2024 Summer NSERC USRA:
Quantifying Climate Change Impacts on Gross World Product using Dynamic Integrated Climate Economy (DICE) Model

Student: Hai Lin Wang (301575427)
Supervisors: Jean-Francois Begin, PhD
Barbara Sanders, MSc

Literature Review and Methodology

Literature Review

In 1977, William D. Nordhaus examined climate change as an external diseconomy. As the result of a free market that does not prioritize social welfare, excessive greenhouse gas (GHG) emissions damage the consumption of future generations. While there is little economic incentive to reduce greenhouse gas emissions in the present time in a free market, there are policy interventions to internalize the externality of excessive GHG emissions. (Nordhaus 1977, Nordhaus 1992, Nordhaus 1994)

As countries have agreed upon an international standard for limiting GHG emissions, Nordhaus proposed the usage of carbon tax to properly price excessive GHG emissions under policy limits. In order to appropriately assign a price to carbon dioxide and other GHG emissions in carbon dioxide equivalents, the interactions between energy systems, as well as supply and demand must be optimized for a future that maximizes social welfare. Under no policy constraints on GHG emissions, however, the above system is unoptimized and results in excess energy consumption and GHG emissions. (Nordhaus 1994)

The earliest version of an optimization model is Nordhaus' dynamic-integrated climate-economy model released in 1992 (DICE-1992). Compared to previous steady-state climate-economy models, DICE-1992 does not assume equilibrium-state in its input variables. Instead, DICE-1992 considers input variables, as well as the evolving interactions between variables, as time-dependent processes that are dynamic in nature. As one of the earliest integrated-assessment models (IAM), DICE-1992 is used for two purposes by both policymakers and economists:

1) Identifying the optimal path for slowing climate change, in which social welfare is maximized for all individuals over time.
2) Establishing competitive market equilibrium where externalities such as excess GHG emissions can be positively priced using the social cost of carbon.

DICE-1992, along with its later successors, all share the following components:

1) An economic model that extends upon Frank P. Ramsey's model on optimal growth (Ramsey 1928) with an optimization factor, which is an output of the climate model.
2) A climate "minimodel" that illustrates the following relationships:
    a. Atmospheric concentration of GHGs with GHG emissions.
    b. Radiative forcing from GHG emissions as a result of atmospheric concentration of GHGs.
    c. Temperature increases in atmosphere, deep oceans and their mixture.
3) A quantified damage caused by temperature increases to the gross world product in each time period in the future.

In 2016, Nordhaus updated the DICE model to include the social cost of carbon, which is a modification of the quantified damage component above. Bringing back the quantified damage from each future time period to the current present time, the social cost of carbon involves the choice of the discount rate. The alternative names for the social cost of carbon in present time value are carbon price and carbon tax. (Nordhaus 2017)

Global climate policy has evolved significantly since the creation of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992, but their effectiveness in mitigating and adapting to the effects of climate change have been questioned by the masses. Using DICE to evaluate the effectiveness of GHG emissions control policy, Nordhaus added the following scenarios to generate social cost of carbon for each policy case:

1) **Baseline Policy**: No policies taken to slow or reverse climate change. This is also the most common policy followed by most countries since the 1989. (Nordhaus 1994)
2) **Optimal Policy**: Every nation internalizes the climate change externality and thus maximizes social welfare. (Nordhaus 1994)

