The main source of energy is the combustion of fossil fuel. However, it produces a great amount of CO_2 emissions. The accumulation of CO_2 in the atmosphere will cause the planet to heat up [NASA, 2011]. In order to decrease the rate of increase in global temperature, this study considered the use of Nuclear Power Plants (NPPs), Electric Vehicles (EVs) and Electric Heaters (EHs) as equivalent replacements of Fossil Fuel Power Plants (FFPPs), Traditional Vehicles (TVs) and Fossil Fuel Heaters (FFHs) all over the world. As they are the main contributors to CO_2 emissions. Further, and importantly, the possible impacts it may have on climate were analyzed.

In order to predict the CO_2 emissions in the years to come, and the impact of CO_2 emissions on climate, the Dynamic Integrated Climate Economic (DICE) model was used and modified. In this study, the DICE model was used to do the simulations until year, 2100. Different target years to decommission all FFPPs, TVs and FFHs were set as the inputs in order to investigate, via DICE simulations, the corresponding different scenarios until the end of this century (2100). The climate related factors such as atmospheric temperature in these scenarios were compared with the business-as-usual scenario (BAUS), thus, the impacts can be analyzed through comparison.

The original DICE model predicted that if no actions was taken, the mass of CO_2 emissions in year 2100 will be 26.8 billion tons per year. In 2019, the annual CO_2 emission is 14.0 billion tons. This means that the worlds' total CO_2 emission will double by 2100, compared to 2019. The DICE model was modified to analyze the impacts of NPPs, EVs and EHs may have on climate. As the modified portion of the model starts to decommission the worlds FFPPs, TVs and FFHS, starting in 2019, CO_2 emission will decrease. Thus, the amount of CO_2 emission avoided will then be fed into the DICE model to further predict the climate related indicators, such as atmospheric temperature and deep ocean temperature.

Based on the equivalent power output from the new NPPs, the FFPPs are decommissioned annually. In addition, the number of traditional vehicles and fossil fuel heaters decrease at the same time as more and more EVs and EHs go into operation. Under different scenarios, the decommission rates of FFPPs, TVs and FFHs are different due to the different time they have in order to decommission all the FFPPs, TVs and FFHs currently in operation in the world. For example, the decommission rate of CPPs is from 162 to 2190 units per year which corresponds to a construction rate of 29 to 393 NPP units each year in order to produce equivalent electricity. Here, some smaller construction rate of NPPs is acceptable if all countries start to decrease CO_2 emission from power generation by using NPP.

However, some huge NPP construction rates are unrealistic due to the limitations of material, construction equipment (construction cranes, large forgings, etc.). But were also evaluated to serve as reference. After all the FFPPs, TVs and FFHs are decommissioned, in 2100, the reduction of CO_2 emission by NPP, EVs and EHs is 6.7 billion tons of carbon which equates to 24.98% (essentially 25%) of the total. This importantly means the decommissioning of all FFPPs, TVs and FFHs in the world will help to reduce the annual CO_2 emissions by 6.7 billion tons of carbon.

As the target year to reach zero CO_2 emission is postponed, the decommission rate of FFPPs, TVs and FFHs will decrease. However, the annual CO_2 emissions in 2100 is equal for each scenario because there will be no FFPP, TV and FFH in the world in all scenarios. The amount of CO_2 emissions from other areas are the same despite the different increasing rate of NNP, EV and EH for each scenario. When there are no FFPP, TV and FFH, additional NPPs, EVs and EHs in this work are assumed to have no influence on the world's CO2 emissions. This approach, in effect, is to investigate the scenarios over the next 80 years.

Although the annual CO_2 emissions for each scenario is the same in 2100, the total amount of CO_2 in the atmosphere is different. This is because for scenarios that initially reduce CO2 emissions at a rapid rate, the long-term total reduction is correspondingly less than less intensive reduction scenarios. As predicted by the DICE model, the total amount of CO_2 in the atmosphere will be 1.32 trillion tons of carbon in 2100 if no action is taken. It’s about 1.5 times to the total amount of CO_2 in 2019 which is 0.87 trillion tons of carbon. However, taking the reduction of CO_2 emissions by NPPs, EVs and EHs into consideration, the total amount of CO_2 can be reduced. In the 2025 scenario, which has the highest increasing rate of NPPs, EVs and EVs, the total CO_2 in the atmosphere can be reduced by 0.21 trillion tons of carbon by 2100 or 15.69% of the total. If the target year to reach zero CO_2 emission is in 2100, a reduction of 0.13 trillion tons of carbon is possible which equates to a reduction of 9.65% of total atmospheric carbon. The CO_2 in the atmosphere can be reduced by 0.13 trillion tons of carbon to 0.21 trillion tons of carbon in other scenarios. This result indicates that NPPs, EVs and EHs do indeed contribute to a decrease in atmospheric CO_2 level.

Similar to using tons of carbon to report the amount of CO_2 in the atmosphere, most publications use the parts per million or ppm. This milligram of solute per liter of solution concentration is also know by the term, "carbon intensity". In order to predict the atmospheric CO_2 concentration in ppm, the original DICE model was modified by using the conversion equation of 1 ppm = 2.13Gt C [CDIAC, 2011]. The global average atmospheric CO_2 in 2019 was 409.8 ppm which is already higher than the safe upper limit 350 ppm [Nordhaus, 2008]. The "safe upper limit" is loosely associated with or corresponds to the likely temperature increase, as figures of merit/demerit in the climate change debate.

According to the DICE model, the CO_2 concentration in the atmosphere will be 619 ppm in 2100 if no action is taken. However, if FFPs, TVs and FFHs start to be replaced, a reduction of CO_2 concentration can be achieved. The simulation results show that atmospheric CO_2 concentration can be reduced by 60 ppm to 97 ppm for different scenarios. The atmospheric CO_2 concentration will reach 522 ppm in 2025 scenario and for the 2100 scenario it will reach 559 ppm. Although the atmospheric CO_2 concentration level is still much higher than the safety level, the 9.6% to 15.7% reduction helps to combat the climate change.

In order to determine whether the results produced by this study is reasonable, the simulation results from another investigation were compared to this study. Figure 5.1 shows the atmospheric concentration of CO_2 resulting from six special reports on emission scenarios.

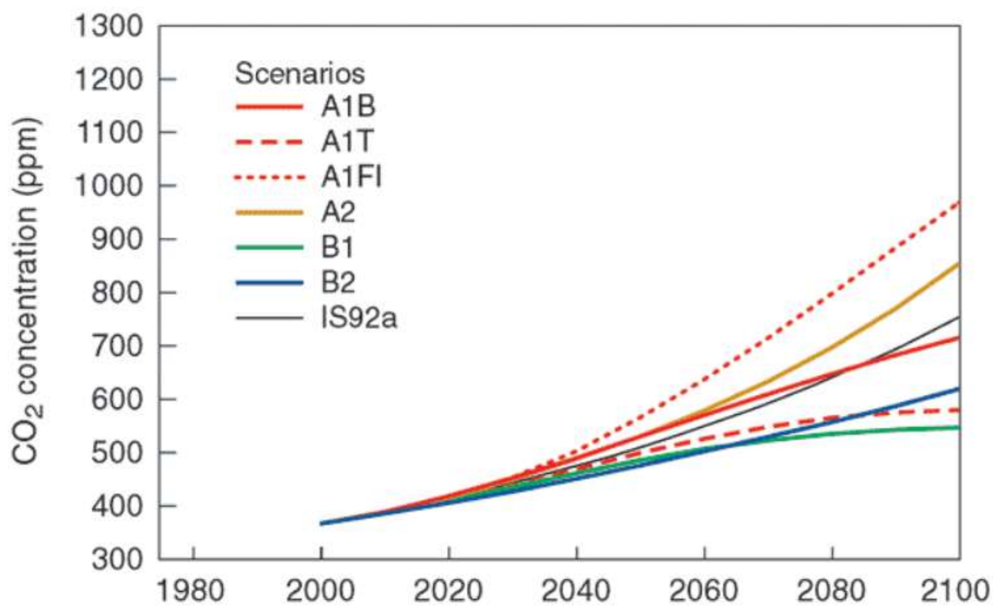


Figure 5.1. Atmospheric concentration of CO2 resulting from the six SRES (Special Report on Emissions Scenarios) scenarios (Cited from [Watson, et al., 2001])

In Figure 5.1, the three A1 scenarios (with subsets B, T and F1) assumed rapid economic growth and introduction of new technologies, global population peaking 2015. The subset FI represents fossil-fuel intensive, T represents non-fossil energy, B represents balanced different energy sources. In the A2 scenario, the model represents a world emphasizing self-reliance and preservation of local identities and economic growth. Further, it is assumed that the global population increases continuously, and further, a slow, fragmented technology change outlook. In the B1 scenario, the model corresponds to a world that experiences rapid change to a service and information economy, cleaner, more efficient technologies; also, global population peaking in 2050, emphasizing global solutions to sustainability, improved equity. In the B2 scenario, global population again increases continuously, and the technology change is not rapid [Watson, et al., 2001].

Comparing the results from this study with the results shown above, it can be seen that the results in 2025, 2030, 2040, 2050, 2060, 2070, 2080,2090 and 2100 scenarios are quite similar to the B1 scenario. In the B1 scenario, the model assumes rapid changes in the economic framework toward a service and information focused economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. In this scenario, the emphasis is on environmental sustainability, thus, in 2100, the atmospheric CO_2 concentration will reach 550 ppm. The result from this study shows that CO_2 concentration will reach 521 ppm to 559 ppm under different scenarios in 2100. These scenarios also considered environmental sustainability via replacement of all FFPPs, TVs and FFHs with NPPs, EVs and EHs.

Besides atmospheric CO_2 concentration, global upper ocean temperature from this study also can be compared with the results from IPCC. Figure 5.2 shows the global surface temperature under different scenarios. As predicted by this study, the upper ocean temperature will reach 2.5℃ to 2.8℃. This figure indicates that the results reported in the A1B scenario is quite similar to this study, which predicted that the surface temperature will reach 2.3℃ to 3.4℃.

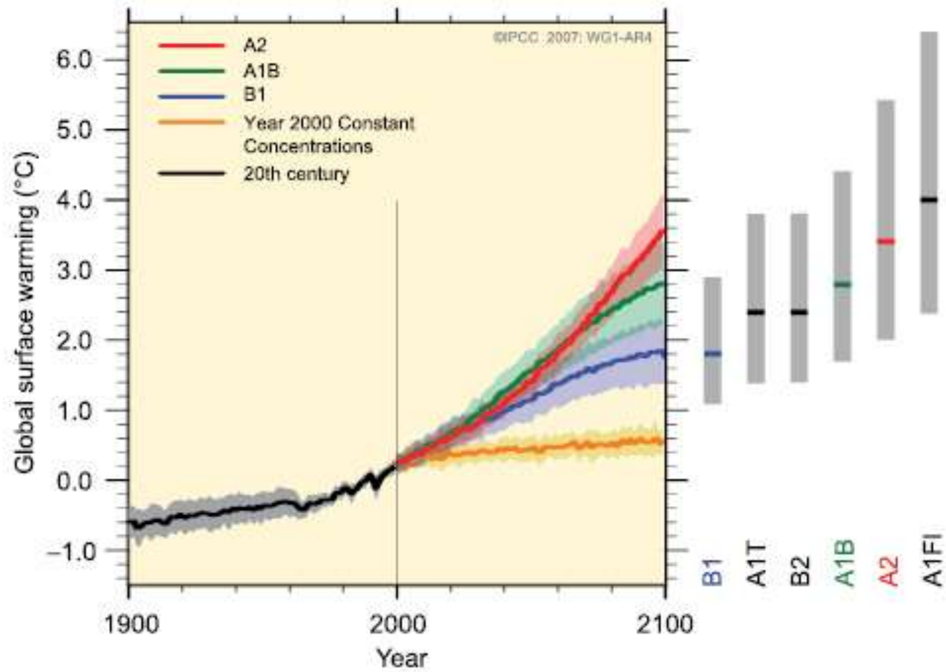


Figure 5.2. Global temperature resulting from the six SRES (Special Report on Emissions Scenarios) scenarios (Cited from [IPCC, 2007])

One of the most obvious impacts of climate change is the global temperature. The DICE model predicted the atmospheric and upper ocean temperature will be 2.98℃ (essentially 3℃) under current policies. However, with the construction of NPPs and the increasing number of EVs and EHs, there will be a mitigating impact on the global temperature increasing. It is estimated that if all FFPPs, TVs and FFHs are decommissioned by 2025, the atmospheric temperature will reach 2.53℃ in 2100 which is a reduction of 0.45℃, compared to the reference scenario. In the 2100 scenario, a reduction of 0.22℃ is predicted. Although it's only accounts 7.21% of the total estimated increase under a business-as-usual scenario, it indicates the replacement will have some impact on combating climate change. Moreover, the results here emphasize the significance of the cumulative impact of climate change, as expressed via global temperature. The current debate is that the climate situation is "dire".

Besides atmospheric temperature, the deep ocean temperature is also an indicator of the climate change. The ocean warms slowly in comparison to the atmosphere, although about 90% of the heat absorbed by earth goes into the ocean [Holden, 2020]. The DICE model predicted the deep ocean temperature will reach 0.46℃ by year, 2100. Due to the reduction of CO_2 emissions from power generation, transportation and heating, a small reduction of 0.011℃ to 0.032℃ is predicted. This is equivalent to a 2.32% to 6.88% of the predicted value of 0.46℃.

Since the DICE model also estimates the additional economic cost attributed to the negative impact of climate change, we summarize the simulation results. In order to combat the climate change, DICE model predicted that as much as 1.51 billion USD may need to be spent in 2100 which in 2019 is just 0.1 trillion US dollars. The cost increases more than 10 times from 2019 to 2100. Taking into account the replacement of FFPPs, TVs and FFHs by NPPs, EVs and EHs, a part of climate damage can be avoided. The biggest reduction of cost can be reached in the 2025 scenario. Under that scenario, about 0.42 billion dollars can be saved in 2100. This is equivalent to 27.84% of the 1.51 billion dollars, predicted by the DICE model. The 2100 scenario will also reduce 13.72% of the total climate damage.

Table 5.1 shows the summary of the simulation results. The reduction of CO_2 in atmosphere, CO_2 concentration, atmospheric temperature, deep ocean temperature and climate damage can be seen in this table.

Target year to reach zero CO_2 emission	Reduction of CO_2 in atmosphere in 2100 (Trillion tons C)	Reduction of CO_2 concentration in 2100 (ppm)	Reduction of atmospheric & Upper Ocean temperature (℃)	Reduction of deep ocean temperature (℃)	Reduction of Climate damage (Trillion Dollars)
Reference	0	0	0	0	0
2100	0.13 (9.7%)	59.69 (9.7%)	0.22 (7.2%)	0.011 (2.3%)	0.21 (13.7%)
2090	0.14 (10.6%)	65.64 (10.6%)	0.24 (8.1%)	0.012 (2.6%)	0.23 (15.3%)
2080	0.15 (11.5%)	71.26 (11.5%)	0.27 (9.1%)	0.014 (3.0%)	0.26 (17.1%)
2070	0.16 (12.4%)	76.57 (12.4%)	0.30 (10.2%)	0.016 (3.5%)	0.29 (19.0%)
2060	0.17 (13.2%)	81.58 (13.2%)	0.34 (11.3%)	0.019 (4.1%)	0.32 (21.0%)
2050	0.18 (14.0%)	86.32 (14.0%)	0.37 (12.4%)	0.022 (4.8%)	0.35 (23.0%)
2040	0.19 (14.7%)	90.79 (14.7%)	0.40 (13.6%)	0.026 (5.6%)	0.38 (25.0%)
2030	0.20 (15.5%)	95.02 (15.5%)	0.44 (14.7%)	0.030 (6.5%)	0.41 (26.9%)
2025	0.21 (15.7%)	97.05 (15.7%)	0.45 (15.2%)	0.032 (6.9%)	0.42 (27.8%)

Table 5.1 Summary of simulation results

Table 5.1 lists all the climate related factors which were analyzed in this study. And a comparison between the business-as-usual scenario and other simulation scenarios was made. The difference between the 2025 to 2100 scenario and reference scenario indicates how the differing rates of introducing NPPs, EVs and EHs, as replacement of counterpart infrastructure can influence climate change.

The results in the 2025 scenario shows the most ambitious reduction that can be reached, based on the scope of this current work. In this scenario, the CO_2 in the atmosphere can be reduced by 0.21 trillion tons of carbon, which is 15.7% of the total predicted by the original DICE model in the business- as-usual scenario. The CO_2 concentration can be reduced by 97ppm or 15.7%. Furthermore, the atmospheric and upper ocean temperature are predicted to decrease by 0.45℃, which corresponds to 15.2%of the total. Although the deep ocean temperature is not as sensitive as upper ocean temperature, a small reduction of 0.032℃ is possible. The climate related cost can be reduced by 0.42 trillion US dollars or 27.8%. Because this 2025 scenario corresponds to a very urgent replacement scenario of FFPPS, TVs and FFHs, it represents at best the urgency of the climate change circumstance we have today.

As more and more countries have publicly pledged to reach carbon neutrality by 2025, analyzing the results in the 2050 scenario is important and necessary. From the Table 5.1, we can see that the accumulation of CO_2 in the atmosphere can be reduced by 0.18 trillion tons of carbon. Correspondingly, the CO_2 concentration will also be reduced by 86 ppm. Moreover, the atmospheric and deep ocean temperature can be reduced by 0.37℃ and 0.022℃ respectively. As the CO_2 emission decreases, the associated climate damage can be reduced by 0.35 trillion dollars. Based on these results, it can be seen that if all FFPPs, TVs and FFHs are decommissioned/replaced by 2050 (or earlier), there will be increasing significance to mitigating climate change.

The results above show that the climate change can be slowed if the world's FFPPs, TVs and FFHs are replaced with NPPs, EVs and EHs. Although the rate of rapid deployment of NPPs, introduction of EVs and EHs are ambitious and thus require additional implementation details, this study indicates that the proposed replacement options do impact and mitigate the serious situation with respect to global warming/climate change while sustaining relative means of energy consumption and mobility. The NPPs, EVs and EHs are only part of the solution, as identified sources of CO_2 emissions. Additional sectors such as agriculture and commercial airline travel (using jet fuel, that produce emissions should also be considered, since the scale of mitigating climate change as reported here, needs to be larger (in scale).

Chapter 6. Conclusions

6.1 Conclusions to date

Various trusted organizations have reported that the negative impacts of global climate change may be linked to the sustainability and continued development of humankind [United Nations, 2021]. The very difficult issues linked to climate change are predicted to challenge current and future generations. With the increasing threats in energy security (insecurity) and the search for a more sustainable economic and social development in different countries, developing a low carbon economy is postulated to be the only way to address the challenging problems of global warming. In this study, Vensim-based simulations of climate change scenarios using a modified DICE model were conducted to investigate the contributions that nuclear power and transition to electrical systems can make in reducing the ongoing accumulation of CO_2.

The DICE model is a dynamic, macro-economic climate change model and here, was replicated by using the Vensim dynamic system modeling and simulation software. Besides the well-cited DICE model, three sub-models were added to the Venism DICE model. In summary, simulations in order to gauge the potential reduction of CO_2 emissions through the replacement of Fossil Fuel Power Plants (FFPPs), Traditional Vehicles (TVs) and Fossil Fuel Heaters (FFHs), respectively by Nuclear Power Plants (NPPs), Electric Vehicles (EVs) and Electric Heaters (EHs) were conducted. Using estimates of the CO_2 reduction from power generation, transportation and heating, this data was then fed into the macro-economic climate change DICE model to evaluate the overall impacts it may have on metrics representative of the negative impact of global climate. The modified portion replaced more than 70,000 FFPPs, 1.2 billion TVs and 1.8 billion FFHs currently existing in the world with NPPs, EVs and EHs. The NPPs, EVs and EHs are considered as essentially zero CO_2 (and related GHGs) emission replacements during their operation.

As the major simulation parameter, we chose different target years to reach net zero CO_2 emissions. This is because high level, announcements of targeted years to reach net zero carbon have been declared by leading nations. In this study, the targeted years were varied by decade as follows: 2030, 2040, 2050, 2060, 2070, 2080, 2090, 2100, except for 2025 which is viewed as only 5 years from the approximate starting time of the simulation. Thus, this spans the next 80 years. Since national declaration can be postponed, as the rate of increase of NPPs, EVs and EHs (per unit time) decreases, the corresponding rate of decommissioning of FFPPs, TVs and FFHs also decreases. A decrease in the replacement rate will cause an increase in the amount of CO_2 emissions. The different CO_2 emissions in each scenario will lead to different impacts on climate. The reference case is continuing forecast increase in CO_2 emissions, herein called, “business as usual”.

The results from this study indicate that if the NPPs, EVs and EHs are used to replace the FFPPs, TVs and FFHs currently in operating in the world, it can maintain the electrical generation capacity in gigawatt order, while reducing emission of CO_2. The simulation results indicate that if all the Fossil Fuel Power Plants are replaced by Nuclear Power Plants, traditional vehicles are replaced by electrical vehicles and Fossil Fueled heaters are replaced by Electric Heaters, CO_2 emission can be potentially reduced up to 15%.

At the end of the century, there will be about 4500 nuclear reactors, 3 billion electric vehicles and 3.9 billion electric heaters in order to be able to decommission all FFPPs, TVs and FFHs, while meeting the increasing demand for electricity, vehicles and heaters as the world's population continues to increase. Although it may be impossible and impractical to have so many NPPs in the world due to the limitations in different areas, based on this work, the CO_2 concentration can be reduced to 521 ppm to 559 ppm by 2100, in contrast to 619 ppm if no action is taken. This is still significantly higher than the consensus safe level concentration of 350ppm. As of 2019-2021, the CO_2 concentration is already approximately, 410 ppm. This study indicates that NPPs, EVs and EHs do offset accumulation of CO_2 linked to global warming, of approximately 100 ppm less than the "business as usual" scenario. This strongly supports the conclusion that the anthropogenic concentration of CO_2 is very high and nearing levels of irreversibility within the current century.

That's said, due to the reduction of additional CO_2 in atmosphere, it is expected that the increase in global temperature will correspondingly be reduced. The simulation results show that there will be a reduction 0.22℃ to 0.45℃ in atmospheric temperature by the end of this century. Under different scenarios, the atmospheric temperature by 2100 will vary from 2.53℃ to 2.77℃. The business-as-usual scenario in contrast predicts 3.0℃. A similar reduction of 0.011℃ to 0.032 ℃ in deep ocean temperature is also possible. The deep ocean temperature is predicted to reach 0.462℃ in 2100 if no action is taken. It is noted that the deep ocean temperature profile is thermally stratified due to slow moving currents, and dependent on three-dimensional (thermal) mixed convective flows.

Related to the atmospheric and deep ocean temperature, the associated climate damage is another important factor considered in the DICE model. Climate damage is the estimated cost due to the impacts of climate change on current infrastructure. Under today's policies and practice, the annual economic output by 2100 is estimated to be 1.52 trillion USD. If the FFPPs, TVs and FFHs are decommissioned, the negative impact of climate change can be partially mitigated and thus decrease the climate change related “damage cost”. For example, mitigating increase in the atmospheric temperature can equally reduce/mitigate costs linked to loss of (existing) landmass due to sea level increase. Thus, climate damage based on the DICE model and simulations, will reduce the estimated damage from 0.21 trillion to 0.42 trillion US dollars by 2100. Although the reduction of climate related cost is relatively small when compared to the world’s total GDP, reported to be 87 trillion US dollars in 2019[O’Neill, 2021], the investigated measures will reduce negative impact on the economy if actions per scenarios considered here are taken.

Most of the simulation results are based on ideal (or idealized) conditions. For example, in some scenarios, the construction rate of NPPs and the production of EVs and EHs cannot be achieved under current technology readiness level and corresponding supply of materials. For example, both global large forging capability (needed for large components such as the reactor vessel) and availability of large construction cranes are finite and thus, limit accelerated construction rate of NPPs. Furthermore, the social license of nuclear power (if opposed) can delay new construction, thus impact the rate of NPPs to replace fossil fuel-based generation. That said, EVs and EHs can be incentivized via government policies and programs that encourage transitions to replace fossil-based units. Here, such policies and incentives were not investigated because this study focused on climate change related analysis based on reduction of further accumulation of CO_2.

As more than 100 countries have pledged carbon neutrality by 2050, more national actions are expected in order to reduce CO_2 emissions. In 2021, during a Leaders Summit on Climate, 40 leaders attended the summit to discuss the challenges posed by global climate change and to seek global cooperation to combat climate change [Newburger, 2021]. During this summit, US President Biden vowed to reduced US emissions by at least 50% by 2030, which more than doubles the US' prior commitment under the 2015 Paris climate agreement [Newburger, 2021]. China as the world's biggest CO_2 emitter, re-affirmed their commitments to reach peak emissions before 2030 and to achieve carbon neutrality by 2060 during this summit [CGTN, 2021]. Finally, US and China agreed to cooperate on climate change. This indicates the two countries' positive attitude towards climate change mitigation but according to this study, aggressive commitments and targets are needed immediately.

This study shows that the pace of global warming can at least be reduced if all the fossil fuel power plants, traditional vehicles and fossil fueled heaters currently in the world are replaced by nuclear power plants, electric vehicles and electric heaters. This reduces but not fully reverses the continued increase in atmospheric CO_2 concentration. One can thus conclude from this study that replacing the sources of CO_2 generation is needed but insufficient to significantly reduce the anthropogenic, accumulated CO_2 concentration. This study provides a reference from which (aggressive) actions can be defined.

6.2 Future work

Based on the work done in this study, there are suggestions for further research. As the domestic heater is a commonly used appliance in many countries, a more precise total number of heaters is needed to address the recognized uncertainty here. Thus, in this study, the number of the fossil fueled and electric heaters were estimated based on the average family size, world population and the existing market of FFHs and EHs. There is partial data in order to support this estimate. In order to calculate the reduction of CO_2 from heating more accurately, further investigation to find more detailed data of FFHs and EHs is needed. Furthermore, the power output, number, location as well as other associated details of each FFPP need further confirmation. For these reasons, the number of FFPPs is estimated based on the power generated by FFPPs and the average power output by one FFPP. Thus, more detailed data (as opposed to aggregated data) can be used in future work. We recognize that realistically, the FFPP is connected to an electrical grid, and each plant may have specific local characteristics.

There are a number of climate models in the world. However, this work focused on the well-cited DICE model. Due to limitation in time and resources, other climate models were not considered in this work. For future work, it would be appropriate to compare simulation results from the DICE model with simulations using another model. The many plausible scenarios associated with (DICE model) reduction of CO_2 emissions estimated in this study should be compared with other macro-economic climate models and simulation tools.

As more and more countries pledge target year to reach carbon neutrality, it is clear that decommissioning FFPPs, TVs and FFHs is not the ultimate path to mitigating or reversing climate change. The CO_2 emissions from all sources should be considered in order to essentially reduce the continuing accumulation of CO_2 concentration. For example, CO_2 emissions from agriculture and aviation sectors should be reduced in order to (quantitatively) contribute to reaching carbon neutrality.

Finally, all the FFPPs are replaced by NPPs. This leads to a high NPP construction rate because the replacement option focused on nuclear generated electricity. Other types of electricity generation such as postulated scale-up of generation from renewable power were not considered. If the solar power, wind power, hydroelectric power, and other renewable sources can be taken into accounts in order to replace localized generation and need, currently dependent on FFPPs, the NPPs construction rate will decrease, and thus become more realistic in terms of current time to completion histories.

References

1. Ward B. A Nobel Prize for the creator of an economic model that underestimates the risks of climate change [Internet]. Grantham Research Institute on climate change and the environment. 2019 [cited 2021 Jul 2]. Available from: https://www.lse.ac.uk/granthaminstitute/news/a-nobel-prize-for-the-creator-of-an-economic-model-that-underestimates-the-risks-of-climate-change/

2. Nordhaus W. A Question of Balance: Weighing the Options on Global Warming Policies [Internet]. Yale University Press; 2008 [cited 2021 Jul 2]. Available from: https://www.jstor.org/stable/j.ctt1npzkh

3. Santer BD, Taylor KE, Wigley TML, Johns TC, Jones PD, Karoly DJ, et al. A search for human influences on the thermal structure of the atmosphere. Nature. 1996 Jul;382(6586):39–46.

4. Eggleton T. A Short Introduction to Climate Change. Illustrated edition. Cambridge; Port Melbourne, Vic: Cambridge University Press; 2012. 250 p.

5. Colpetzer JL. A study on the impact of nuclear power plant construction relative to decommissioning Fossil Fuel Power Plant in order to reduce carbon dioxide emissions using a modified Nordhaus Vensim DICE model [Internet]. Ph.D. Thesis. 2014 [cited 2021 Jul 2]. Available from: https://ui.adsabs.harvard.edu/abs/2014PhDT........85C

6. Johnson JM-F, Franzluebbers AJ, Weyers SL, Reicosky DC. Agricultural opportunities to mitigate greenhouse gas emissions. Environ Pollut. 2007 Nov;150(1):107–24.

7. IPCC. AR5 Climate Change 2014: Mitigation of Climate Change — IPCC [Internet]. 2014 [cited 2021 Jul 2]. Available from: https://www.ipcc.ch/report/ar5/wg3/

8. IPCC. AR5 Synthesis Report: Climate Change 2014 — IPCC [Internet]. 2014 [cited 2021 Jul 2]. Available from: https://www.ipcc.ch/report/ar5/syr/

9. Statista. Car production: Number of cars produced worldwide 2018 [Internet]. Statista. [cited 2021 Jul 2]. Available from: https://www.statista.com/statistics/262747/worldwide-automobile-production-since-2000/

10. Mukhopadhyay R, Karisiddaiah SM, Mukhopadhyay J. Chapter 5 - Threat To Opportunity. In: Mukhopadhyay R, Karisiddaiah SM, Mukhopadhyay J, editors. Climate Change [Internet]. Elsevier; 2018 [cited 2021 Jul 2]. p. 99–117. Available from: https://www.sciencedirect.com/science/article/pii/B9780128121641000050

11. Schulze ED, Stupak I, Hessenmöller D. Chapter 7 - The climate mitigation potential of managed versus unmanaged spruce and beech forests in Central Europe. In: Magalhães Pires JC, Cunha Gonçalves ALD, editors. Bioenergy with Carbon Capture

and Storage [Internet]. Academic Press; 2019 [cited 2021 Jul 2]. p. 131–49. Available from: https://www.sciencedirect.com/science/article/pii/B9780128162293000077

12. CGTN. China reiterates climate change commitments, says efforts underway [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://news.cgtn.com/news/2021-04-22/President-Xi-attends-Leaders-Summit-on-Climate-via-video-link-ZFKPiQ9yCc/index.html

13. Watson R. Climate Change 2001: Synthesis Report. Climate Change 2001: Synthesis Report, Edited by Robert T Watson, pp 408 ISBN 0521807700 Cambridge, UK: Cambridge University Press, March 2002. 2002 Mar 1;

14. NASA. Climate Change Evidence: How Do We Know? [Internet]. Climate Change: Vital Signs of the Planet. 2021 [cited 2021 Jul 2]. Available from: https://climate.nasa.gov/evidence

15. EPA. Climate Change Indicators: Weather and Climate [Internet]. US EPA. 2016 [cited 2021 Jul 2]. Available from: https://www.epa.gov/climate-indicators/weather-climate

16. Climate Atlas of Canada. Climate Change Projections [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://climateatlas.ca/climate-change-projections

17. Kaddo J. Climate Change: Causes, Effects, and Solutions. A with Honors Projects [Internet]. 2016 Jan 1; Available from: https://spark.parkland.edu/ah/164

18. National Academy of Sciences. Climate Change: Evidence and Causes: Update 2020 [Internet]. 2020 [cited 2021 Jul 2]. Available from: https://www.nap.edu/catalog/25733/climate-change-evidence-and-causes-update-2020

19. Dahlman L, Lindsey R. Climate Change: Global Temperature | NOAA Climate.gov [Internet]. 2020 [cited 2021 Jul 2]. Available from: https://www.climate.gov/news-features/understanding-climate/climate-change-global-temperature

20. IEA. CO2 Emissions from Fuel Combustion: Overview – Analysis [Internet]. IEA. 2020 [cited 2021 Jul 2]. Available from: https://www.iea.org/reports/co2-emissions-from-fuel-combustion-overview

21. Shieber J. CO2 in the atmosphere just exceeded 415 parts per million for the first time in human history | TechCrunch [Internet]. 2019 [cited 2021 Jul 2]. Available from: https://techcrunch.com/2019/05/12/co2-in-the-atmosphere-just-exceeded-415-parts-per-million-for-the-first-time-in-human-history/

22. Yue X-L, Gao Q-X. Contributions of natural systems and human activity to greenhouse gas emissions. Advances in Climate Change Research. 2018 Dec 1;9(4):243–52.

23. NASA. Data.GISS: GISS Surface Temperature Analysis (v4): Analysis Graphs and Plots [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://data.giss.nasa.gov/gistemp/graphs_v4/

24. Nordhaus W. DICE 2013R: Introduction and User's Manual [Internet]. PCHES. 2013 [cited 2021 Jul 2]. Available from: https://www.pches.psu.edu/bib-items/Nordhaus2013-lc/

25. Repetto R, Easton R. DICE Model Reassessment: Summary and key findings from first phase of analysis [Internet]. International Institute for Sustainable Development. 2014 [cited 2021 Jul 2]. Available from: https://www.iisd.org/publications/dice-model-reassessment-summary-and-key-findings-first-phase-analysis

26. OECD. Doing Better for Families [Internet]. 2011 [cited 2021 Jul 2]. Available from: https://www.oecd.org/social/soc/doingbetterforfamilies.htm

27. Bradford A. Effects of Global Warming | Live Science [Internet]. 2017 [cited 2021 Jul 2]. Available from: https://www.livescience.com/37057-global-warming-effects.html

28. Poovanna P, Davis R, July 9 CAO published on PO, 2018. Electric vehicles as part of Canada's climate change solution [Internet]. Policy Options. [cited 2021 Jul 2]. Available from: https://policyoptions.irpp.org/magazines/july-2018/electric-vehicles-as-part-of-canadas-climate-change-solution/

29. IEA. Electricity generation mix, 2018 – Charts – Data & Statistics [Internet]. IEA. 2019 [cited 2021 Jul 2]. Available from: https://www.iea.org/data-and-statistics/charts/electricity-generation-mix-2018

30. Zeiss G. Energy Efficiency of Fossil Fuel Power Generation [Internet]. Between the Poles. 2010 [cited 2021 Jul 2]. Available from: https://geospatial.blogs.com/geospatial/2010/01/energy-efficiency-of-fossil-fuel-power-generation.html

31. Fanchi JR. Energy in the 21st century. 3rd edition. Hackensack], New Jersey: World Scientific; 2013.

32. Yan Q, Wang Y, Baležentis T, Sun Y, Streimikiene D. Energy-Related CO2 Emission in China's Provincial Thermal Electricity Generation: Driving Factors and Possibilities for Abatement. Energies. 2018 May;11(5):1096.

33. EnergySage. Environmental Impact of Electric Vehicles [Internet]. 2019 [cited 2021 Jul 2]. Available from: https://www.energysage.com/electric-vehicles/advantages-of-evs/evs-environmental-impact/

34. Nordhaus W. Evolution of modeling of the economics of global warming: changes in the DICE model, 1992–2017. Climatic Change. 2018;148(4):623–40.

35. Hausefather Z. Explainer: How scientists estimate climate sensitivity [Internet]. Carbon Brief. 2018 [cited 2021 Jul 2]. Available from: https://www.carbonbrief.org/explainer-how-scientists-estimate-climate-sensitivity

36. Laffoley D, Baxter JM, editors. Explaining Ocean Warming: Causes, scale, effects and consequences [Internet]. IUCN, International Union for Conservation of Nature; 2016 [cited 2021 Jul 2]. Available from: https://portals.iucn.org/library/node/46254

37. Hausefather Z. Factcheck: How electric vehicles help to tackle climate change [Internet]. Carbon Brief. 2019 [cited 2021 Jul 2]. Available from: https://www.carbonbrief.org/factcheck-how-electric-vehicles-help-to-tackle-climate-change

38. Kopp O. fossil fuel | Meaning, Types, & Uses [Internet]. Encyclopedia Britannica. 2020 [cited 2021 Jul 2]. Available from: https://www.britannica.com/science/fossil-fuel

39. Ritchie H, Roser M. Fossil Fuels. Our World in Data [Internet]. 2017 Oct 2 [cited 2021 Jul 2]; Available from: https://ourworldindata.org/fossil-fuels

40. Rapier R. Fossil Fuels Still Supply 84 Percent Of World Energy — And Other Eye Openers From BP's Annual Review [Internet]. Forbes. 2020 [cited 2021 Jul 2]. Available from: https://www.forbes.com/sites/rrapier/2020/06/20/bp-review-new-highs-in-global-energy-consumption-and-carbon-emissions-in-2019/

41. World Resources Institute. Global Emissions [Internet]. Center for Climate and Energy Solutions. 2017 [cited 2021 Jul 2]. Available from: https://www.c2es.org/content/international-emissions/

42. IEA. Global EV Outlook 2020 – Analysis - IEA [Internet]. 2020 [cited 2021 Jul 2]. Available from: https://www.iea.org/reports/global-ev-outlook-2020

43. O'Neill A. Global GDP 2014-2024 [Internet]. Statista. [cited 2021 Jul 2]. Available from: https://www.statista.com/statistics/268750/global-gross-domestic-product-gdp/

44. EPA. Global Greenhouse Gas Emissions Data [Internet]. US EPA. 2016 [cited 2021 Jul 2]. Available from: https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data

45. NOAA. Global Monitoring Laboratory - Carbon Cycle Greenhouse Gases [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://gml.noaa.gov/ccgg/trends/

46. Riebeek H. Global Warming [Internet]. NASA Earth Observatory; 2010 [cited 2021 Jul 2]. Available from: https://earthobservatory.nasa.gov/features/GlobalWarming

47. Rossati A. Global Warming and Its Health Impact. Int J Occup Environ Med. 2017 Jan;8(1):7–20.

48. World Nuclear Association. Heat values of various fuels [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://world-nuclear.org/information-library/facts-and-figures/heat-values-of-various-fuels.aspx

49. Newburger E. Here's what countries pledged on climate change at Biden's global summit [Internet]. CNBC. 2021 [cited 2021 Jul 2]. Available from: https://www.cnbc.com/2021/04/22/biden-climate-summit-2021-what-brazil-japan-canada-others-pledged.html

50. Saja F. HOW MANY CARS ARE THERE IN THE WORLD? [Internet]. DriveTribe. 2020 [cited 2021 Jul 2]. Available from: https://drivetribe.com/p/how-many-cars-are-there-in-the-dqbpAzrATLOOSgDfRrgkjQ

51. EIA. How much carbon dioxide is produced when different fuels are burned? [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://www.eia.gov/tools/faqs/faq.php

52. Cole L. How to cut carbon out of your heating [Internet]. [cited 2021 Jul 2]. Available from: https://www.bbc.com/future/article/20201116-climate-change-how-to-cut-the-carbon-emissions-from-heating

53. IEA. Improving the sustainability of passenger and freight transport [Internet]. IEA. 2021 [cited 2021 Jul 2]. Available from: https://www.iea.org/topics/transport

54. Stehfest E, Planbureau voor de Leefomgeving. Integrated assessment of global environmental change with IMAGE 3.0: model description and policy applications. 2014.

55. Nordhaus WD. Integrated Economic and Climate Modeling [Internet]. Cowles Foundation Discussion Papers. Cowles Foundation for Research in Economics, Yale University; 2011 Dec [cited 2021 Jul 2]. (Cowles Foundation Discussion Papers). Report No.: 1839. Available from: https://ideas.repec.org/p/cwl/cwldpp/1839.html

56. EPA. Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2015 [Internet]. US EPA. 2016 [cited 2021 Jul 2]. Available from: https://www.epa.gov/ghgemissions/inventory-us-greenhouse-gas-emissions-and-sinks-1990-2015

57. Fingerprint. Is it safe to double atmospheric Carbon Dioxide over a 200 year period? [Internet]. Skeptical Science. 2010 [cited 2021 Jul 2]. Available from: https://skepticalscience.com/Is-it-safe-to-double-atmospheric-Carbon-Dioxide-over-200-year-period.html

58. UNFCCC. Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount. esocialsciences.com, Working Papers. 2009 Jan 1;

59. Lenzen M. Life cycle energy and greenhouse gas emissions of nuclear energy: A review. Energy Conversion and Management. 2008 Aug 1;49(8):2178–99.

60. Carbon Brief. Mapped: The world's coal power plants in 2020 [Internet]. Carbon Brief. 2020 [cited 2021 Jul 2]. Available from: https://www.carbonbrief.org/mapped-worlds-coal-power-plants

61. Johnson S, Chau K. More U.S. coal-fired power plants are decommissioning as retirements continue - Today in Energy - U.S. Energy Information Administration (EIA) [Internet]. 2019 [cited 2021 Jul 2]. Available from: https://www.eia.gov/todayinenergy/detail.php?id=40212

62. Ma Q. NASA GISS: Science Briefs: Greenhouse Gases: Refining the Role of Carbon Dioxide [Internet]. 1998 [cited 2021 Jul 2]. Available from: https://www.giss.nasa.gov/research//briefs/1998_ma_01/

63. Levitus S, Doc U, Nesdis, Antonov J, Boyer T, Baranova O, et al. NCEI ocean heat content, temperature anomalies, salinity anomalies, thermosteric sea level anomalies, halosteric sea level anomalies, and total steric sea level anomalies from 1955 to present calculated from in situ oceanographic subsurface profile data (NCEI Accession 0164586). In 2017.

64. Goverment of Canada. Net-Zero Emissions by 2050 [Internet]. 2020 [cited 2021 Jul 2]. Available from: https://www.canada.ca/en/services/environment/weather/climatechange/climate-plan/net-zero-emissions-2050.html

65. Northon K. NOAA Data Show 2016 Warmest Year on Record Globally [Internet]. NASA. 2017 [cited 2021 Jul 2]. Available from: http://www.nasa.gov/press-release/nasa-noaa-data-show-2016-warmest-year-on-record-globally

66. Marton Dunai, Geert De Clercq. Nuclear energy too slow, too expensive to save climate: report. Reuters [Internet]. 2019 Sep 24 [cited 2021 Jul 2]; Available from: https://www.reuters.com/article/us-energy-nuclearpower-idUSKBN1W909J

67. IEA. Nuclear Power in a Clean Energy System – Analysis [Internet]. IEA. 2019 [cited 2021 Jul 2]. Available from: https://www.iea.org/reports/nuclear-power-in-a-clean-energy-system

68. Shaftel H. Overview: Weather, Global Warming and Climate Change [Internet]. Climate Change: Vital Signs of the Planet. 2021 [cited 2021 Jul 2]. Available from: https://climate.nasa.gov/resources/global-warming-vs-climate-change

69. European Commission. Paris Agreement [Internet]. Climate Action - European Commission. 2016 [cited 2021 Jul 2]. Available from: https://ec.europa.eu/clima/policies/international/negotiations/paris_en

70. Denchak M. Paris Climate Agreement: Everything You Need to Know [Internet]. NRDC. 2021 [cited 2021 Jul 2]. Available from: https://www.nrdc.org/stories/paris-climate-agreement-everything-you-need-know

71. Council for Agricultural Science and Technology. Preparing U.S. Agriculture for Global Climate Change [Internet]. 1992 [cited 2021 Jul 2]. Available from: http://www.ciesin.org/docs/004-181/004-181.html

72. Mcsweeney R, Hausefather Z. Q&A: How do climate models work? [Internet]. Carbon Brief. 2018 [cited 2021 Jul 2]. Available from: https://www.carbonbrief.org/qa-how-do-climate-models-work

73. Nordhaus WD. Reflections on the Economics of Climate Change. Journal of Economic Perspectives. 1993 Dec;7(4):11–25.

74. Chafe Z, Brauer M, Heroux M, Klimont Z, Lanki T, Salonen R, et al. Residential heating with wood and coal: health impacts and policy options in Europe and North America. undefined [Internet]. 2015 [cited 2021 Jul 2]; Available from: https://www.semanticscholar.org/paper/Residential-heating-with-wood-and-coal%3A-health-and-Chafe-Brauer/8dedab05124e2504421a4873f5d1e5ad7e7d2251

75. IPCC. SAR Climate Change 1995: The Science of Climate Change — IPCC [Internet]. 1996 [cited 2021 Jul 2]. Available from: https://www.ipcc.ch/report/ar2/wg1/

76. EPA. Sources of Greenhouse Gas Emissions [Internet]. US EPA. 2015 [cited 2021 Jul 2]. Available from: https://www.epa.gov/ghgemissions/sources-greenhouse-gas-emissions

77. Buis A. Study Confirms Climate Models are Getting Future Warming Projections Right [Internet]. Climate Change: Vital Signs of the Planet. 2020 [cited 2021 Jul 2]. Available from: https://climate.nasa.gov/news/2943/study-confirms-climate-models-are-getting-future-warming-projections-right

78. Newbold SC. Summary of the DICE model. 2010;8.

79. Bergman J. Temperature of Ocean Water - Windows to the Universe [Internet]. 2011 [cited 2021 Jul 2]. Available from: https://www.windows2universe.org/earth/Water/temp.html

80. Holden E. Temperatures of deepest ocean rising quicker than previously thought [Internet]. the Guardian. 2020 [cited 2021 Jul 2]. Available from: http://www.theguardian.com/environment/2020/oct/14/enormous-amount-of-heat-even-deepest-ocean-is-warming-study

81. Nordhaus W. The "DICE" Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming [Internet]. Cowles Foundation for Research in Economics, Yale University; 1992 Feb [cited 2021 Jul 2]. Report No.: 1009. Available from: https://econpapers.repec.org/paper/cwlcwldpp/1009.htm

82. Gaffney O, Steffen W. The Anthropocene equation. The anthropocene review. 2017;4(1):53–61.

83. NASA. The Carbon Cycle [Internet]. NASA Earth Observatory; 2011 [cited 2021 Jul 2]. Available from: https://earthobservatory.nasa.gov/features/CarbonCycle/page5.php

84. Serreze MC, Barrett AP, Stroeve JC, Kindig DN, Holland MM. The emergence of surface-based Arctic amplification. The Cryosphere. 2009 Feb 4;3(1):11–9.