3) **Ten-Year Delay of Optimal Policy**: Optimal Policy implemented 10 years later than 1990. (Nordhaus 1994)
4) **Stabilizing Emissions at 1990 Levels**: GHG emissions to remain at 1990 level. (Nordhaus 1994)
5) **Twenty-Percent Reduction from 1990 Levels**: GHG emissions to reduce by 20% from 1990 level. (Nordhaus 1994)
6) **Climate Stabilization**: Most ambitious policy to slow climate change to reduce major ecological impacts, though there are no defined emissions control metrics for countries. (Nordhaus 1994)
7) **Kyoto Protocol**: Developed countries must reach the legally binding target of reducing their GHG emissions to 5.2% below 1990 levels during 2008 to 2012. (Nordhaus & Boyer 1999)
8) **Kyoto-Bonn Accord**: With U.S. participation as optional, this policy evaluates the Kyoto Protocol. (Nordhaus 2001)
9) **Copenhagen Accord**: Globally, countries will cooperate to reduce average temperature increase to below 2ºC above pre-industrial levels. (Nordhaus 2010)
10) **Paris Agreement**: Following the Copenhagen Accord, this policy requires that national climate policy for each country to reduce greenhouse gas emissions by 2030. (Nordhaus 2017)

In all the above scenarios, the optimal policy scenario is demonstrated to be the most effective policy at reducing global average temperature increase, as well as maximizing social welfare, in a period of over 500 years. (Nordhaus 2017)

As an advocate for market-based solutions in solving the climate crisis, Nordhaus has criticized the UNFCCC and its resulting policies as ineffective due to its voluntary and top-down nature. (Nordhaus & Boyer 1999, Nordhaus 2001, Nordhaus 2010) The lack of international enforcement, as well as the regard of environmental benefits as a public good, has also given rise to the free-rider problem, which Nordhaus defines as countries taking advantage of the GHG emissions reduction efforts of other countries and neglecting their own respective action. Proposing the "Climate Club" instead of top-down, non-legally binding international temperature and emissions control goals, Nordhaus proposes a cooperative framework based on pricing GHG emissions universally using the social cost of carbon and promoting economic incentives for emissions mitigation. Countries who do not participate in the Climate Club would be penalized by tariffs on their exports to club members, thereby creating an economic incentive for participation. (Nordhaus 2015)

However, the ethics behind the pricing of the social cost of carbon is still up for debate between scholars, policymakers and political campaigners. The selection of the discount rate is central to climate justice in intergenerational equity. In advocating for a high discount rate, Nordhaus is prioritizing the negative impacts incurred by climate change in the short term, while other scholars, such as Nicholas Stern, have argued for a low discount rate to give value to the negative impacts incurred in the long term. Though the difference between a low and high discount rate is only under 2%, the resulting difference in the social cost of carbon is significant to policymakers, as carbon pricing reflects the extent to which society values the economic and physical damages felt by future generations. (Goulder and Williams 2012) In the 2024 United States presidential elections, the discount rate used by the Environmental Protection Agency (USEPA) is a point of contention, with Donald J. Trump arguing for a high discount rate and subsequently a low carbon price.

At the same time, scholars like Stanton (2009) have addressed the failure of IAMs to address for income inequality. Though every IAM, such as DICE and its regionally disaggregated model RICE, recommends an optimal scenario that maximizes social welfare for every time period, it incorporates the process of Negishi weighting prior to optimization, which freezes income distribution around the world. In Nordhaus' DICE-2016 model, the optimal scenario provides a Pareto optimal solution, but the social welfare of richer regions is weighed more heavily than that of poorer regions.

Additionally, economists have criticized the usage of IAMs in climate policy altogether. Keen (2020), a critic of neoclassical economics, have pointed out the unrealistic nature of DICE in its applications to policymaking. Firstly, DICE inadequately represents climate change and its impacts. The assumption of economic damages growing in a quadratic nature has no empirical basis and underestimates catastrophic risks. Second, climate scientists in the UNFCCC process have agreed upon an average temperature increase limit of 2ºC to avert catastrophic levels of global economic and physical damage. Nordhaus' DICE-2016 assumes that an average increase of 6ºC would lead to only moderate reductions in gross world product. Finally, DICE does not include the study of tipping points, which are significant damages to critical ecosystems that would lead to the irreversible collapse of the climate system. Generally, Keen has criticized the usage of neoclassical economics in climate policy as it overly relies on equilibrium models.