85. Wade K. The impact of climate change on the global economy [Internet]. The impact of climate change on the global economy. 2016 [cited 2021 Jul 2]. Available from: https://www.schroders.com/en/us/institutional/insights/economic-views3/the-impact-of-climate-change-on-the-global-economy/

86. Cooper R. The ocean has absorbed more than 90% of the heat gained by the planet - Climate Action [Internet]. 2019 [cited 2021 Jul 2]. Available from: https://www.climateaction.org/news/the-ocean-has-absorbed-more-than-90-of-the-heat-gained-by-the-planet

87. Brand C, Tran M, Anable J. The UK transport carbon model: An integrated life cycle approach to explore low carbon futures. Energy Policy. 2012 Feb;41:107–24.

88. SmarterHouse. Types of Heating Systems [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://smarterhouse.org/heating-systems/types-heating-systems

89. Vensim. User Guide - Vensim Introduction & Tutorials [Internet]. 2002 [cited 2021 Jul 2]. Available from: https://www.vensim.com/documentation/users_guide.html

90. National Academies of Sciences. Valuing Climate Damages: Updating Estimation of the Social Cost of Carbon Dioxide [Internet]. 2017 [cited 2021 Jul 2]. Available from: https://www.nap.edu/catalog/24651/valuing-climate-damages-updating-estimation-of-the-social-cost-of

91. Blogger G. What Are Climate Models and How Accurate Are They? [Internet]. State of the Planet. 2018 [cited 2021 Jul 2]. Available from: https://news.climate.columbia.edu/2018/05/18/climate-models-accuracy/

92. World Nuclear Association. Where does our electricity come from? [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://world-nuclear.org/nuclear-essentials/where-does-our-electricity-come-from.aspx

93. Darby M, Gerretsen I. Which countries have a net zero carbon goal? [Internet]. Climate Home News. 2019 [cited 2021 Jul 2]. Available from: https://www.climatechangenews.com/2019/06/14/countries-net-zero-climate-goal/

94. Swiss Re Institute. World economy set to lose up to 18% GDP from climate change if no action taken, reveals Swiss Re Institute's stress-test analysis [Internet]. 2021 [cited 2021 Jul 2]. Available from: https://www.swissre.com/media/news-releases/nr-20210422-economics-of-climate-change-risks.html

95. ENSIA. 8 Ways to Sequester Carbon to Avoid Climate Catastrophe [Internet]. EcoWatch. 2017 [cited 2021 Aug 13]. Available from: https://www.ecowatch.com/carbon-sequestration-2461971411.html

96. Albeck-Ripka L. How to Reduce Your Carbon Footprint [Internet]. 2021 [cited 2021 Aug 13]. Available from: https://www.nytimes.com/guides/year-of-living-better/how-to-reduce-your-carbon-footprint

97. Lindsey R. Climate and Earth's Energy Budget [Internet]. NASA Earth Observatory; 2009 [cited 2021 Aug 16]. Available from: https://earthobservatory.nasa.gov/features/EnergyBalance/page7.php

98. United Nations. IPCC report: 'Code red' for human driven global heating, warns UN chief [Internet]. UN News. 2021 [cited 2021 Aug 19]. Available from: https://news.un.org/en/story/2021/08/1097362

Appendices

Since this research rests on application of DICE model, the equations and correlations in the DICE model are shown below in Appendix A. Furthermore, a part of the work was presented and published in Canadian Nuclear Society (CNS) Annual Conference in 2021 (give reference as footnote). Thus, the accepted CNS conference paper is attached in Appendix E. Appendix F is the corresponding slide presentation from the CNS conference paper.

Appendix A

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) CO_2 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: Ton C/year

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

Causes:

- (006) CO_2 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) CO_2 And CFC Intens Capital - CO2 and CFC Emissions per Unit of Capital (tons carbon equiv/year/$)
- (007) CO_2 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) CO_2 in Atmos = INTEG (CO_2 Net Emiss - CO2 Storage, 6.77e+011)

Units: Ton C

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

Causes:

- (007) CO_2 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) CO_2 Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

Uses:

- (009) CO_2 Rad Forcing - Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO2. [Cowles, pg. 22]
- (010) CO_2 Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

(004) CO_2 Intens Dec Rt Decline Rt =

CO_2 Intens Decline Rt* Fact Prod Gr Rt Dec Rt

Units: 1/year/year

Causes:

- (005) CO_2 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) CO_2 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) CO_2 Intens Decline Rt = INTEG (- CO_2 Intens Dec Rt Decline Rt, init CO_2 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) CO_2 Intens Dec Rt Decline Rt -
- (016) init CO_2 intens decline rt -

Uses:

- (004) CO_2 Intens Dec Rt Decline Rt -
- (011) Decline CO_2 Intens - Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]

(006) CO_2 Intensity of Output = INTEG (- Decline CO_2 Intens, 0.000519)

Units: Ton C/$

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 CO_2 Intens - Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]

Uses:

- (002) CO_2 Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]
- (011) Decline CO_2 Intens - Decline of GHG Intensity of Output (tons carbon equivalent/$/year) [Cowles, pg. 20]
- (087) Reference CO_2 Emissions - Reference CO_2 Emissions at normal CO2 intensity, with no abatement.

(007) CO_2 Net Emiss = Atmos Retention* CO_2 Emiss

Units: Ton C/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:

- Atmos Retention - Atmospheric Retention Fraction [beta] (dimensionless) Fraction of Greenhouse Gas Emissions which accumulate in the atmosphere. [Cowles, pg. 21]
- (002) CO_2 Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]

Uses:

- (003) CO_2 in Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]

(008) CO_2 Rad Force Coeff = 4.1

Units: watt/meter/meter

Coefficient of Radiative Forcing from CO_2 (W/m^2) Coeff. of additional surface warming from accumulation of CO_2. [Cowles, pg. 22]

Uses:

- (009) CO_2 Rad Forcing - Radiative Forcing from CO2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO_2. [Cowles, pg. 22]

(009) CO2_Rad_Forcing = CO_2 Rad Force Coeff * LOG (CO_2 in Atmos/Preindustrial CO_2 ,2)

Units: watt/meter/meter

Radiative Forcing from CO_2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO_2. [Cowles, pg. 22]

Causes:

- (003) CO_2 in Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]
- (008) CO_2 Rad Force Coeff - Coefficient of Radiative Forcing from CO_2 (W/m^2) Coeff. of additional surface warming from accumulation of CO_2. [Cowles, pg. 22]
- (021) Preindustrial CO_2-

Uses:

- (041) Radiative Forcing - Radiative Forcing from All GHGs (W/m^2) Additional surface warming from accumulation of CO_2& CFCs. [Cowles, Sec. III.F]

(010) CO_2 Storage = (CO_2 in Atmos-Preindustrial CO_2) * Rate of CO_2 Transfer

Units: Ton C/year

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

Causes:

- (003) CO_2 in Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]
- (021) Preindustrial CO_2 -
- (022) Rate of CO_2 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) CO_2 in Atmos - Greenhouse Gases in Atmosphere [M(t)] (tons carbon equivalent) [Cowles, pg. 21]

(011) Decline CO_2 Intens = CO_2 Intensity of Output* CO_2 Intens Decline Rt

Units: Ton C/$/year

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

Causes:

- (005) CO_2 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) CO_2 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) CO_2 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 CO_2 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) CO_2 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 CO_2 intens decline rt = 0.01168

Units: 1/year

Uses:

- (005) CO_2 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 CO_2 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 S abilization)))

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 CO_2 and CFC Emissions Controlled (dimensionless) Stabilization of Emissions. Estimated from graph in [Science, Fig. 1].
- (013) Emissions Scenario -
- (017) No Controls - Fraction of CO_2 and CFC Emissions Controlled (dimensionless) Uncontrolled scenario.
- (019) Optimal Controls - Fraction of CO_2 and CFC Emissions Controlled (dimensionless) Optimal control scenario. [Cowles, table IV-3]
- (025) Temp Stabilization - Fraction of CO_2 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 CO_2 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) CO_2 Rad Forcing - Radiative Forcing from CO_2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO_2. [Cowles, pg. 22]
- (010) CO_2 Storage - Greenhouse Gas removal from the atmosphere and storage by long-term processes. (tons carbon equivalent/year) [Cowles, pg. 21]

(022) Rate of CO_2 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) CO_2 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 CO_2 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 CO_2 Emissions

(025) Temp Stabilization

Units: dmnl

Fraction of CO_2 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/Degrees C/(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: Degrees C

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: Degrees C/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 CO_2 & 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: Degrees C/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] (Wyr/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) ^ Climat 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/Degrees C

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: Degrees C

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/Degrees C/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] (Wm^ 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*Degrees C)

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] (Wyr/ 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] (Wyr/ 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] (Wyr/ 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 CO_2 & CFCs. [Cowles, Sec. III.F]

(041) Radiative Forcing = CO_2 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) CO_2 Rad Forcing - Radiative Forcing from CO_2 [F(t)] (W/m^2) Additional surface warming from accumulation of CO_2. [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: Degrees C

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: Degrees C

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 CO_2 CFC Rad Force

Units: watt/meter/meter

IPCC Scenario for Radiative Forcing from CO_2 and CFCs (W/m^2) As interpolated by Nordhaus. [Cowles, Table III.E-5]

(049) Nord CO_2 in Atm

Units: GTon C

Nordhaus' CO_2 & CFC Concentrations (Gt Carbon Equivalent) Uncontrolled scenario [Cowles, Table IV-4].

(050) Nord CO_2 Intensity

Units: GTon C/$

(051) Nord Emiss

Units: GTon C/year

Nordhaus' CO_2& 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: Degrees C

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) CO_2 And CFC Intens Capital - $CO_2$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) CO_2 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 $/year)
- (002) CO_2 Emiss - Greenhouse Gas Emissions [E(t)] (tons carbon equivalent/year) [Cowles, pg. 20]
- (057Consumption - Consumption ($/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 CO_2Emissions
- (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 CO_2 Emissions - Reference CO_2 Emissions Emissions at normal CO_2intensity, 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 = ReferenceOutput*(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) CO_2 And CFC Intens Capital = CO_2 Emiss/Capital

Units: Ton C/year/$

CO_2 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) CO_2 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 CO_2 Emissions*Red Cost Scale *Red Cost Nonlinearity *if then else (GHG Reduction Frac&gt0, (GHG Reduction Frac) ^ (Red Cost Nonlinearity -1),0)

Units: $/Ton C

Marginal Productivity of CO_2 Emissions

Causes:

- (015) GHGReduction_ 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 CO_2 Emissions - Reference CO2 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 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 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 CO_2 Emissions = Reference Output* CO_2 Intensity of Output

Units: Ton C/year

Reference CO_2 Emissions at normal CO_2 intensity, with no abatement.

Causes:

- (006) CO_2 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 CO_2 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 the policy

Uses:

- (096) Policy Times - Year of implementation of the 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 the 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 the policy

Causes:

- (091) Init Policy Times - Year of implementation of the 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) shiftswitch -

(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 the 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 the 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 [deltapop] (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) Capita _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

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 TimePref - 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]

Appendix B. The availability of uranium and lithium analysis

As the increasing number of NPPs in each scenario, it's important to analyze the availability of uranium. Also, the availability of lithium for EVs also needs to be analyzed. According to IAEA, the world's conventional identified uranium resources amounted to 8,070,400 tonnes of uranium metal as of 1 January 2019 [IAEA, 2020]. For a typical nuclear power plant which has an electric generating capacity of 1,000 Mwe, the annual consumption of natural uranium is about 250 tonnes [Nuclear Power for Everybody,2021]. If only consider these data, it can be seen that the identified amount of uranium is not enough to supply the huge number of NPPs in each scenario. However, there are several methods that can extend the uranium supply. For example, it can help to save as much as 30% per metric ton of low-enriched uranium if using more enrichment work [Fetter, 2019]. Also, separating plutonium and uranium from spent low-enriched uranium and using them to maker fresh fuel could reduce by another 30% of uranium [Fetter, 2019]. By using these two methods would cut the uranium requirements of an LWR in half.

Besides the two methods mentioned above, there are two technologies can help to extend the uranium supply. The first one is the extraction of uranium from seawater which would make available of 4.5 billion metric tons of uranium [Fetter, 2019]. Secondly, fuel-recycling fast-breeder reactors can be used as it only use less than 1% of the uranium needed for current LWRs [Fetter, 2019].

Based on the methods mentioned above, it can be seen that the supply of uranium would not be a big problem if nuclear power considered to be used to combat the climate change. Besides the supply of uranium, lithium also needs to be considered as the increasing number of EV in the world. Since 2001, the identified lithium resources have increased substantially worldwide from 12 million metric tons to about 86 million tons by 2021[Gerber, 2021]. Meantime, the estimated global lithium reserves increased form 3.4 billion metric tons in 2001 to 21 million metric tons in 2020 [Gerber, 2021]. However, a typical EV has roughly 10 kilograms of lithium in it [Root, 2020]. Based on these two data, the current identified lithium can supply more that 7 billion EVs. As estimated by this research, there would be about 3 billion EVs in the world in 2100. Thus, lithium may be a risk for EV. However, there are methods can help to solve this problem. For example, recycling the materials in used batteries and using advanced mining technologies [Gerber, 2021].

Reference:

1. IAEA. World's Uranium Resources Enough for the Foreseeable Future, Say NEA and IAEA in New Report [Internet]. IAEA; 2020 [cited 2021 Aug 13]. Available from: https://www.iaea.org/newscenter/pressreleases/worlds-uranium-resources-enough-for-the-foreseeable-future-say-nea-and-iaea-in-new-report
2. Nuclear Power for Everybody. Fuel Consumption of Conventional Reactor [Internet]. Nuclear Power. 2021 [cited 2021 Aug 13]. Available from: https://www.nuclear-power.com/nuclear-power-plant/nuclear-fuel/fuel-consumption-of-conventional-reactor/
3. Fetter S. How long will the world's uranium supplies last? [Internet]. Scientific American. 2009 [cited 2021 Aug 13]. Available from: https://www.scientificamerican.com/article/how-long-will-global-uranium-deposits-last/
4. Gerber K. Why we are probably not running out of lithium [Internet]. 2021 [cited 2021 Aug 13]. Available from: https://www.linkedin.com/pulse/why-we-probably-running-out-lithium-katharina-gerber-ph-d-/
5. Root A. Why Lithium Could Be a New Risk for Tesla and Other Electric-Vehicle Makers [Internet]. 2020 [cited 2021 Aug 13]. Available from: https://www.barrons.com/articles/new-risk-tesla-other-electric-vehicle-makers-lithium-supply-batteries-51601498472

Appendix C: A note to stakeholders and others who use the results of this thesis

This thesis, consisting of modifications to the Nordhaus DICE, macro-economic climate change model (created using the VENSIM dynamic modeling software tool), contains results from simulations herein described to fulfill graduate-level academic requirements stipulated by the Ontario Tech University[1], School of Graduate and Post Graduate Studies.

The research linked to this thesis was not commissioned nor funded by a commercial, for-profit entity. In particular, it was not funded by an entity with commercial interests in the energy sectors, including nuclear energy, electric vehicles and/or domestic electric heaters.

We further note that since the Nordhaus DICE model is a macro-economic climate change model, simulation results generated by time-based iterations of the DICE model used here do not contain micro-economic analytic methods nor associated detailed climate change models. In broad terms, macro-economic methods focus on decisions made by countries, government, large regions (such as cities), based on studies of scenarios, options and objectives. In contrast, micro-economic methods focus on individuals and localized businesses, and commonly the supply and demand of commodities (such as money), that determine pricing and taxations of various types. Specifically, the DICE model thus consist of a set of algebraic equations and empirical relationships, whereas micro-economic methods may contain a set of partial differential or integro-differential or difference equation wherein discretization and time-steps are part of the concern in running a

[1] The University is officially, University of Ontario Institute of Technology or UOIT.

simulation. This work used the macro-economic approach, and thus, citation of this work should note the limitation of the method used.

Further, the results presented such as the concentration of CO2 (given in ppm), ocean surface temperature and deep ocean temperature are example variables commonly noted in public discourse on climate change. These variables and the time-based results given here are representative examples of indicators of interest that correspond to the scenarios considered. The represented variables are not all the variable and parameters that can be considered. This depends on the particular focus when using the DICE model.

Thus, to organizations and stakeholders who may reference the results herein contained, please properly cite the thesis in whole. We caution any who may be interested in the work to take any single or few results given in the work, to advocate a position, an agenda or set of beliefs and values, advantageous, relative to another. We also caution the use of single or few results given in advocacy, as possible in social media.

We thank you for your interest in this work. In case of questions, we ask that you contact the co-supervising professors, Dr. Filippo Genco and Dr. Akira Tokuhiro.

Appendix D: Response to questions from examination committee members

Question from Prof. Daniel Hoornweg

1.Canadian environmentalist, David Suzuki, recently said the at nuclear is not for climate change. Is this a correct view? From your research, is drastic action needed? What is drastic? Are your results correct if the sum total of electrical generation, EVs and EHs is only ~45% of the CO2 generations? Does your result make sense?

I think a part of view in his paper is correct. He said may be solar power and wind power is better than nuclear power, however, replacing all the fossil fuel power by this renewable power is impractical due to the limitation of material, space to build them, et al. Based on different scenarios, the construction rate of NPPs is different, some are drastic and some are practical. Although my study only considers the CO2 emission from electricity generation, transportation and heating which accounts for 45% of the total CO2 emissions, the results still make sense and can be a reference because it indicates the possible carbon footprint in the scenario which reduction the CO2 emission from these three specific areas.

2.Explain what you mean by PPP. Are these petroleum plants, including diesel fuel plants? How many PPPs in the world? What is the average electrical or thermal output assumed if the estimate is ~31,000?

Power plants that burn petroleum liquids (such as distillate or residual fuel oils). It was estimated that there are about 31,000 operating unit in the world in 2019. And the average output is 24.896MWh/unit.

3.What about the dangers in particulate pollution? Which is more dangerous, particulate pollution or CO2?

Particle pollution — also called particulate matter (PM) — is made up of particles (tiny pieces) of solids or liquids that are in the air.

Breathing in particle pollution can be harmful to your health. Coarse (bigger) particles, called PM10, can irritate your eyes, nose, and throat. Dust from roads, farms, dry riverbeds, construction sites, and mines are types of PM10.

Fine (smaller) particles, called PM2.5, are more dangerous because they can get into the deep parts of your lungs — or even into your blood.

We can see that the particular pollution is dangerous to individuals, however, the impact of CO2 is mainly on our climate which will then influence our daily life. Thus, the particular pollution is more dangerous than CO2.

Reference: Centers for Disease Control and Prevention. Particle Pollution [Internet]. 2021 [cited 2021 Aug 13]. Available from: https://www.cdc.gov/air/particulate_matter.html

4.If we increased the number of NPPs, how many more operators and nuclear operators will we needed. With 450 nuclear plants, how big is the workforce now? How many more are needed if we increased to 4500 (~5000) and more?

Each nuclear power plant employs 500 to 800 workers.

Building a nuclear power reactor employs up to 7,000 workers at peak construction.

There are 56 NPPs (94 reactors) in Us which directly employs nearly 100,000 people in high - quality, long term jobs.

If there are 4500 nuclear reactors in world as predicted by this study, about 4,787,000 people are needed.

Reference: Northwest & Ethical Investments, A single nuclear power plant creates more jobs than any other type of energy generation facility [Internet]. Nuclear Energy Institute. 2021 [cited 2021 Aug 13]. Available from: https://www.nei.org/advantages/jobs

Question from Prof. Denina Simmons

1.What is the safe upper limit of CO2 concentration if it is 390 ppm as you stated and we are at 410-420 ppm? What is the additional danger, for every 10 ppm above 390ppm? What are the likely consequences of each 10ppm increment above 390ppm?

Many leading climate scientists do not have that appetite for risk. A December 2013 report by James Hansen, Johan Rockström, and 15 other scientists, "Assessing 'Dangerous Climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature," declares that 2°C of global warming would have disastrous consequences and could cause major dislocations for civilization. It advocated for a target of 350 ppm as the maximum safe concentration of CO2 concentration, which would stabilize the global temperature at 1°C above pre-industrial levels and avoid runaway climate destabilization.

As the global temperature is quite related to co2 concentration. Let's see the difference of 1.5 or 2 degrees Celsius of additional global warming.

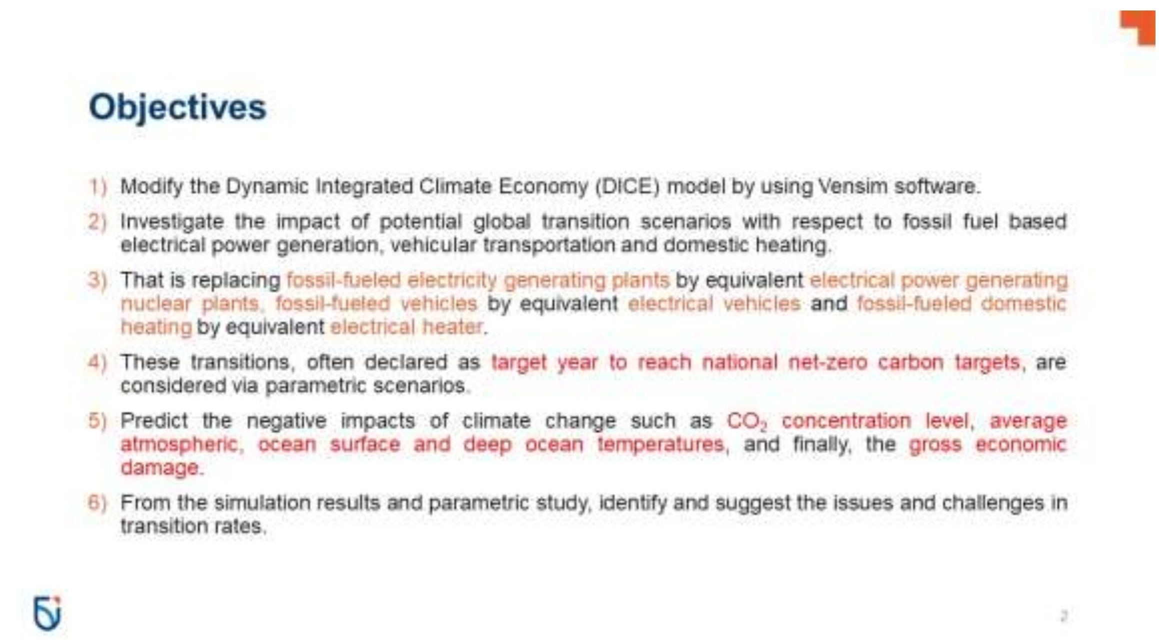
a. With a 1.5 degrees Celsius increase, extreme hot days in the mid- latitude will be 3 degrees Celsius hotter than pre-industrial levels. However, with a 2 degrees Celsius increase, it will be about 4 degrees Celsius hotter than pre-industrial levels.
b. With a 1.5 degrees Celsius increase, sea levels are projected to rise by 2100 by 0.26 to 0.77 meters relative to 1986-2005. However, with a 2 degrees Celsius increase, it will rise 0.36 to 0.87 meters.
c. With a 1.5 degrees Celsius increase, 6% of insects, 8% of plants and 4% of vertebrates are projected by 2100 to lose more than half of their climatically

determined geographic ranges. However, a 2 degrees Celsius increase will lead to those percentage double or triple.

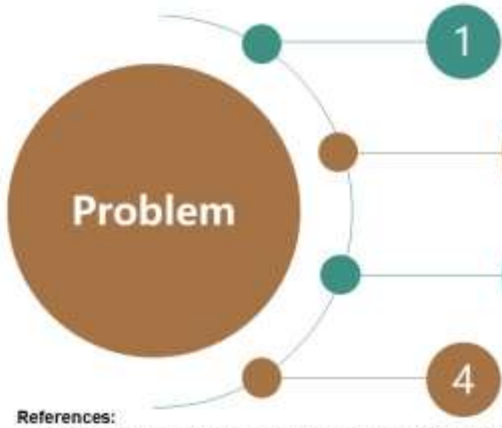
d. With a 1.5 increase, scientist projected that the Arctic Ocean would become ice-free in the summer about once every 100 years. However, with a 2 degrees Celsius increase, the Arctic Ocean could become ice free in the summer once every 10 years.
e. With a 1.5 degrees Celsius increase, coral reefs around the world are projected to decline further by 70% to 90%. With a 2 degrees Celsius increase, coral reefs are projected to decline by more than 99%.
f. Limiting warming to 1.5 degrees Celsius could reduce the number of people worldwide are exposed to climate related risks and resulting poverty by hundreds of millions of people compared with a rise of 2 degree.

Reference: Lieberman B, 1.5 or 2 degrees Celsius of additional global warming: Does it make a difference? [Internet]. Yale Climate Connections. 2021 [cited 2021 Aug 13]. Available from: http://yaleclimateconnections.org/2021/08/1-5-or-2-degrees-celsius-of-additional-global-warming-does-it-make-a-difference/

Appendix E: Thesis defense presentation PowerPoint



Introduction



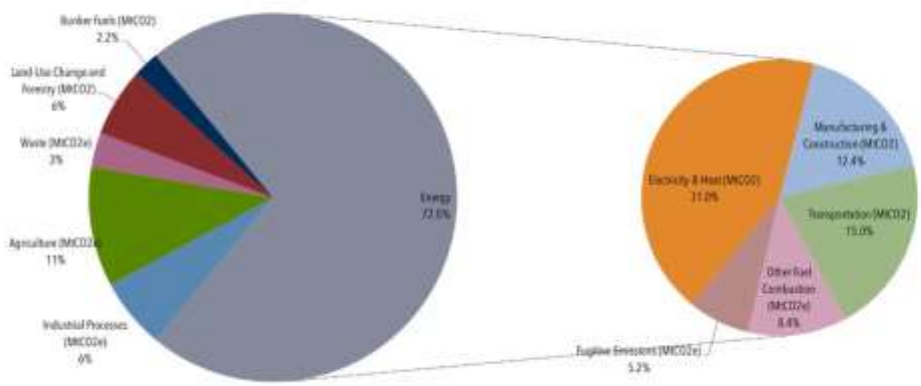
1. The impact of global climate change characterized by global warming continues to attract concern and debate.
2. According to the Fifth Assessment Report Published by the Intergovernmental Panel on Climate Change (IPCC) in 2014, the main contributor to climate change is CO_2 emissions [1].
3. Human activities are responsible for almost all of the excess greenhouse gas emissions over the last 150 years [2].
4. A growing number of governments are declaring "net-zero emissions" target to curtail global warming [3].

References:

- [1] Yan Q et al., Energy-Related CO_2 Emission in China's Provincial Thermal Electricity Generation: Driving Factors and Possibilities for Abatement. *Energies* 2018, *11*, 1096.
- [2] EPA. Sources of greenhouse gas emissions, 2018.
- [3] Darby Megan, Gerretsen Isabelle, Which countries have a net zero carbon goal?, Climate Home News, 2019

3

CO_2 emissions by sectors



Source: Climate Analysis Indicators Tool (World Resources Institute, 2017)

4

Impacts of global warming

References:

- [4] Alina Bradford, Effects of global warming, Live science contributor, 2017
- [5] Riduna, Effects of global warming, Skeptical Science, 2019
- [6] Union of Concerned Scientists, Global warming effects around the world, 2011

5

Possible solutions

- Data show that nuclear power plant (NPP) only produce approximately 6% of the CO_2 emissions per Megawatt (MW) compared to a fossil fuel power plant (FFPP) [7].
- Supply and demand of Electric Vehicles (EV) continue to increase and provide a path to emission reduction in transportation [8].

- Majority of households depend on central furnace to provide heating, many use natural gas or oil. Electric heaters (EH) can provide home heating without CO_2 emission [9].

Question: Can nuclear power plants, electric vehicles and electric heaters provide relevant and significant paths to mitigating the impact of climate change (reduction of CO_2)?

References:

- [7] Colpetzer JL, A study on the impact of nuclear power plant construction relative to decommissioning fossil fuel power plant in order to reduce carbon dioxide emissions using a modified Nordhaus Vensim DICE model, University of Idaho, 2014.
- [8] Hausfather Zeke, How electric vehicles help to tackle climate change, Carbon Brief, 2019
- [9] Smarter House, Types of Heating System, 2015

6

How can the impacts of nuclear power plant, electric vehicle and electric heater be evaluated?

- Use the Dynamic Integrated Climate Economy model (DICE).
- Predicts climate change "metrics" based on available climate, economic data.
- This work modified the DICE model to predict the impact on climate change metrics due to different target year to reach zero CO_2 emissions (relative to current levels).
- The sub-models developed for this study decommission/replace fossil fuel power plants, traditional (fossil fueled) vehicles and fossil fueled heaters.
- The model and simulations then estimate the reduction of CO_2 emissions resulting from the decommissions of fossil fuel power plants, traditional vehicles and fossil fueled heaters.
- The reduction of CO_2 is then fed into the DICE model to simulate changes to climate change metrics such as reduction of CO_2 emissions, atmospheric temperatures and fiscal estimates of damage due to climate change, relative to today and status quo.

What is the DICE model?

Integrated macro-economic climate model [10].

A simplified analytical and empirical model that represents the economics, policy and scientific aspects of climate change [10].

Developed by Professor William D. Nordhaus at Yale University originally in 1991 [10].

Widely cited by climate economists and policy professionals and in its successive versions has been influential in climate policy deliberations for several decades [11].

References:

- [10] Nordhaus William, DICE 2013R: Introduction and User's Manual, 2013.
- [11] Easton Robert, Repetto Robert, DICE model reassessment summary and key findings from first phase of analysis, International Institute of for Sustainable Development, 2014.

Features of DICE model

1.Model views the economy of climate change from the standpoint of neoclassical growth theory. [13].

2.Economic growth determined using Labor, Capital and Technology.

3.Emissions are estimated based on the economic output.

4.Climate change is evaluated based on the increasing emissions.

5. A global model that aggregates different countries into a single level (data from all major countries is used).

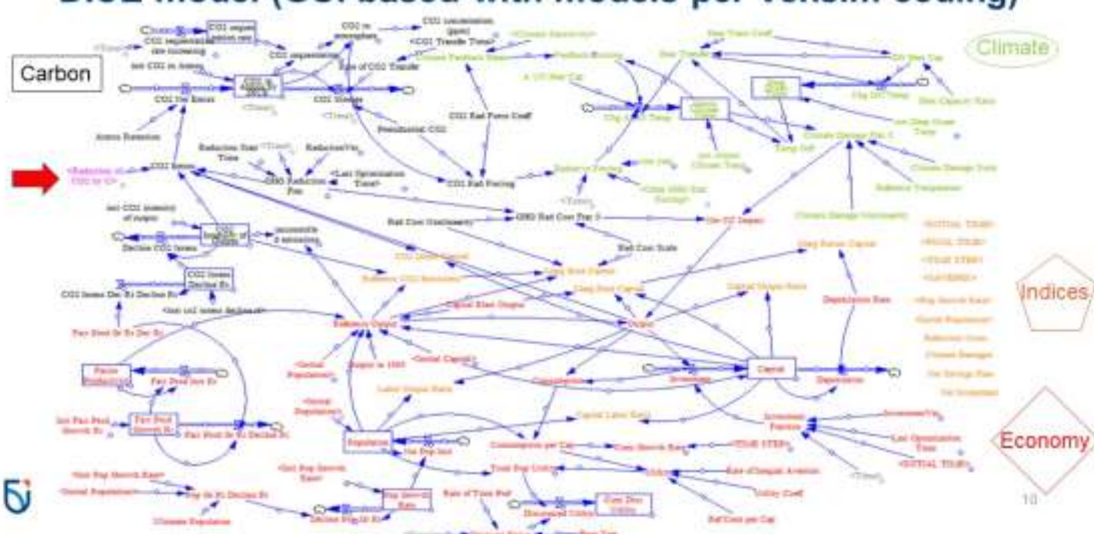
6.The energy input involves both carbon-based fuels and non-carbon based technologies.

7.The equations use available data to determine CO_2 emissions and the associated climate change and environmental damages.

Reference:

- [13] Nordhaus William, DICE 2013R: Introduction and User's Manual, 2013.

DICE model (GUI-based with models per Vensim coding)



Modification to the DICE model

- Vensim is a modeling simulation tool that allows you to conceptualize, document, simulate, analyze and optimize models of dynamic systems. Models are constructed via algebraic functions, it's not a partial differential equation solver.
- Model replicated for Vensim by Tom Fiddaman of MIT.
- The nuclear power plant sub-model was created by Jason Colpetzer at University of Idaho in 2014 [14].
- This work optimized the NPP sub-model by adding the power demand increasing portion and do the simulations for the world not just US as Colpetzer did. Also, adding the transportation model and heating model to simulate the amount of CO_2 emissions avoided.
- The relative climate change with 2019 conditions as the reference is then modeled using the simulation to estimate reduction of CO_2 emissions.

Reference:

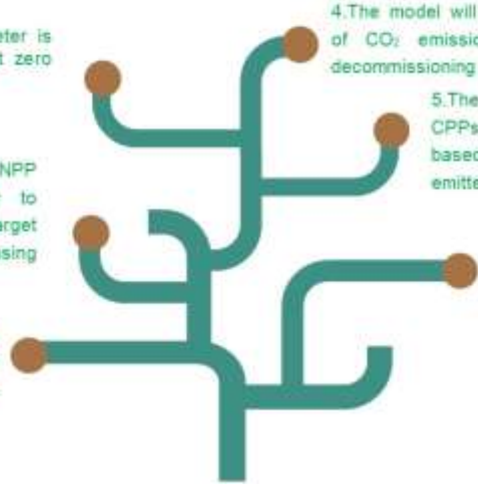
- [14] Colpetzer JL, A study on the impact of nuclear power plant construction relative to decommissioning fossil fuel power plant in order to reduce carbon dioxide emissions using a modified Nordhaus Vensim DICE model, University of Idaho, 2014.

Features of NPP sub-model

1.Input or simulation parameter is the target year to reach net zero CO_2 emission.

2.Model will determine the NPP construction rate in order to replaced all FFPPs in the target year and also meet the increasing power demand.

3.The FFPP decommissioning rate of will be determined based on the amount of power produced by the new NPPs.

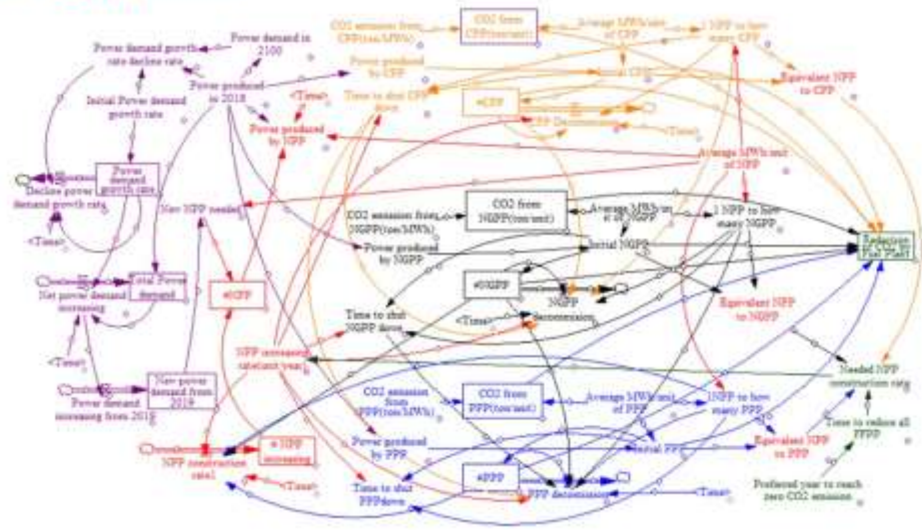


4.The model will then calculate the amount of CO_2 emissions avoided due to the decommissioning of FFPPs.

5.The model decommissions CPPs then NGPPs then PPPs based on the amount of CO_2 emitted, from highest to lowest.

6.The total CO_2 emissions avoided is then subtracted directly from the standard DICE model CO_2 emission variable.

NPP sub-model



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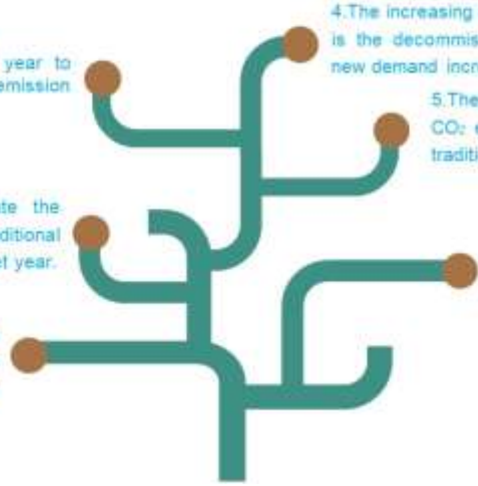
Feature of Transportation (traditional vehicle) sub-model



1.The input is the target year to reach net zero CO_2 emission around the world.

2.The model will calculate the time to replace all traditional vehicles based on the target year.

3.The demand for new vehicles will be calculated as the increasing in population.

4.The increasing rate of electric vehicles is the decommission rate of TVs plus new demand increasing rate.

5.Then, estimating the reduction of CO_2 emission via reduction in the traditional vehicles.

6.Finally, the composite CO_2 emissions avoided by the transportation model is fed into the CO_2 emission variable in the DICE model.

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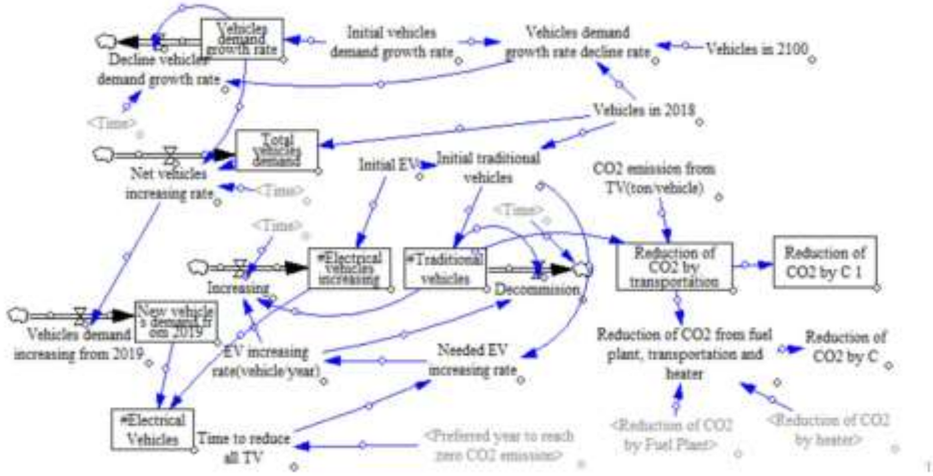
Transportation **sub**-model



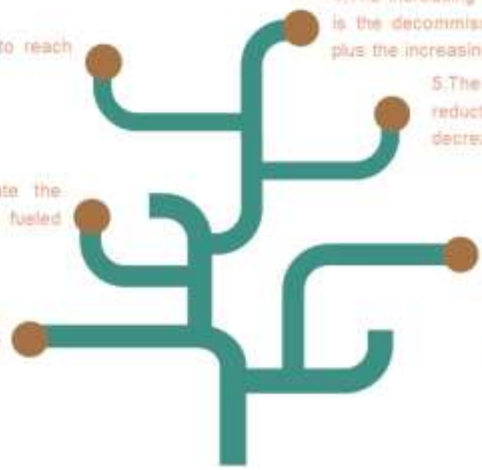
15

Feature of Heating **sub**-model

1.Input is the target year to reach zero CO_2 emission.

2.The model will calculate the time to replace all fossil fueled heaters.

3.The number of new heaters will increase as the increase of population.



4.The increasing rate of the electric heaters is the decommission rate of existing FFHs plus the increasing demand rate of heaters.

5.The model will then calculate the reduction of CO_2 emissions by decreasing FFH.

6. Finally, the total amount of CO_2 emissions avoided by the heating model is fed into the CO_2 emission variable in the DICE model.

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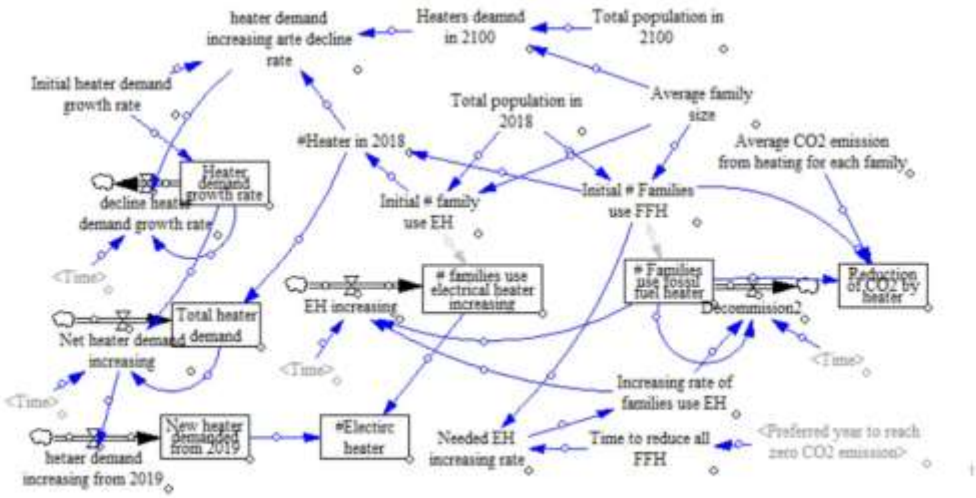
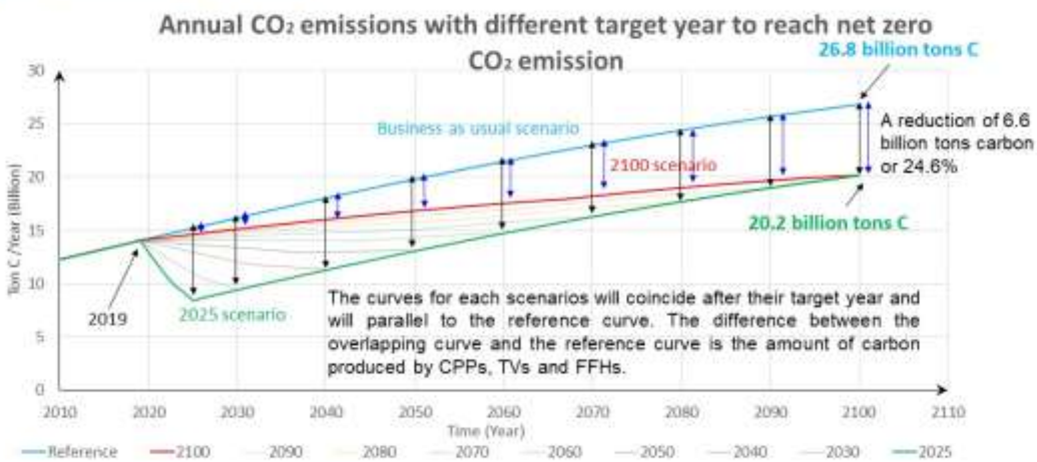
Heating sub-model



Simulation results



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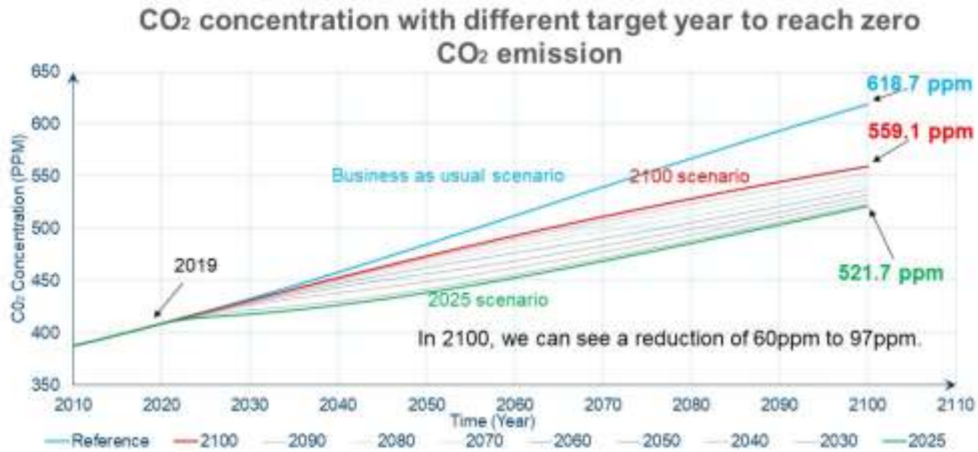