Stern et al. (2022) have also supported Keen's comments in criticizing IAMs as generally too simplistic for the complex study of the interaction between the global economy and the climate system. IAMs must be improved to account for tipping points, uncertainties, the non-linear nature of damage and the intergenerational inequities present in the current climate crisis.

Methodology

DICE-1992 is an extension of the Ramsey's model on optimal growth that was published in 1928 (Ramsey 1928). While Ramsey's model posits that an economically efficient society under optimal growth should maximize social welfare by finding an optimal savings rate and an optimal investment rate, Nordhaus' DICE further customized the model by adding a greenhouse gas emissions control component to the optimal investment rate.

The development of the initial version of DICE in 1992 (DICE-1992) can be examined with Ramsey's model on optimal growth. As Ramsey posits that an economically efficient society under optimal growth maximizes social welfare by finding an optimal savings rate, $S(t)$, and an optimal investment rate, $I(t)$, that both provide enough capital accumulation for future generations and ensures consumption in the present time. (Solow 1970)

To obtain these optimal rates, the society's benevolent social planner should maximize social welfare by discounting utility of the entire society, which represents the satisfaction gained by all individuals in society from consuming goods and services over each time period in the future. (Nordhaus 1994)

$$\boldsymbol{V(t) = \sum_{t} U[c(t), L(t)](1+\rho)^{-t}} \tag{1.1}$$

$V(t)$ represents the total future utility of the entire society at the present time. The social planner can discount this aggregated utility using a social rate of time preference, ρ, which measures the relative weight given to the welfare of future generations as compared to the present generation. In order to maximize the total utility, $U[c(t), L(t)]$, and therefore ensure maximum satisfaction from consumption for every generation in the future, the social planner needs to optimize equation 1.1, which can be performed by programming languages such as R, Python and GAMS.

$$\boldsymbol{W(t) = \max_{[c(t)]} \sum_{t} U[c(t), L(t)](1+\rho)^{-t}} \tag{1.2}$$

Once equation 1.2 is implemented by the planner, the optimal savings rate and investment rate determined from the optimization process will result in a Pareto efficient economy, where no generation can be made better off without damaging the total utility of another generation, as the optimization process has ensured that the marginal utility in the present period is equal to the discounted marginal utility in future generations. (Solow 1970)

The process of obtaining the total utility of the entire society, $U[c(t), L(t)]$, is determined by the population size, $L(t)$, and individual utility, $u[c(t)]$.

$$\boldsymbol{U[c(t), L(t)] = L(t)\{[c(t)]^{1-\propto} - 1\}/(1-a)} \tag{1.3}$$

$$\boldsymbol{u[c(t)] = \{[c(t)]^{1-\propto} - 1\}/(1-\propto)} \tag{1.4}$$

In both equations above, individual utility is characterized by per capita consumption, $c(t)$, and the elasticity of marginal utility, α.

This Ramsey model is subject to economic constraints. As explained in equation 1.5, per capita consumption is total consumption, $C(t)$, divided by the population participating in labour force, $L(t)$, which is also an exogenous variable.

$$\boldsymbol{c(t) = C(t)/L(t)} \tag{1.5}$$

The total consumption of a society contributes then to the gross world product (GWP), $Q(t)$, along with another variable, investments $I(t)$.

$$\boldsymbol{Q(t) = C(t) + I(t)} \tag{1.6}$$

The gross world product is a product of an exogenous level of technology in society, $A(t)$, a function of capital stock, $K(t)^{\gamma}$, as well as the exogenous function of the labour force that is relatively stable overtime, $L(t)^{1-\gamma}$.

$$\boldsymbol{Q(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma}} \tag{1.7}$$

To obtain capital stock of the current period in equation 1.7, investment in capital stock from the previous period, $I(t-1)$, along with the capital stock from the previous period after depreciation, $(1-\delta_K)K(t-1)$.

$$\boldsymbol{K(t) = (1-\delta_K)K(t-1) + I(t-1)} \tag{1.8}$$

Though Ramsey's model of optimal growth is widely used by policymakers in areas such as taxation and has been further developed by other economists (Solow 1970), the emerging issue of anthropogenic climate change in the late 20th century presented a novel opportunity to apply the Ramsey model to calculate the cost of excessive greenhouse gases.