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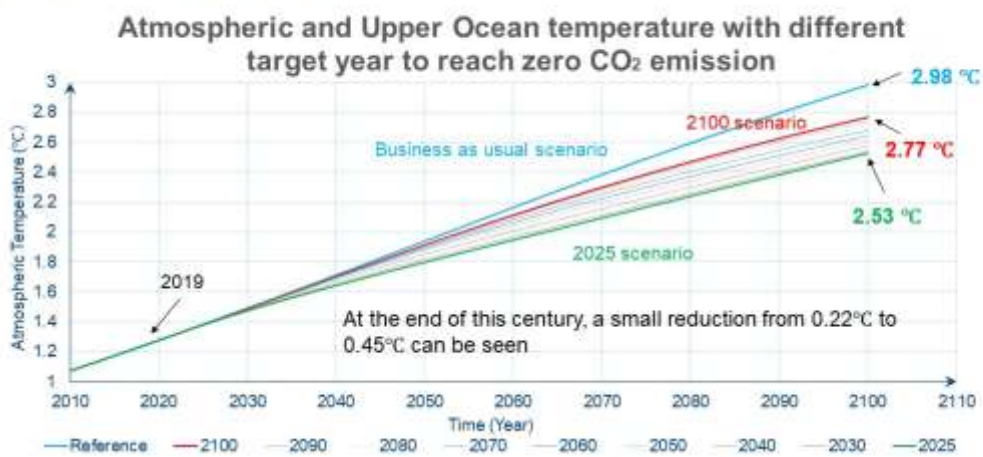

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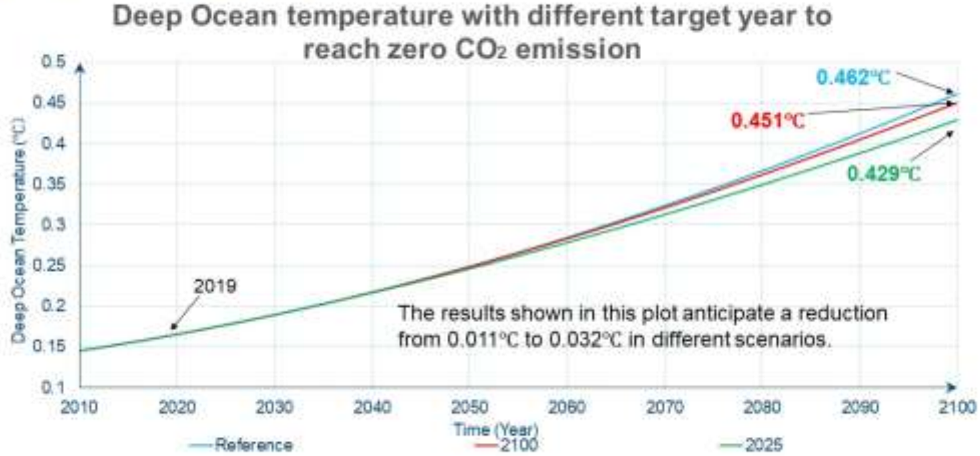

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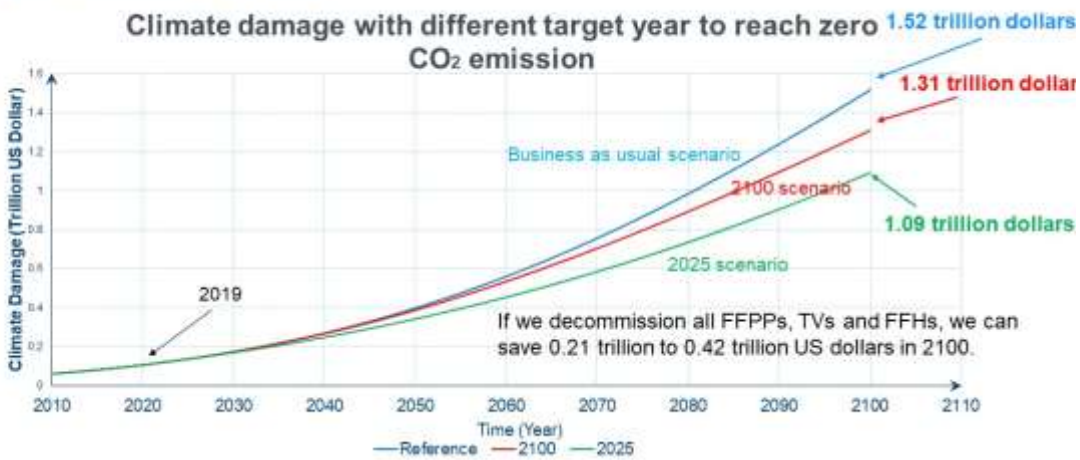

Summary (Results in different scenarios compared to BAUS)

Target year to reach zero CO_2 emission	Reduction of CO_2 in atmosphere in 2100 (Trillion tons C)	Reduction of CO_2 concentration in 2100 (ppm)	Reduction of atmospheric & Upper Ocean temperature (℃)	Reduction of deep ocean temperature (℃)	Reduction of Climate damage (Trillion Dollars)
Reference	0	0	0	0	0
2100	0.13 (9.7%)	59.69 (9.7%)	0.22 (7.2%)	0.011 (2.3%)	0.21 (13.7%)
2090	0.14 (10.6%)	65.64 (10.6%)	0.24 (8.1%)	0.012 (2.6%)	0.23 (15.3%)
2080	0.15 (11.5%)	71.26 (11.5%)	0.27 (9.1%)	0.014 (3.0%)	0.26 (17.1%)
2070	0.16 (12.4%)	76.57 (12.4%)	0.30 (10.2%)	0.016 (3.5%)	0.29 (19.0%)
2060	0.17 (13.2%)	81.58 (13.2%)	0.34 (11.3%)	0.019 (4.1%)	0.32 (21.0%)
2050	0.18 (14.0%)	86.32 (14.0%)	0.37 (12.4%)	0.022 (4.8%)	0.35 (23.0%)
2040	0.19 (14.7%)	90.79 (14.7%)	0.40 (13.6%)	0.026 (5.6%)	0.38 (25.0%)
2030	0.20 (15.5%)	95.02 (15.5%)	0.44 (14.7%)	0.030 (6.5%)	0.41 (26.9%)
2025	0.21 (15.7%)	97.05 (15.7%)	0.45 (15.2%)	0.032 (6.9%)	0.42 (27.8%)

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Results to date -1

- Using the developed Vensim DICE model it can be determined that replacing all the FFPPs, TVs and FFHs with NPPs, EVs and EHs will reduce 24.4 billion tons CO_2 emissions or 24.8% annually.
- This in turn reduces the cumulative amount of CO_2 in the atmosphere by 127 billion tons to 207 billion tons or 9.65% to 15.69% in 2100.
- Also, it reduces the CO_2 concentration in the atmosphere by 60ppm to 97 ppm or 9.7% to 15.7%.
- Unfortunately, this still results in 522 ppm to 559 ppm CO_2 concentration in the atmosphere in 2100.
- The increasing in atmospheric & upper ocean temperature will be reduced by 0.22℃ to 0.45℃ or 7.2% to 15.2% in 2100.
- The DICE model predicts the atmospheric temperature will reach 2.98℃ in 2100 if no action is taken.

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Results to date -2

- Average deep ocean temperature will also have a small reduction of 0.011℃ (2.3%) to 0.032℃ (6.9%) in 2100.
- The DICE model predicts average deep ocean temperature will reach 0.46℃ in 2100.
- The climate damages will have a reduction of 208 billion (13.7%) to 422 billion (27.8%) US dollars in 2100.

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Modeling uncertainties

- Model assumes immediate start of NPPs, EVs, EHs and decommission of FFPPs, TVs and FFHs.
- Limitations may also exist with the electrical grid and where NPPs are sited. Different obstacles may exist in each country in regards to new NPP construction.
- Changes will occur over time with technology and policy, etc. that will affect how actual data will compare to the predicted.

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Conclusions

- Replacing the current fleet of FFPPs, TVs and FFHs with NNPs , EVs and EHs will have a beneficial effect; that is, reduce the CO_2 footprint by replacing/eliminating sources of emission.
- In year 2100, the CO_2 concentration in atmosphere will decrease 82.3 ppm and the atmospheric temperature will decrease 0.37 ℃ if the target year to reach zero CO_2 emission is in 2050.
- This study shows the climate damage can be reduced by 348 billion per year in 2100 if the target year to reach zero CO_2 emission is in 2050.
- Replacing all the FFPPs, TVs and FFHs in the world with NPPs, EVs and EHs will not be enough to mitigate the negative impacts of climate change.
- NPP, EV and EH are only part of the solution.
- In other words, in order to reach carbon neutrality as many countries pledged, more actions need be taken to reduce the CO_2 emissions.

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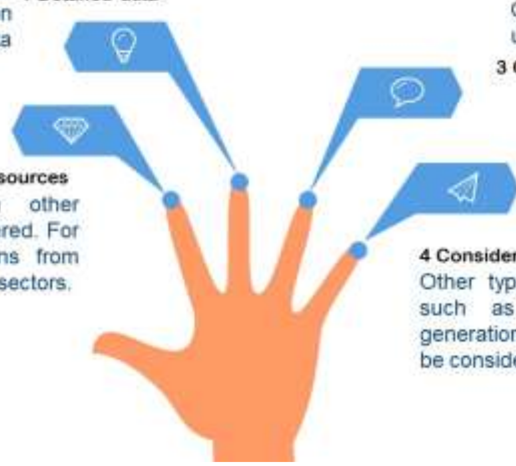
Future work



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Acknowledgements

- My sincere gratitude to **Prof. Akira Tokuhiro** and **Prof. Filippo Genco**.
- My appreciation to the committee members (**Prof. Jennifer McKellar**, **Prof. Daniel Hoornweg** and **Prof. Denina Simmons**).

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Thank You!
Questions?

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Macroeconomics" vs "Microeconomics"

- DICE model deals with problems related to climate change using a macroeconomics approach primarily looking at possible decisions made by countries and/or governments as a whole.
- Economics is divided into two categories: microeconomics and macroeconomics [12].
- Microeconomics is the study of individual and business decisions [12].
- Macroeconomics looks at the decisions of countries and governments [12].
- Microeconomics focus on supply and demand and other forces that determine price levels in economy, making it a bottom-up approach [12].
- Macroeconomics takes a top-down approach and looks at the economy as a whole [12].

Reference:
- [12] Staff Investopedia, Microeconomics vs. macroeconomics : what is the difference, 2021

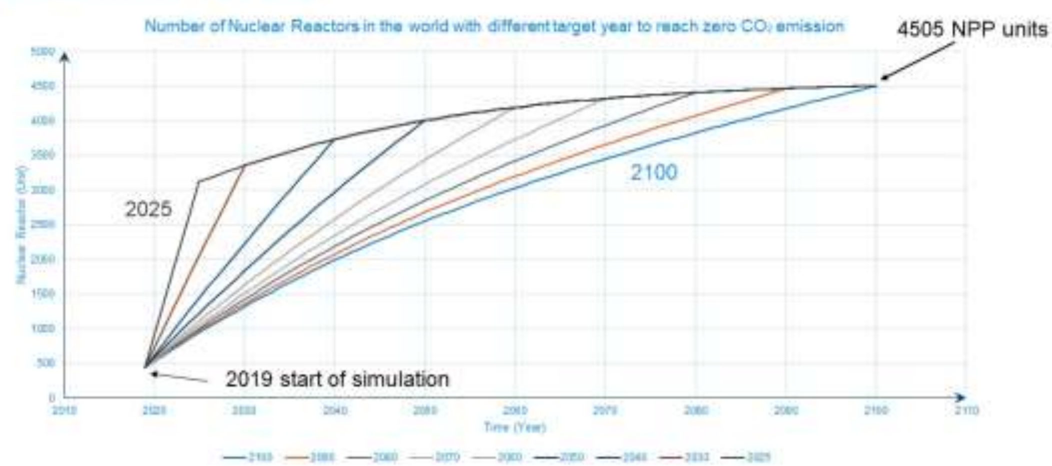
Appendix - 1

Plant	Operating units	MWh/unit	Ton CO_2 emissions/ unit	Annual output of CO_2 (tons)	Ton CO_2/ MWh	% of CPP
Coal Power Plant (CPP)	7813	1,300,000	1,365,000	10,664,745,000	1.05	100%
Petroleum Power Plant (PPP)	31136	24,896	19,419	604,629,984	0.78	74%
Natural Gas Power Plant (NGPP)	32439	189,522	83,390	2,705,088,210	0.44	42%
Nuclear Power Plant (NPP)	440	7,250,000	500,940	220,413,600	0.07	6%

Appendix - 2

Preferred Year to Reach Zero CO_2 Emission	Nuclear Power Plant Construction Rate (Units/year)	Electric Vehicle Increasing Rate (Million Vehicles/year)	Electric Heater Increasing Rate (Million Heaters/Year)
2100	29	14.75	22.46
2090	33	16.83	25.62
2080	39	19.59	29.82
2070	46	23.43	35.67
2060	58	29.14	44.37
2050	76	38.54	58.68
2040	112	56.90	86.62
2030	214	108.62	165.37
2025	393	199.13	303.18

Simulation results



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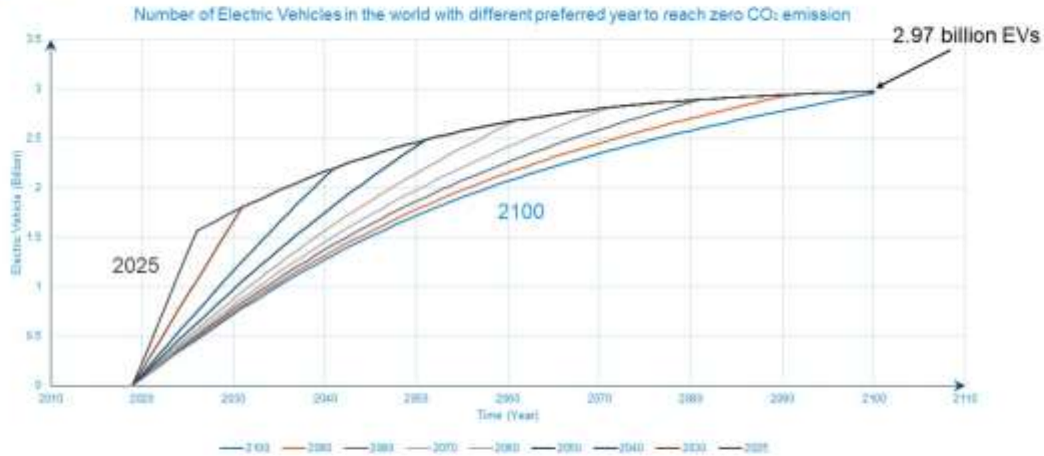

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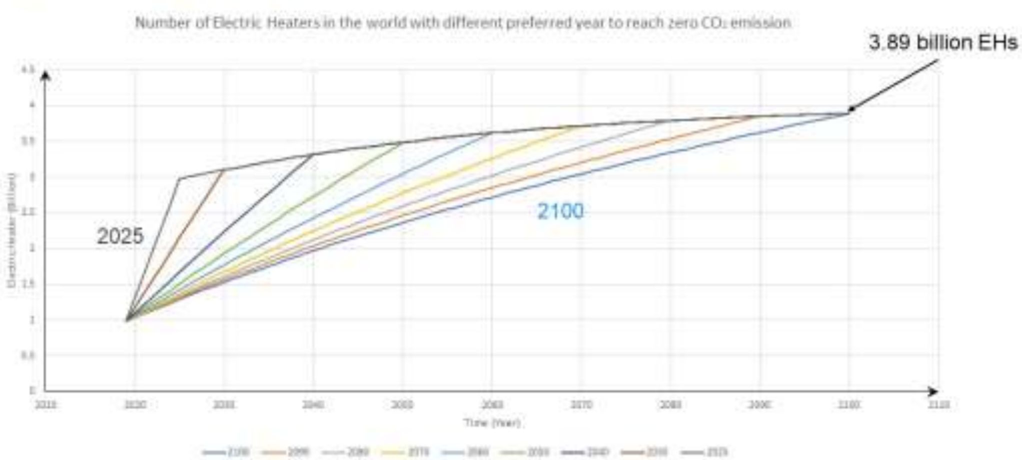
Simulation results



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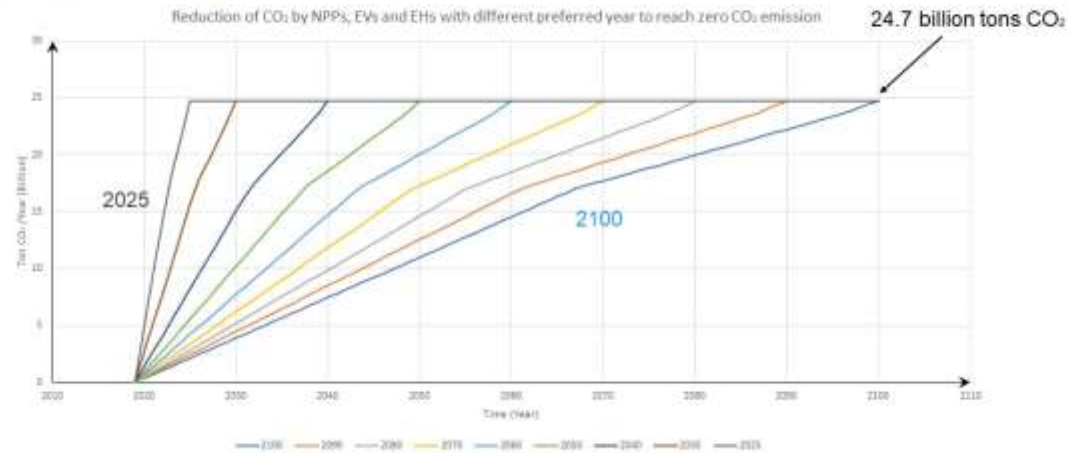
Simulation results



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Summary

Preferred year to reach zero CO_2 emission	CO_2 in atmosphere in 2100 (Trillion tons C)	CO_2 concentration in 2100 (ppm)	Atmospheric & Upper Ocean temperature (℃)	Deep ocean temperature (℃)	Climate damage (Trillion Dollars)
Reference	1.32	618.74	2.98	0.462	1.52
2100	1.19	559.05	2.77	0.451	1.31
2090	1.18	553.10	2.74	0.449	1.28
2080	1.17	547.48	2.71	0.448	1.26
2070	1.15	542.17	2.68	0.445	1.23
2060	1.14	537.16	2.65	0.443	1.20
2050	1.13	532.43	2.61	0.440	1.17
2040	1.12	527.95	2.58	0.436	1.14
2030	1.12	523.72	2.54	0.432	1.11
2025	1.11	521.69	2.53	0.429	1.09

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Appendix F: CNS conference paper

APPLICATION OF A MODIFIED DICE MODEL TO EVALUATE SCENARIOS OF A REDUCED CARBON FOOTPRINT

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Abstract

The accumulated level of CO_2 in the atmosphere continues to increase globally in spite of societal outcry to address this problem in an urgent manner. This work modifies the Nordhaus Dynamic Integrated Climate Economy (DICE) model, using the Vensim dynamic systems modeling tool, in order to investigate the impact of replacing three identified CO_2 emitting systems, these being: 1) fossil-fueled power plant (FFPP) with nuclear plants, 2) fossil-fueled transport vehicles with electric vehicles, and 3) fossil-fueled domestic heat with electric heaters. Simulations were performed with the various national net-zero targets in mind in increments of 10 years, starting from year, 2019 to 2100. Representative simulations results indicate that replacing more than 70,000 FFPPs currently operating in the world, would reduce CO_2 emissions roughly 25% compared to the business as usual scenario. In terms of national target scenarios, if the goal is to reach net-zero CO_2 emission by 2060, a reduction in atmospheric CO_2 concentration by year 2100 is estimated to be 13%, or some 82 ppm. The DICE model further predicts a reduction in global warming of 0.3°C or 11% by the end of the century. These system-wide output metrics from DICE simulations, relative to replacement rate scenarios will be explained.

1. Introduction

Global climate change characterized by global warming has attracted more and more attention in the world due to the potential catastrophic consequences over our entire planet. According to the Fifth Assessment Report Published by the Intergovernmental Panel on Climate Change (IPCC), the main contributor to climate change is CO_2 emissions, and the daily concentration of CO_2 in the atmosphere hit the highest level ever recorded in 2014 [1]. Human activities are responsible for almost all of the excess greenhouse gas emissions over the last 150 years: among those activities, burning fossil fuels for electricity production, heat and transportation are the largest sources of greenhouse gas emissions. Data show that the amount of CO2 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 [2]. As one of the most low-carbon energy sources, nuclear power can significantly contribute to a drastic reduction in CO_2 emissions. Recent studies show that nuclear power plants only produce approximately 6% of the CO_2 emissions per Megawatt (MW) when compared to fossil fuel power plant [3]. According to the World Nuclear Association, there are ~440 operating power reactors in the world producing about 10% of the world electricity. Further, there are 55 reactors under construction and 109 reactors planned at this time. Thus, there’s a clear need for Nuclear Power Plants (NPPs), both to meet the increased, global demand for electricity and to displace the large net contribution of GHG emissions attributed to fossil fueled power plants. Studies have shown that besides power generation, (vehicular) transport is also a contributor to CO_2 emission. The International Energy Agency (IEA) estimates that the transportation sector accounts for approximately 19% of global energy consumption and

23% of energy-related CO_2 emissions [4]. In particular, the ongoing economic development in India and China generally contribute to electricity and automobile ownership demands. This adds to real and projected, additional CO_2 emissions. In this respect, transition to substantial Electric Vehicle (EV) use (away from fossil fueled vehicles) is needed [5]. Finally, it can be said that the public's awareness of climate change risks is stimulating reconsideration of many fossil fueled devices. As various global regions lack full electrification, we also considered the replacement of fossil fueled home heater by Electric Heaters (EHs) as a path to CO_2 emission reduction.

There are a number of integrated assessment models used in the scientific community to analyze the interactions of the "primary drivers" of climate change. The models are often used to predict future variations in climate, the impact of emissions, damage to the environment, as well as change in the average temperature trends in both the ocean and atmosphere [6]. As known, meeting or exceeding agreed to target temperature rise, "1.5°C, 2.0°C or other", is the focal point of the net-zero carbon, global discourse. In brief, notable integrated assessment models include, in name: IMAGE, GCAM, and DICE.

In our work, we used the DICE Model (Dynamic Integrated model of Climate and Economy). This model was originally developed in 1992 by W. D. Nordhaus, Yale University [7]. The DICE model "integrates in an end-to-end fashion the economics, carbon cycle, climate science, and (its) impacts in a highly aggregated manner that allows a weighing of the costs and benefits of taking steps to slow greenhouse warming" [8]. For the current work, a nuclear power plant model, a transportation model and a (home) heater model were added and integrated into the Nordhaus DICE model using the Vensim dynamic modeling and simulation software platform. Vensim allows construction of algebraic models behind a graphic user interface.

In the Nuclear Power Plant model, currently operating, fossil fuel power plants, including Coal Power Plants (CPP), Natural Gas Power Plants (NGPP) and Petroleum Power Plants (PPP)) around the world are replaced by nuclear plants. Similarly, the Electric Vehicle and Electric Heater models are replacement models of existing units and demand trends of each device. The goal of this study is to assess the combined impact of NPPs, EVs and EHs in mitigating the continuing accumulation of CO_2, within the macro-model as simulated by DICE.

2. Greenhouse gas emissions

Greenhouse gases (GHGs) are defined as those gases that absorbs and releases infrared radiation, while in measurable concentrations in the atmosphere. Greenhouse gas layers in the atmosphere cause a thermal insulating “greenhouse effect”, and reduce the large scale thermal energy exchange phenomena from the earth’s surface. This effect is linked to “global warming”. According to the Kyoto Protocol, the six GHGs that should be controlled and mitigated are: carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulfur hexafluoride (SF6). Among these, the latter three are particularly effective in contributing to the greenhouse effect. That said, CO_2 is a key contributor because it is a source of large scale anthropogenic generation. Thus, managing CO_2 emissions is understood as a means of controlling the negative impacts of global warming. Without GHGs, the average temperature of the Earth’s surface would be about -18℃ (0°F) lower than it is [9]. Human activity is the main cause of the excessive CO_2 emissions present in the atmosphere, and since the start of the Industrial Revolution (since ~1760), the atmospheric concentration of carbon dioxide has increased 45%, from 280ppm as measured in 1750, to 415 ppm, measured in 2019 [10]. Anthropogenic reliance on combustion of fossil fuels and deforestation are understood to contribute to atmospheric accumulation of GHGs.

Global CO_2 emissions generated from combustion of fossil fuels have significantly increased since 1900 [11]. Since 1970, CO_2 emissions have increased of about 90%, with emissions from fossil fuel combustion and industrial processes contributing about 78% of the total GHG emissions increase from 1970 to 2011 [12]. Fossil fuels still supply 84% of world energy in 2019. The biggest share of global energy consumption is attributed to oil (33%), with other sources as follows: (27%) from coal, (24%) from natural gas, (6%) from hydropower, (5%) from renewable energy and (4%) from nuclear power [13]. Global CO_2 emissions from fossil fuel reached a (recorded) historical high of 33.5 $GtCO_2$ in 2018 [14]. Although the earth can absorb part of then CO_2 present in the atmosphere, consensus understanding is that humans need to significantly reduce CO_2 emissions to mitigate the accumulation thereof and thus slow the pace of global warming.

3. Dynamic Integrated Climate Model (DICE)

The Dynamic Integrated Climate Change (DICE) is an integrated macro-economic model used to assess the global impact of climate change on macroeconomics. The model relies on cost minimization, welfare (or utility) maximization and general equilibrium conditions. DICE combines labor and capital assuming a constant return rate. The model precludes economy collapse either in form of mass unemployment or financial crisis as fundamental assumptions. The uniqueness of DICE is that it links climate change phenomena to macroeconomics, and in so doing, it supports (or can support) decisions made by countries or governments. Equally, it supports a classical top to bottom approach wherein the impact of policies on a global scale - primarily industrial economies of scale, gross domestic product (GDP) variations, rates of growth (including population) and (global) price levels, can be based on hypothetical “what if” scenarios. DICE thus provides, via a set of (user input) algebraic equations, macro econometric correlations in contrast to microeconomics models, limited here to problems of local supply and demand (thus, supply chain), labor economics and cost of production. DICE models do not deal directly or indirectly with human choices, local decisions or allocation of resources but rather seek the least-cost emission pathway providing an evaluation of the “social cost of carbon (CO2 emissions)”.

The algebraic equations integrated in DICE define one variable in terms of others that are casually connected; thus, explicit functional or empirical relationships. DICE does not set or solve (a set of) partial differential or integro-differential equations and as such, assumes that the cost of reducing emissions for a given period is substantially unrelated to the previous determined pathway nor influences in any way subsequent evaluations or future prospects. This can in effect be understood as Markovian. This temporal independence can be seen as the biggest limitation of its applicability in climate change related research studies [15]. However, this is beyond the current paper.

In this model, the atmospheric CO_2 concentration is assumed as the “natural capital”, and this capital has a negative effect on economic output because of its influence on global average surface temperature. In documented use thereof, DICE can be viewed as an optimal simulation tool from which stakeholders recommend or advocate decisions, that seeks to balance the cost and benefit approach with respect to CO_2 emissions. Figure 1 shows the entire DICE model with color-coded sub-model (or regions) as below.

There are various versions of the model which has been widely cited by climate economists and policy professionals. For example, it has been used by the US government to estimate the "social cost of carbon" which is understood by the government as key to setting policy to address mitigation and adaptation actions [16].

This model is divided into four major sections in Figure 1. We note the GUI-type representation. That is, algebraic relationships appear underneath the graphic representation, within the Vensim developer window. The black region represents the carbon production or emission sub-model, the green region represents the climate model, the red region represents economic factors model, and the orange represent indices that tracks "units" in time and programmatic registry. In the current research, four climate change output variables, as traditionally cited, have been used; these being: CO_2 in atmosphere, (average) atmospheric and ocean temperature, and finally monetary estimates climate damage per definition in the DICE original model.

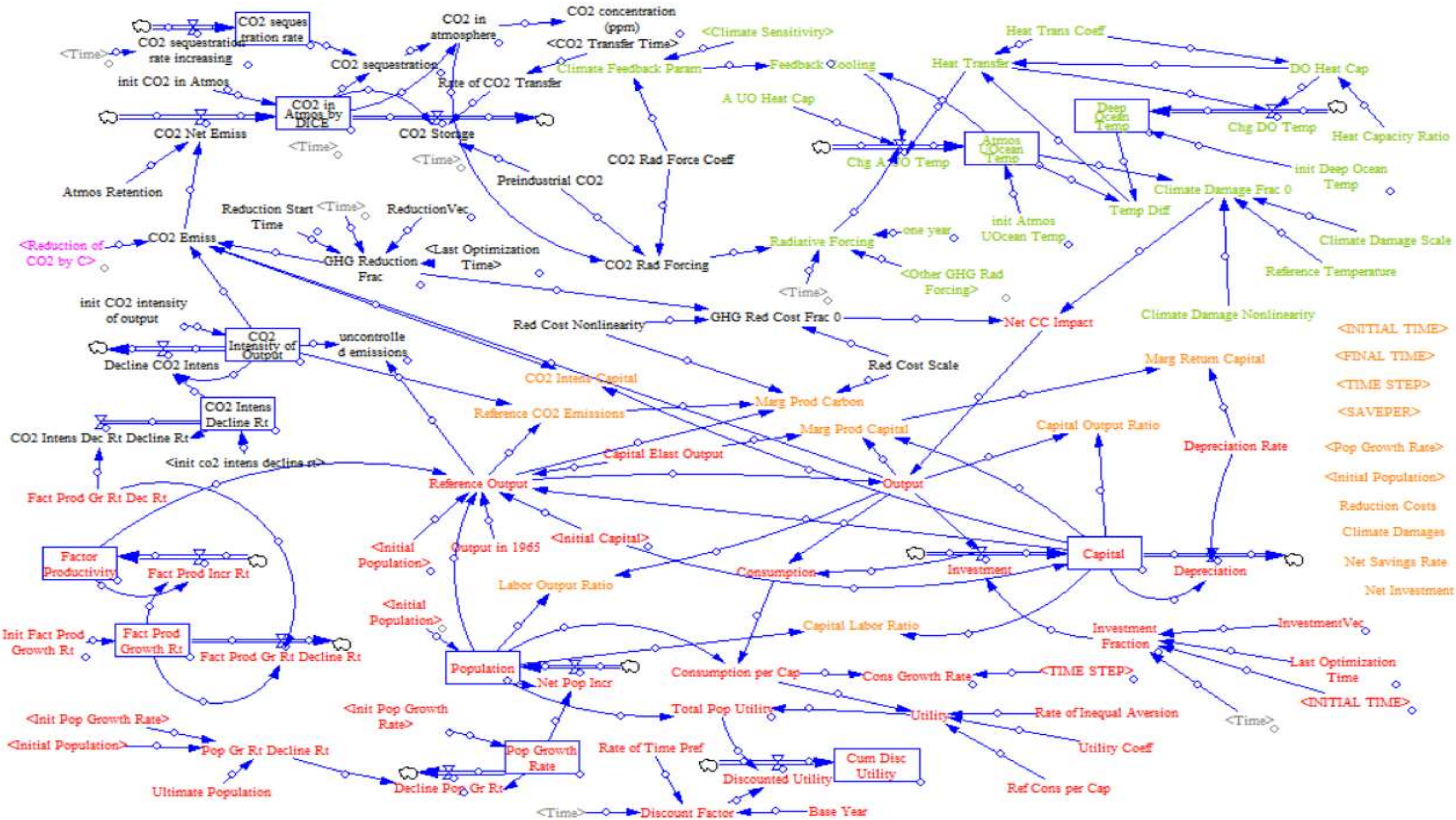


Figure 1. DICE model

In order to understand the impact of deployment of nuclear power plants, electrical vehicles and electric heaters with respect to reduction of CO_2 emissions, the DICE model was modified. Three new sub-models were added. First, the nuclear power plant model replaces existing generating capacity of fossil fuel power plants (FFPPs). Here, one or more existing FFPPs are assumed to promptly shutdown when a NPP is constructed, based on the determined ratio of the power produced by a NPP compared to a FFPP. Subsequently, the GHG emissions attributed to the FFPPs is reduced to zero, and a net reduction in accumulated CO_2 is realized. Further, as nations have declared meeting net zero CO_2 emission level, the targeted year (beyond 2020) to reach this status was used as a parameter. As a consequence, the replacement or NPP construction rate in time was estimated. Lastly per DICE model output metrics, in addition to CO_2 concentration (ppm), atmospheric and deep ocean temperatures, as well as estimate of the monetized climate damage were used as characteristic metrics. Figure 2 shows the proposed nuclear power plant sub-model.

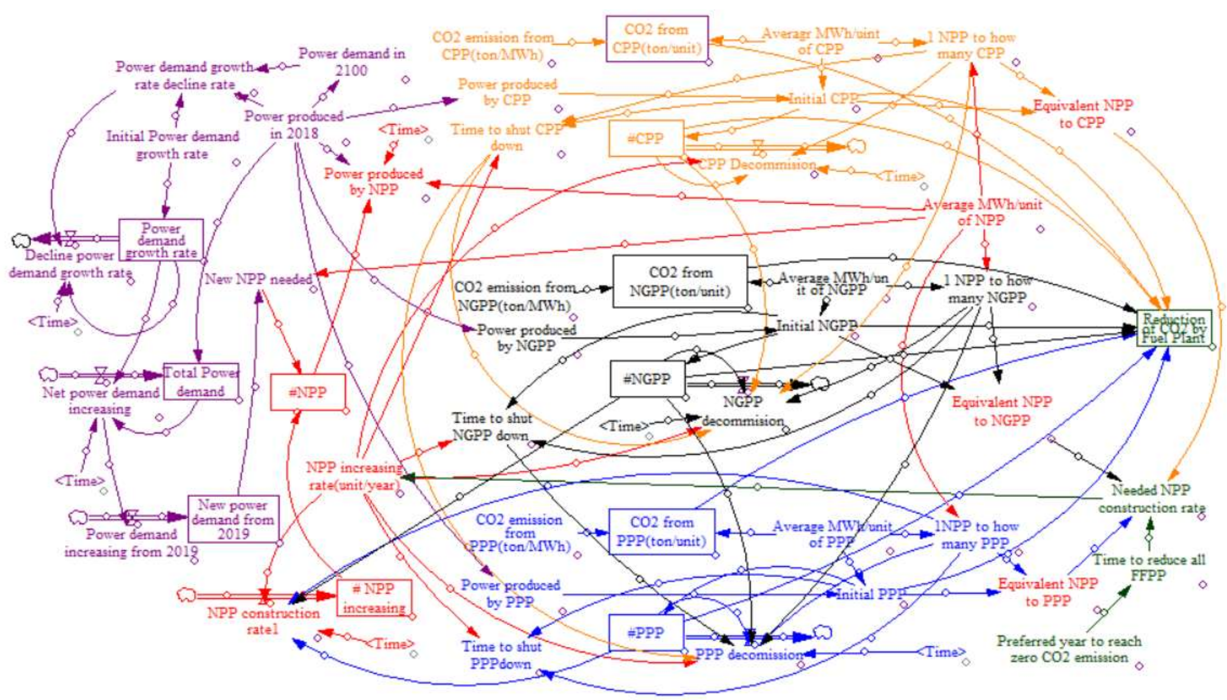


Figure 2. Nuclear power plant sub-model

We note that in the NPP model integrated into DICE, the FFPPs are replaced starting in 2019. However, the DICE model's internal "clock" starts in 1965, in order to track the historical trending of datasets linked to its macro-economic climate change model.

Due to the CO_2 emissions attributed to vehicular transportation, a sub-model replaces all traditional (fossil fueled) vehicles was added per data from Car Green Reports [17]. Within the context of this sub-model, both the national, target year to net zero CO_2 emission and thus, deployment rate of EVs were evaluated. As a macro-economic model, the key assumption here was that the demand for EVs would be met by EV producers. As reference, there are more than 10 billion traditional vehicles, compared to the small fraction of 4.2 million EVs as of early 2019. Thus, all internal combustion engines vehicles are assumed to be gradually replaced in time. The replacement "clock" is again started in 2019. As previously noted, the reduction in CO_2 emission from this sub-model is fed into the DICE model. Figure 3 shows the implemented EV transportation sub-model.

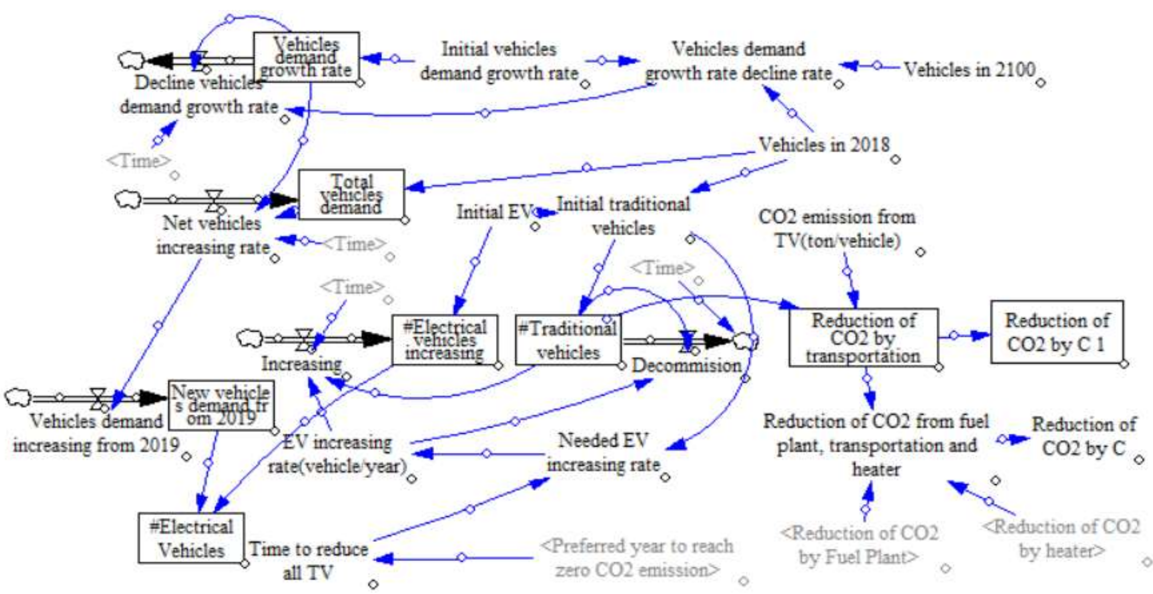


Figure 3. EV Transportation sub-model

Finally, besides power generation and transition to EV-based transportation, fossil fuel based home heating was considered. Again, a sub-model was developed in order to consider the replacement scenarios. Although electrification for the purpose of home heating is complete in parts of the world, reliance on fossil fuels for home heating, in scale is significant in many other parts of the world. According to OECD, the average family size is 2.63 person [18], and based on market data on prevalence of fossil fueled heaters (FFH) and electric heaters (EH), the number of EH as replacement of FFHs was estimated. Then, as before, based, the replacement/deployment rate of FFHs, relative to national net zero CO2 target year, can be estimated. Figure 4 shows the home heating sub-model.

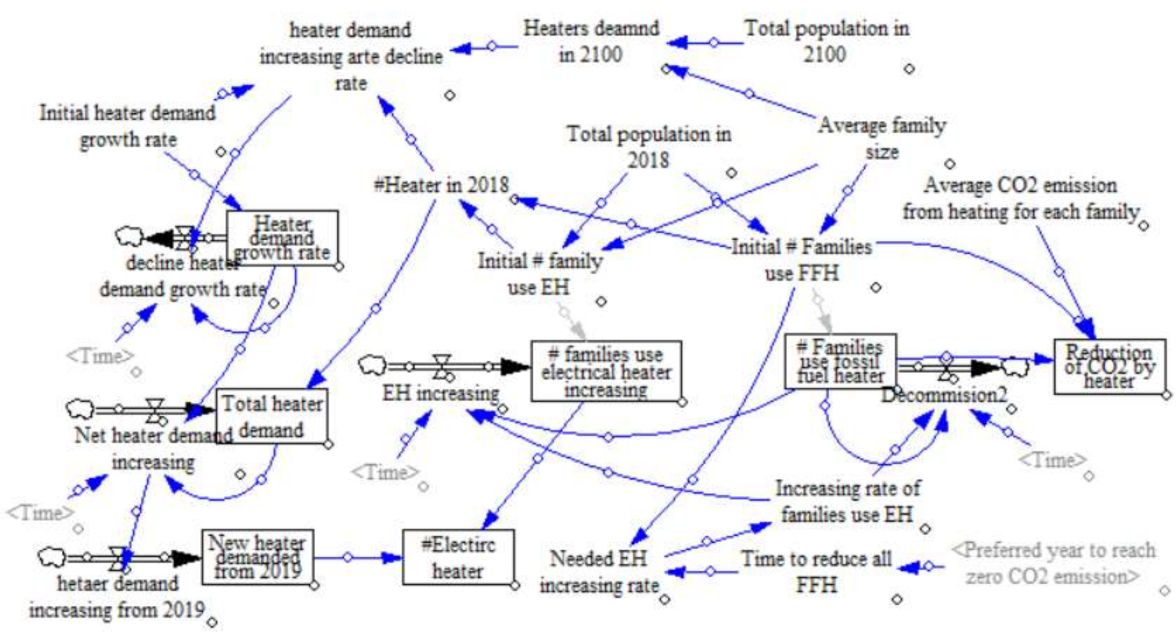


Figure 4. Heating sub-model

4. Simulation and results

After the three models (NPP, transportation and heating) have been designed and integrated with the DICE model, several simulations have been carried out changing several inputs.

All data used for input have been taken from IEA [19]. The countries contributing for carbon emissions that have been considered are in order of importance: China, USA, Japan, South Korea, Russia, European Union, Brazil, South Africa, Mexico, Saudi Arabia,

Results have been studied with zero net CO_2 emissions to be reached respectively in 2025, 2030, 2040, 2050, 2060, 2070, 2080, 2090 and 2100. For these different scenarios, construction rates of NPPs, EVs and EHs are varied and tested. Table 1 shows the detailed data and the proposed rates of production/installation of new zero carbon contributors versus the existing ones.

Preferred Year to Reach Zero CO2 Emission	**Global Nuclear Power Plant Construction Rate (Units/year)**	**Global Electric Vehicle Increasing Rate (Million Vehicles/year)**	**Global Electric Heater Increasing Rate (Million Heaters/Year)**
2100	29	15	22
2090	33	17	26
2080	39	20	30
2070	46	23	36
2060	58	29	44
2050	76	39	59
2040	112	57	87
2030	214	109	165
2025	393	199	303

Table 1. Increasing rate of Nuclear Power Plant, Electric Vehicle and Electric Heater with different preferred year to reach zero CO2 emission

It is quite clear from the table, that the closer in time we set the ambitious goal of zero net contribution, the higher is the immediate effort as well as construction rate. For example, it is estimated that a minimum of 393 new nuclear power plants must be built and installed by 2025 in order to see significant changes in the current trends. Similarly, possible CO_2 emission savings per year in different scenarios have been evaluated and shown in figure

5. The results show that the earlier the zero CO_2 emission is set, the less the CO_2 per year will be emitted compared to the reference curve justifying an aggressive energy policy in this direction. Simulations are started in the year 2019. The cyan line indicates BAUS (business as usual) while other lines show the results for different scenarios accordingly set for the year anticipated as the one with zero emissions. The lowest curve (in green) shows the annual CO_2 emission if zero new emissions is set by 2025. As the preferred year to reach zero CO_2 emission is pushed forward in time, the lowest points of annual CO_2 emission curves will increase while the needed rates for substituting power plants, vehicles and heaters will decrease accordingly as shown and explained in Table 1. As described earlier, the aggressive substitution rates of major CO_2 emitters, lead to a substantial drop of CO_2 from the one recorded in 2019. The drop is very evident at the beginning because Coal Power Plants are shut down first followed by Gas Power Plant and Petroleum Power Plant. After all the CPPs are shut down, the decline rate is predicted to decrease, as the net contribution of other sources is by number or percentage less significant. As shown in Figure 5, the net CO_2 contribution per year is mitigated but not fully reversed. The red line represents the possible scenario intervening with the least aggressive construction and substitution rates. Comparing the 2025 and 2100 scenarios vs the BAUS-reference the global savings trend of CO_2 emitted per year is immediately evident as indicated in Table 2. As the chosen scenario is moved forward in time the difference in savings becomes less and less significant.

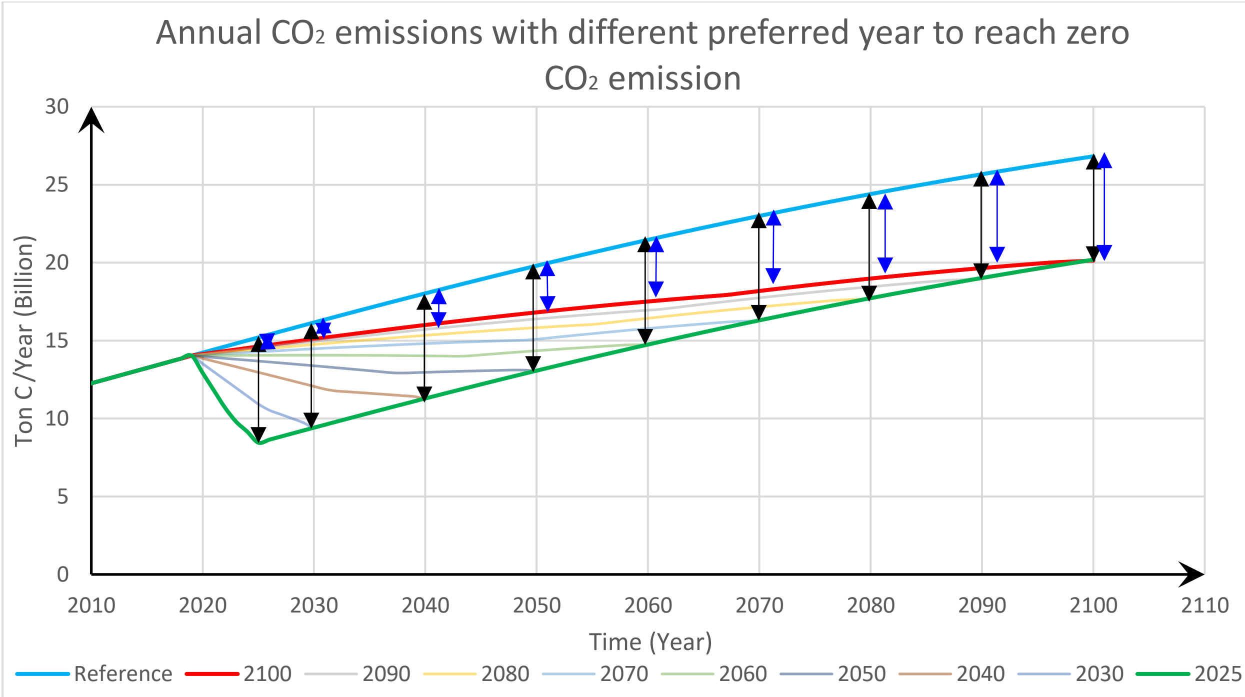


Figure 5. CO2 emission with different preferred year to reach zero CO2 emission

Year	Annual CO2 reduction in 2025 scenario (Billion tons CO2 /Year)	Annual CO2 reduction in 2100 scenario (Billion tons CO2 /Year)
2020	1.3	0.1
2025	6.7	0.6
2030	6.7	1.0
2040	6.7	2.0
2050	6.7	3.0
2060	6.7	4.0
2070	6.7	4.8
2080	6.7	5.4
2090	6.7	6.0
2100	6.7	6.7

Table 2. Annual CO2 reduction in 2025 and 2100 scenario

In 2100, about 6.7 billion tons carbon are predicted to be eliminated accounting for 25% of the total: this proves that the combined use NPP, EV and EH can have a significant impact on CO_2 emissions reduction. These two scenarios (2025 vs 2100) are chosen as reference and compared because are indicative of two possible, but extreme solutions: one extremely aggressive and much closer in time and one much more relaxed and far in the future. It is interesting to notice that if we consider 2030 (“year zero” according to policy makers in USA at this time) as the “point of no return” in terms of climate change effect particularly over Earth temperature, the effort needed to quench the situation appears titanic and most probably industrially impossible: in fact the world industry would need to produce more than 200 NPP per year, roughly 170 million of electric heaters and produce approximately 110 million of electric cars per year to reach net zero carbon emission.

Monitoring the CO_2 concentration in atmosphere is of great importance. Concentrations of CO_2 in the atmosphere were as high as 4,000 parts per million (ppm, on a molar basis) during the Cambrian period about 500 million years ago to as low as 180 ppm during the Quaternary glaciation of the last two million years [20].

Figure 6 shows the CO_2 concentration versus time in different scenarios. The simulation results shown prove that additional CO_2 concentration can be reduced from about 60 ppm to 97 ppm in different scenarios or 10% to 16% respectively.

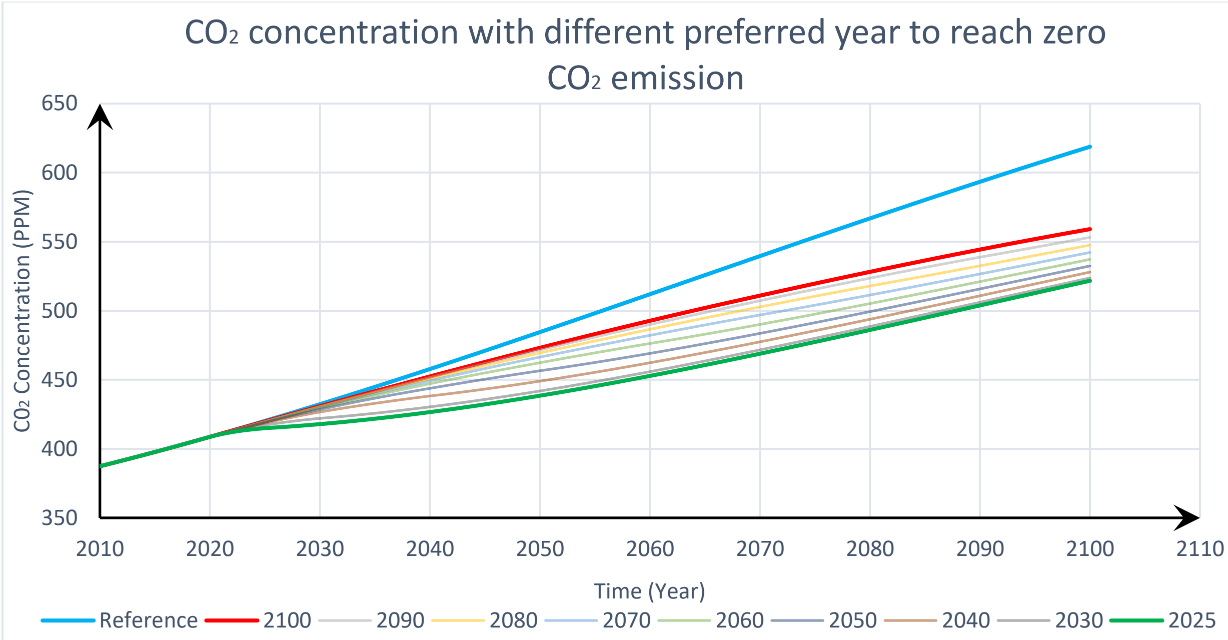


Figure 6. CO2 concentration with different preferred year to reach zero CO2 emission

The difference between the curves for each scenario and the reference line shows correspondingly ppm reduction of CO_2 in the atmosphere. The cyan curve is the reference line (BAUS), which is based on the current and implemented policy. The other curves show the CO_2 concentration using different scenarios. The lowest curve in green in Figure 6 is the prediction for the year 2025 (most aggressive scenario): as the preferred year to reach zero CO_2 emission is pushed forward in time, the installation rate of NPPs, EVs and EHs is decreased; consequently, more CO_2 production is predicted in 2100 with a significant difference.

The increased concentration of CO_2 in atmosphere directly provokes damage to the climate. In this study, the upper and deep ocean temperature were predicted through DICE model, while the total and effective "social cost" of carbon will be treated in a different publication.

According to the US National Oceanic and Atmospheric Administration (NOAA), the upper Ocean temperature has increased by approximately 0.1℃ per decade over the past 100 years.

There are many terrible consequences predicted due ocean warming [21], such as sea level rise and continental ice melting. For these reasons, it's of great importance to study the ocean temperature changes along time. The prediction of atmospheric and upper ocean temperatures is shown in Figure 7.

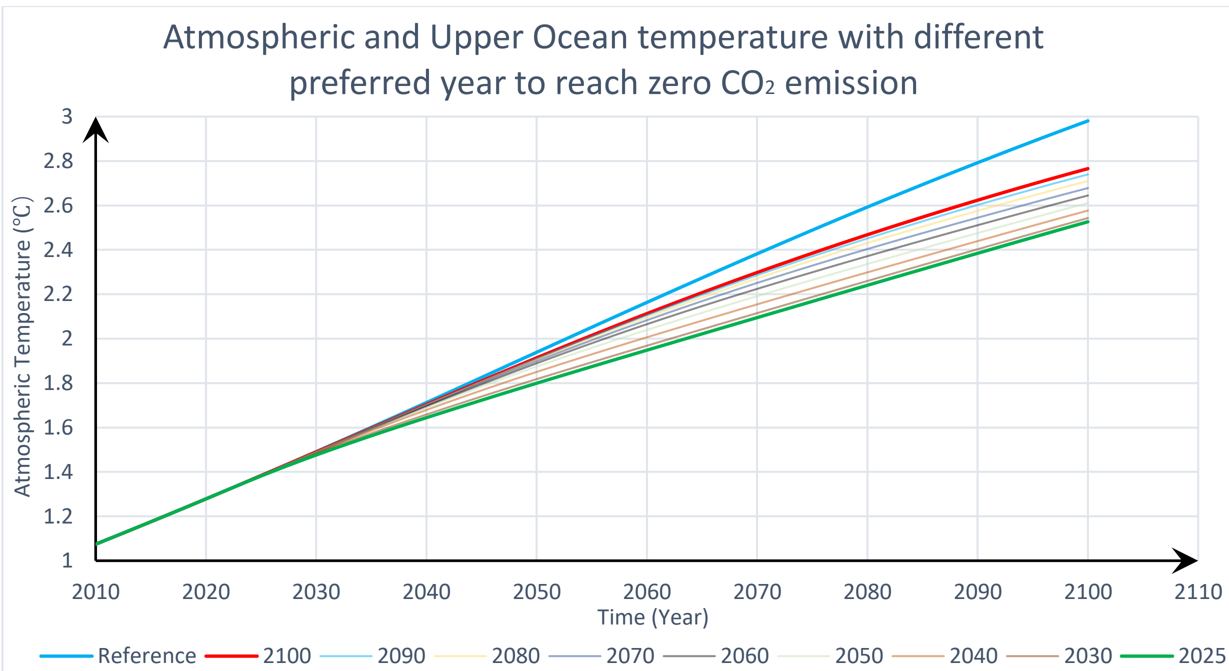


Figure 7. Atmospheric and Upper Ocean temperature in different scenarios

The simulation carried out shows a significant difference (roughly of 0.5 degrees) between the BAUS (reference) scenario and the 2025 (most aggressive) one. The atmospheric temperature is increasing continuously, after 2019 even though with slightly different rates according to the scenario proposed. At the end of the century, the atmospheric temperature difference between the 2100 scenario and the 2025 scenario is calculated around 0.2℃. This clearly indicates that by replacing the FFPP, traditional vehicle and FFH with NPP, EV and EH will be helpful to control the temperature increase but not decisive.

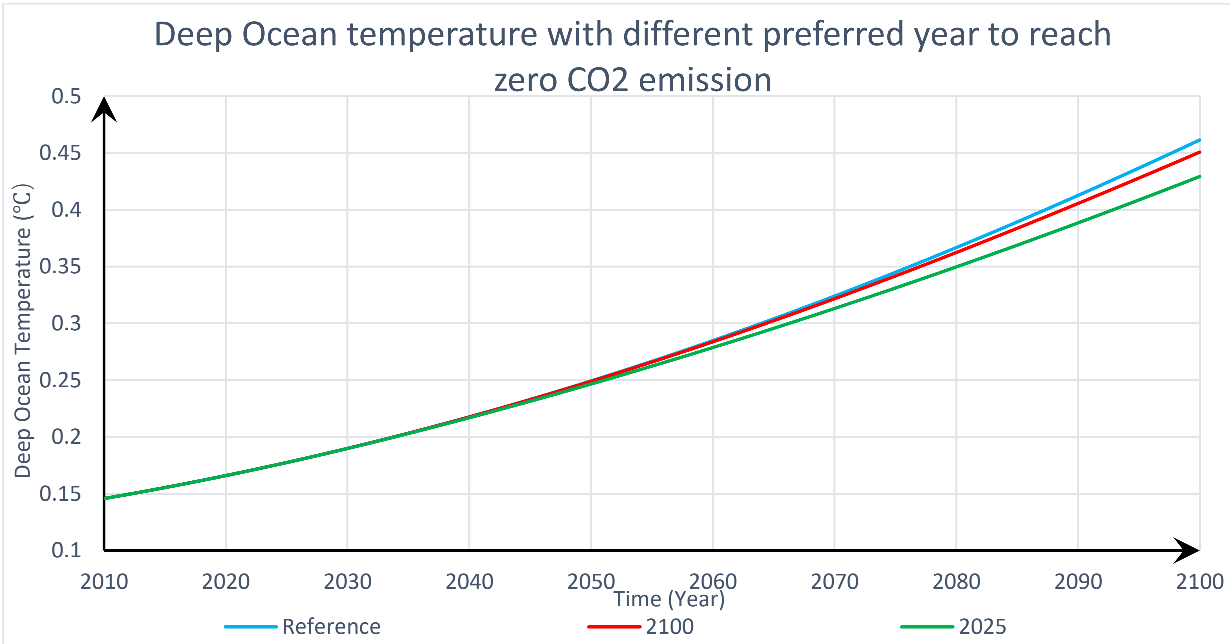


Figure 8. Deep Ocean temperature in different scenarios

Finally, the ocean temperatures have been studied. According to [22], the ocean is divided into three major layers: the top part is called the surface layer; the lowest layer is the deep ocean while an intermediate boundary layer called the thermocline separates the surface layer and the deep water of the ocean. The average deep ocean temperature and its changes is also a factor that has been considered. Similar to the upper ocean temperature, with the NPP construction rate, EV and EH increasing rate increase, the predicted growth of deep ocean temperature will be slowed down. However, the increase in deep ocean temperature is much less than upper ocean temperature. In fact, high radiative exposure warms the atmospheric layer, with consequent upper ocean warming, while varies gradually warming the deep ocean [23]. The results shown in Figure 8, anticipate then a reduction from 0.01℃ to 0.03 ℃ in different scenarios with an identical color scheme introduced previously.

5. Conclusions

Global climate change is closely related to human development and survival representing a very difficult challenge for actual and future generations. With the increasing threats for energy security and the search for a more sustainable economic and social development in different countries, developing low carbon economy has become a common global goal: in fact, it is the only way to address properly the problems related global warming and increased extreme weather events. In this study, a modified DICE model is proposed to analyze the contributions of nuclear power in order to reach this ultimate goal. The results of the simulations carried out show that if all the Fossil Fuel Power Plants are replaced by Nuclear Power Plants, traditional vehicles are replaced by electrical vehicles and Fossil Fueled heaters are replaced by Electric Heaters, CO_2 emission can be potentially reduced of at least 15%. Consequently, at the end of the century, there will be about 4500 nuclear reactors, three billion electric vehicles and four billion electric heaters. Although it may impossible to have so many NPPs in the world, it is concluded that CO_2 concentration can be reduced to 521 ppm using the most aggressive zero carbon emission scenario (2025) up to a maximum of 559 ppm in 2100 if a more relaxed approach is undertaken. This is still significantly higher than 350 ppm (considered safe for our planet) and the one present in today’s atmosphere ranging around 417 ppm. A more comprehensive discussion needs to be carried out in order to quantify properly mitigation of social and climate cost using this methodology. However, it is estimated that a reduction ranging from 0.2℃ to 0.5℃ of the atmospheric temperature will take place. A similar reduction ranging from 0.1℃ to 0.3 ℃

of deep ocean temperature is also possible. Thus, this study shows that the pace of global warming can be at least slowed down if all the fossil fuel power plants, traditional vehicles and fossil fueled heaters currently in the world are replaced by nuclear power plants, electric vehicles and electric heaters contributing significantly, but not fully reversing the increasing trend of dangerous CO_2 concentration in our environment.

6. Acknowledgements

I express my sincere appreciation to Professor Akira Tokuhiro for his invaluable guidance and continuous support throughout my research activities. I also would like to extend my gratitude to Dr. Filippo Genco for his advice and insightful contributions to my research.

7. References

[1] Q. Yan et al., “Energy-Related CO_2 Emission in China’s Provincial Thermal Electricity Generation: Driving Factors and Possibilities for Abatement”, Energies, Vol. 11, No. 5, 2018, pp. 1-25.

[2] W.D. Nordhaus, “Reflections on the Economics of Climate Change”, Journal of Economic Perspectives, Vol. 7, No. 4, 1993, pp. 13.

[3] J.L. Colpetzer, “A study on the impact of nuclear power plant construction relative to decommissioning fossil fuel power plant in order to reduce carbon dioxide emissions using a modified Nordhaus Vensim DICE model”, [Order No. 1556942], University of Idaho; 2014.

[4] C. Brand, M. Tran, J. Anable, “The UK transport carbon model: an integrated life cycle approach to explore low carbon futures”. Energy Policy, Vol. 41, 2012, pp. 107-124.

[5] Z. Hausfather, “How electric vehicles help to tackle climate change”, Carbon Brief, 2019

[6] R. McSweeney, Z. Hausfather et al., “How do climate models work”, Carbon Brief,2018.

[7] W.D. Nordhaus, “The "Dice" Model: Background and Structure of a Dynamic Integrated Climate-Economy Model of the Economics of Global Warming”, Cowles Foundation discussion paper no. 1009, 2014.

[8] S. Newbold, “Summary of the DICE model”, U.S. EPA, National Center for Environmental

Economics, 2010.

[9] NASA GISS, “Science Briefs: Greenhouse Gases: Refining the Role of Carbon Dioxide”, 2016.

[10] S. Jonathan, “CO_2 in the atmosphere just exceeded 415 parts per million for the first time in human history”, TechCrunch, 2019.

[11] U.S. Environmental Protection Agency, “Global greenhouse gas emissions data”, 2020.

[12] Intergovernmental Panel on Climate Change, “Climate change 2014: Mitigation of climate change”, 2014.

[13] P. Robert, “Fossil fuels still supply 84 percent of world energy- and other eye openers from BP’s annual review”, 2020.

[14] International Energy Agency, “CO_2 emissions from fuel combustion: overview”, 2020.

[15] M. Grubb et al, “Modeling myths: On DICE and dynamic realism in integrated assessment models of climate change mitigation”, 2021.

[16] R. Easton, R. Repetto, "DICE model reassessment summary and key findings from first phase of analysis", International Institute of for Sustainable Development, 2014.

[17] J. Voelcker, 1.2 billion vehicles on world's road now, 2 billion by 2035: report, 2014.

[18] Organization for Economic Co-operation and Development, "Doing better for families", 2011.

[19] IEA, Electricity generation mix, 2018.

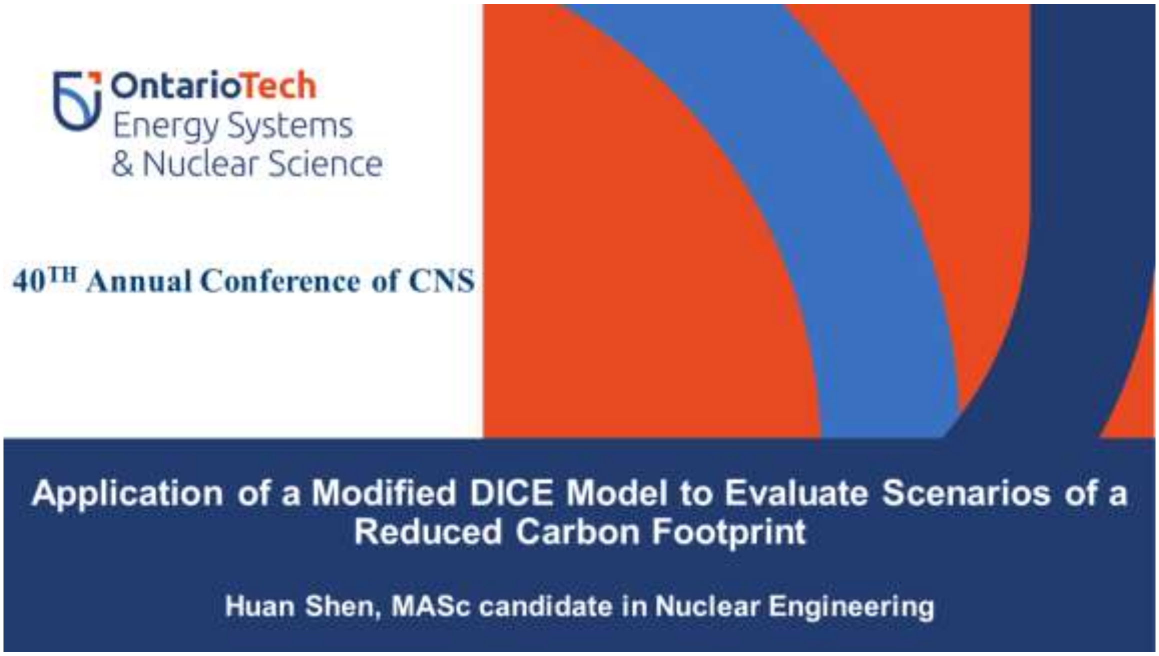
[20] T. Eggleton, "A Short Introduction to Climate Change", Cambridge University Press, p. 52. ISBN 9781107618763, 2013.

[21] D. Laffoley, J.M. Baxter, "Explaining ocean warming: causes, scale, effects and consequences", Switzerland: IUCN, 2016.

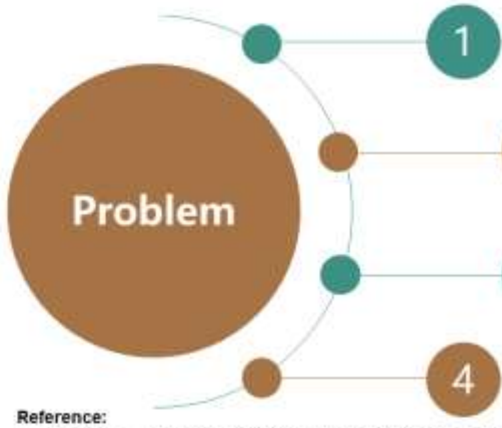
[22] J. Bergman, "Temperature of ocean water", Windows to the Universe, 2011.

[23] W.D. Nordhaus, "Integrated Economic and Climate Modeling", Cowles Foundation Discussion Paper No. 1839, 2011.

Appendix G: CNS conference presentation PowerPoint



Introduction



1. The impact of global climate, change characterized by global warming continues to attract concern and debate.
2. According to the Fifth Assessment Report Published by the Intergovernmental Panel on Climate Change (IPCC) in 2014, the main contributor to climate change is CO_2 emissions.
3. Human activities are responsible for almost all of the excess greenhouse gas emissions over the last 150 years
4. A growing number of governments are setting "net-zero emissions" target to curtail global warming.

Reference:

- Yan Q et al., Energy-Related CO_2 Emission in China's Provincial Thermal Electricity Generation: Driving Factors and Possibilities for Abatement. *Energies* 2018, *11*, 1096.
- EPA, Sources of greenhouse gas emissions, 2018.
- Darby Megan, Gerretsen Isabelle, Which countries have a net zero carbon goal?, Climate Home News, 2019

Possible solutions

- Data show that nuclear power plant (NPP) produce approximately 6% of the CO_2 emissions per Megawatt (MW) compared to a fossil fuel power plant (FFPP).
- Supply and demand of Electric Vehicle (EV) continue to increase, and provide a path to emission reduction in transportation

- Majority of households depends on central furnace to provide heating; they use natural gas or oil. Electric heaters (EH) can provide home heating without CO_2 emission.

Can nuclear power plants, electric vehicles and electric heaters provide relevant and significant paths to mitigating the impact of climate change (reduction of CO2?

Reference:

- Colpetzer JL, A study on the impact of nuclear power plant construction relative to decommissioning fossil fuel power plant in order to reduce carbon dioxide emissions using a modified Nordhaus Vensim DICE model, University of Idaho, 2014.
- Hausfather Zeke, How electric vehicles help to tackle climate change, Carbon Brief, 2019
- Smarter House, Types of Heating System, 2015

How can the impact of NPP, EV and EH be evaluated?

- Use the Dynamic Integrated Climate Economy model (DICE). (see next slide)
- Predicts climate change "metrics" based on available climate, economic data and "macro-economic" models.
- This work modified the DICE model to predict the impact on climate change metrics due to different target year to reach zero CO_2 emissions (relative to current levels).
- The sub-models developed for this study decommissions/replaces fossil fuel power plants, traditional (fossil fueled) vehicles and fossil fueled heaters.
- The model and simulations then estimates the reduction of CO_2 emissions resulting from the decommissions of fossil fuel power plants, traditional vehicles and fossil fueled heaters.
- The reduction of CO_2 is then fed into the DICE model to simulate changes to climate change metrics such as reduction of CO_2 emissions, ocean surface temperature and fiscal estimates of damage due to climate change, relative to today.

5

What is the DICE model?

Integrated macro-economic model.

Developed by Professor William D. Nordhaus at Yale University originally in 1991

A simplified analytical and empirical model that represents the economics, policy and scientific aspects of climate change

Widely cited by climate economists and policy professionals; in its successive versions has been influential in climate policy deliberations for several decades

Reference:
- Nordhaus William, DICE 2013R: Introduction and User's Manual, 2013.
- Easton Robert, Repetto Robert, DICE model reassessment summary and key findings from first phase of analysis, International Institute of for Sustainable Development, 2014.

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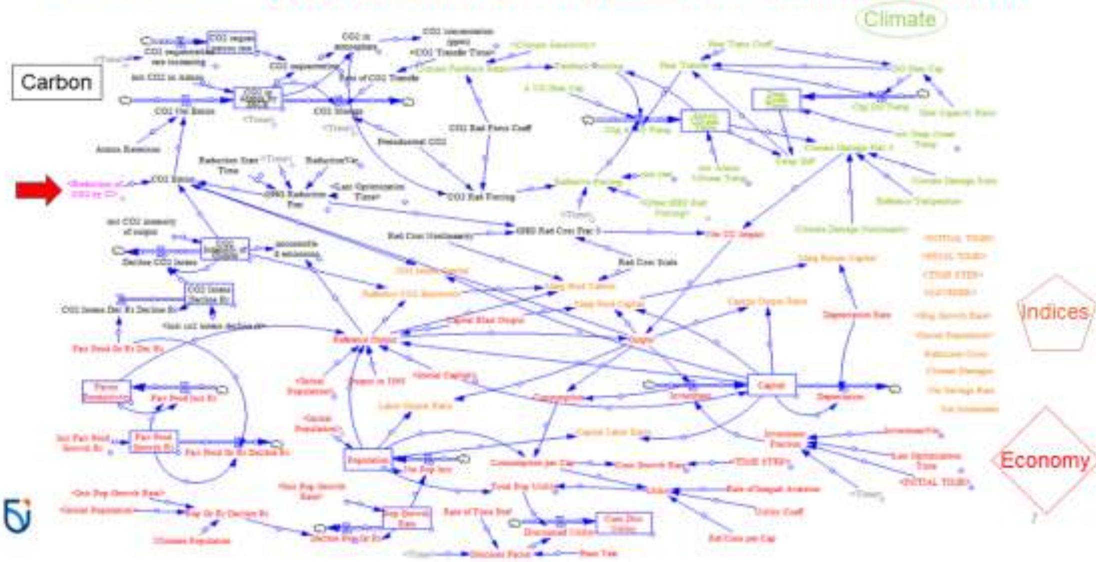
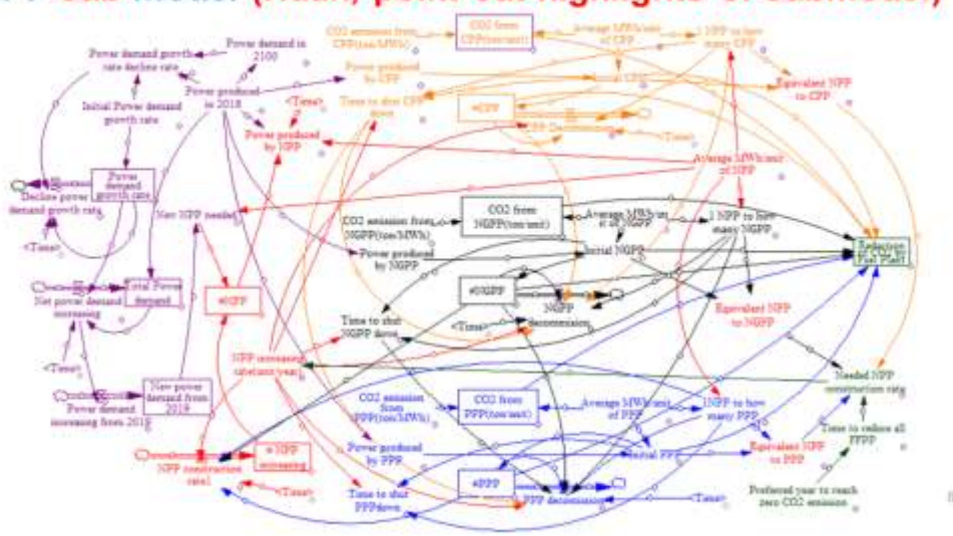
DICE model (GUI-based with models per Vensim coding)



NPP sub-model (Huan, point out highlights of submodel)

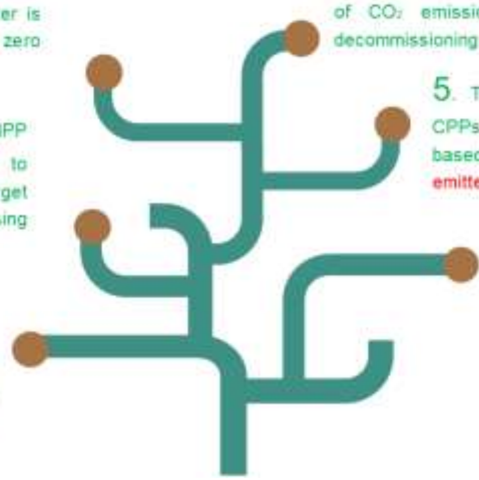


Feature of NPP sub-model

1. Input or simulation parameter is the target year to reach net zero CO_2 emission.

2. Model will determine the NPP construction rate in order to replaced all FFPPs in the target year and also meet the increasing power demand.

3. The FFPP decommissioning rate will be determined based on the amount of power produced by the new NPPs.



4. The model will then calculate the amount of CO_2 emissions avoided due to the decommissioning of FFPPs.

5. The model decommissions CPPs, then NGPPs, then PPPs based on the amount of CO_2 emitted, from highest to lowest.

6. The total CO_2 emissions avoided is then subtracted directly from the standard DICE model CO_2 emission variable.

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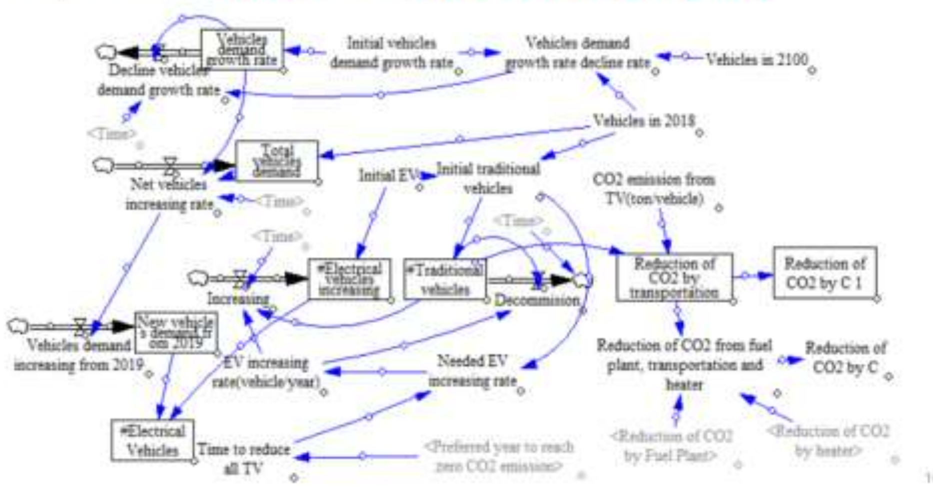
Transportation sub-model (point out highlights)



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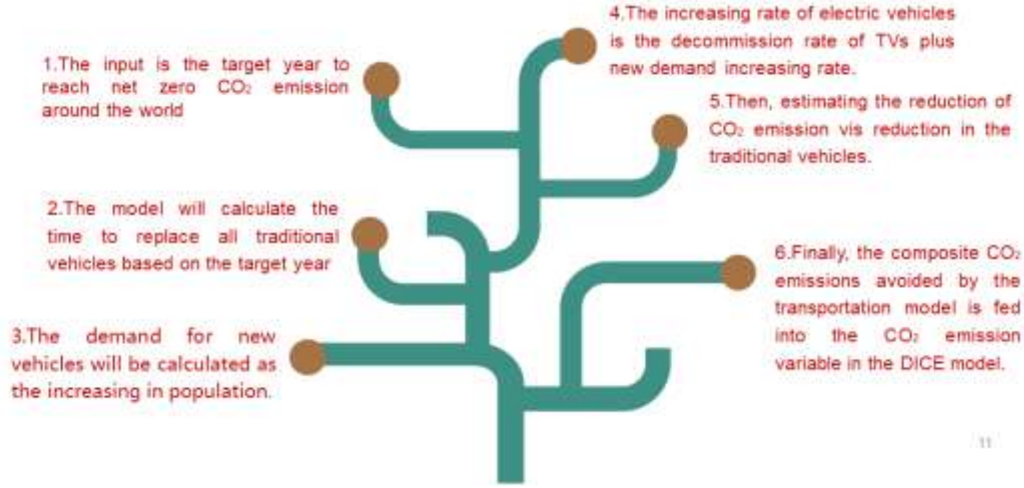
Feature of Transportation sub-model



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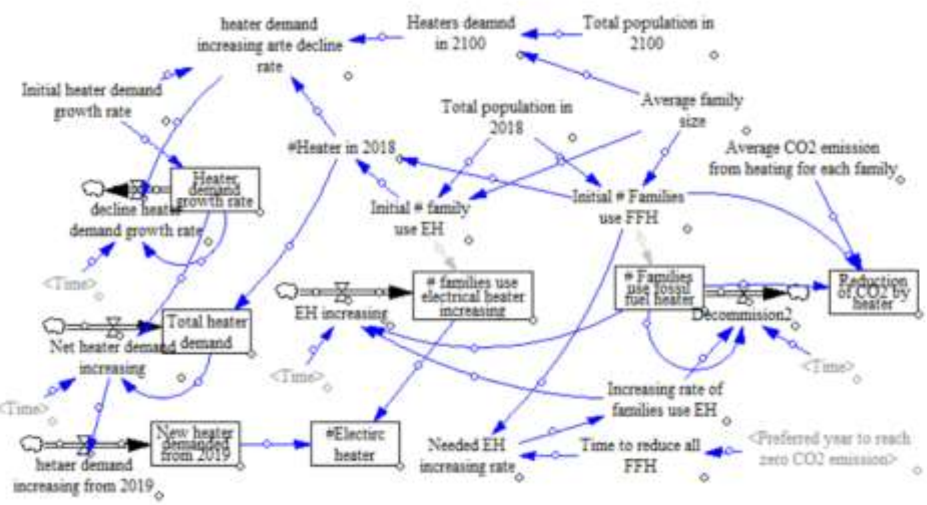
Heating sub-model (again, point out highlights)



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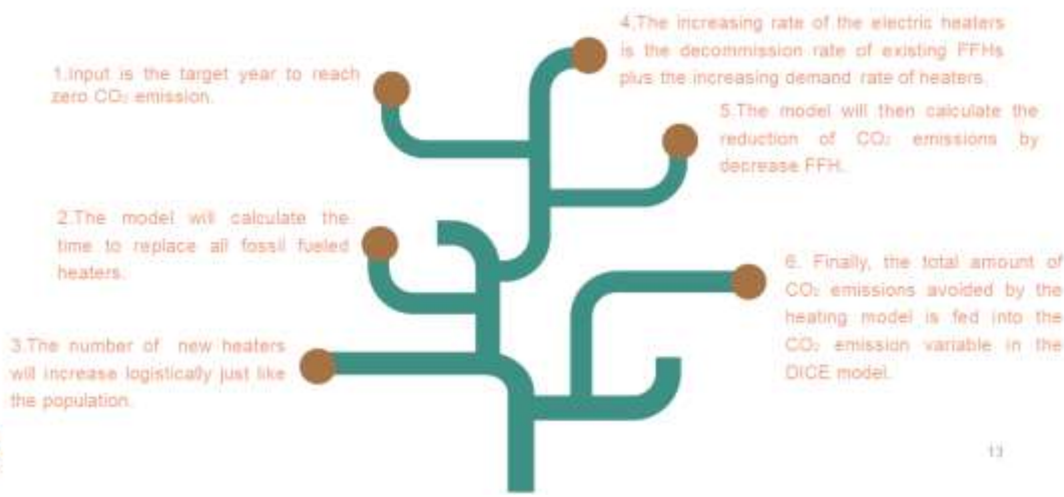
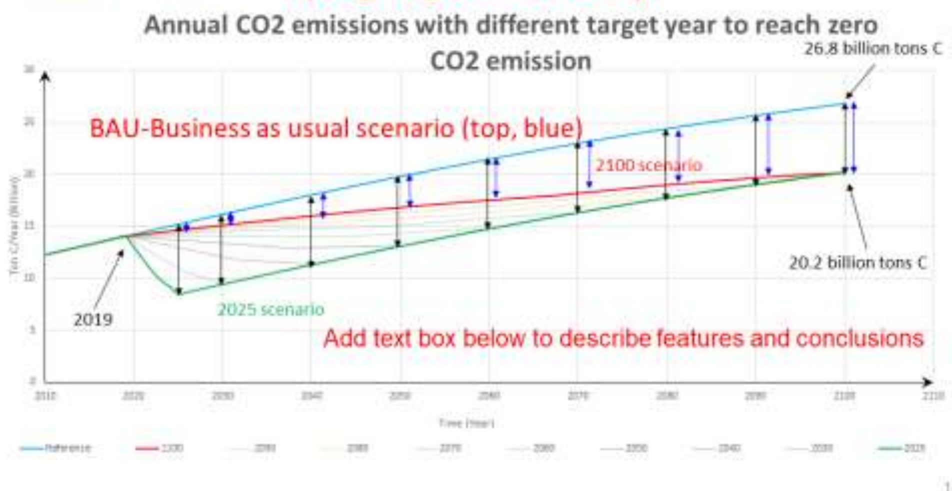
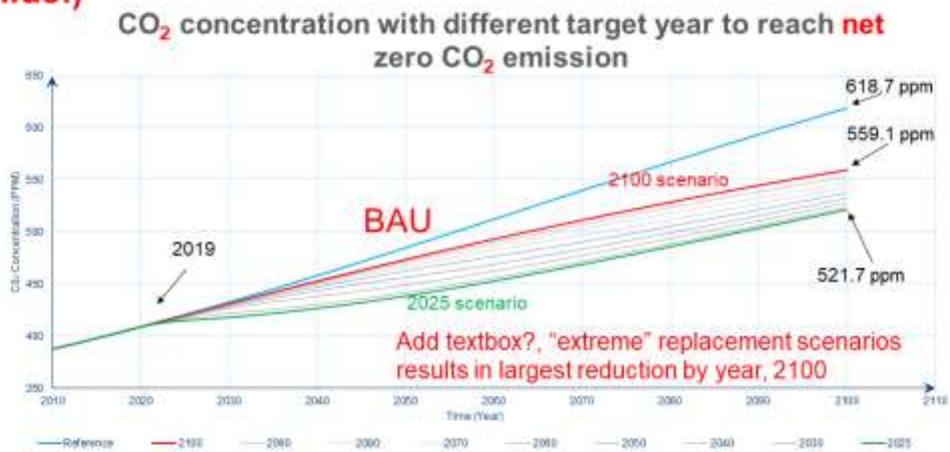
Feature of Heating sub-model



Simulation results (englarge numbers!)



Simulation results (again, enlarge numbers on each slide!)



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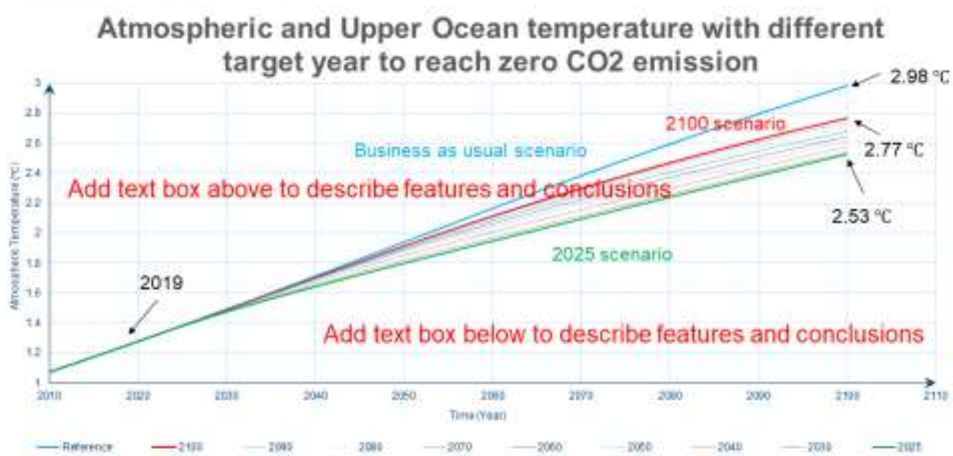
Simulation results



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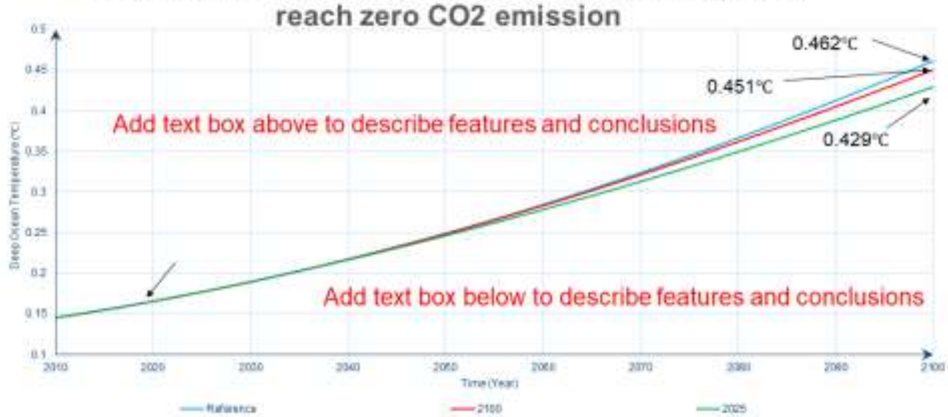
Simulation results

Deep Ocean temperature with different target year to reach zero CO2 emission



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Summary (what is this table showing? What is compared?)

Target year to reach zero CO_2 emission	Reduction of CO_2 concentration in 2100 (ppm)	Reduction of atmospheric & Upper Ocean temperature (℃)	Reduction of deep ocean temperature (℃)
Reference	0	0	0
2100	59.69 (9.7%)	0.22 (7.2%)	0.011 (2.3%)
2090	65.64 (10.6%)	0.24 (8.1%)	0.012 (2.6%)
2080	71.26 (11.5%)	0.27 (9.1%)	0.014 (3.0%)
2070	76.57 (12.4%)	0.30 (10.2%)	0.016 (3.5%)
2060	81.58 (13.2%)	0.34 (11.3%)	0.019 (4.1%)
2050	86.32 (14.0%)	0.37 (12.4%)	0.022 (4.8%)
2040	90.79 (14.7%)	0.40 (13.6%)	0.026 (5.6%)
2030	95.02 (15.5%)	0.44 (14.7%)	0.030 (6.5%)
2025	97.05 (15.7%)	0.45 (15.2%)	0.032 (6.9%)

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Results to date (by or in 2100? Which? "by" means accumulated savings each year; "in" just means in year 2100.)

- Using the developed Vensim DICE model it can be determined that replacing all the FFPPs, TVs and FFHs with NPPs, EVs and EHs will reduce CO_2 emissions 24.4 billion tons or 24.8% per year by 2100 (by or in 2100?).
- This in turn reduces the cumulative amount of CO_2 in the atmosphere by 127 billion tons to 207 billion tons or 9.7% to 15.7% in 2100.
- Also, it reduces the CO_2 concentration in the atmosphere by 60ppm to 97 ppm or 9.7% to 15.7%.
- Unfortunately, this still results in a 522ppm to 559ppm CO_2 concentration in the atmosphere in 2100.
- The increasing in atmospheric & upper ocean temperature will be reduced by 0.22℃ to 0.45℃ or 7.2% to 15.2% in 2100.
- Average deep ocean temperature will also have a small reduction of 0.011℃ (2.3%) to 0.032℃ (6.9%) in 2100.

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Conclusions to date

- Replacing the current fleet of FFPPs, TVs and FFHs with NNPs , EVs and EHs will have a beneficial effect; that is, reduce the CO_2 footprint replacing/eliminating sources of emission.
- In year 2100, the CO_2 concentration in atmosphere will decrease 82.3 ppm and the atmospheric temperature will decrease 0.37 ℃ if the target year to reach zero CO_2 emission is in 2050.
- Replacing all the FFPPs, TVs and FFHs in the world with NPPs, EVs and EHs will not be enough to mitigate the negative impacts of climate change.
- NPP, EV and EH are only part of the solution.
- Although higher NPP construction rate and increasing the EV, EH replacement rate will reduce CO_2 emissions as a means to combat climate change, the current construction rate of nuclear plants will be insufficient to significantly counter climate change. Further integration of options such as renewable generation, energy storage, work from home, energy conservation are needed.
- In other words, in order to reach carbon neutrality as many countries pledged, more actions need be taken to reduce the CO_2 emissions.

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Thank You!
Questions?

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