While climate scientists had been calling for significant emissions curbs since the 1970s, it wasn't until the 1992 United Nations' Earth Summit in Rio de Janeiro, Brazil that world leaders agreed to adopt a convention, the United Nations Framework Convention on Climate Change (UNFCCC), dedicated to preventing anthropogenic impacts on the climate system by stabilizing greenhouse gas emissions to levels before industrialization (Nordhaus 1994). Economists and policymakers were thus presented with a quandary: how can nations ensure maximized social welfare from consumption in the face of increasing economic and physical damages from excessive greenhouse gas emissions.

That year, economist William D. Nordhaus developed DICE as an extension to Ramsey's model of optimal growth. Instead of the planner choosing a savings rate to result in a Pareto efficient economy that results in no generation being worse off in terms of aggregated utility, Nordhaus assigned the planner with two policy instruments which can be optimized: emissions reduction rate, $\mu(t)$, and savings rate, $S(t)$.

Adding a climate model to the Ramsey model of optimal growth, DICE-1992 was designed to answer the following question: what emissions reduction rate and savings rate would enable society to reach Pareto efficiency, where costs of emissions controls are balanced against the costs of the impacts to ecosystems and agricultural systems? DICE posits that society will focus on emissions reduction in the present period in order to increase future consumption, while recognizing that a portion of consumption in the present period must be forgone due to emissions reduction efforts. The resulting maximized social welfare describes a world where "countries efficiently internalize in their decision-making the global costs of their emissions decisions". (Nordhaus 1994, p. 9)

The main alteration made by Nordhaus to equation 1.7 is to scale GWP with an optimization factor, $\Omega(t)$, by accounting for the portion of GWP lost by damages brought on by increasing greenhouse gas emissions, as well as investments into abatement.

$$\boldsymbol{Q(t) = \Omega(t)A(t)K(t)^{\gamma}L(t)^{1-\gamma}} \tag{1.9}$$

The optimization factor is obtained by dividing the percent of GWP leftover after investing in greenhouse gas emissions reductions, $(1 - b_1\mu(t)^{b2})$, with the percent of GWP that would be lost due to climate change, $[1 + \theta_1 T(t)^{\theta 2}]$.

$$\boldsymbol{\Omega(t) = (1 - b_1\mu(t)^{b2})/[1 + \theta_1 T(t)^{\theta 2}]} \tag{1.10}$$

DICE-1992's Climate Model

Equation 1.11 explains the relationship between global temperature increase and income loss. This economic damage is a function of GWP adjusted for θ_1, the scale of damage, and temperature increase. However, due to the nonlinearity of the damage function, the increase of temperature has a quadratic effect on income loss, and this effect is represented by θ_2.

$$\boldsymbol{D(t) = Q(t)\theta_1 T(t)^{\theta 2}} \tag{1.11}$$

Similarly, the total cost of reducing emissions is a function of GWP adjusted for the percentage of emissions reduced, $\mu(t)$, a policy tool. Due to the nonlinearity of this cost function as well, the scaling factors b_1 and b_2 are included mathematically but has no conceptual meaning.

$$\boldsymbol{TC(t) = Q(t)b_1\mu(t)^{b2}} \tag{1.12}$$

DICE-1992 considers both the increase in temperature in the atmosphere, $T(t)$, and the deep oceans, $T^*(t)$.

Temperature increase in the mixture of the atmosphere and the upper ocean takes into account the temperature of the previous period and the radiative forcing, $F(t)$, leftover from the previous time period and the loss of heat to the deep layer of the ocean, $T(t-1) - T^*(t-1)$. The scaling factors here are $\frac{1}{R_1}$ and $\frac{R_2}{\tau_{12}}$ to indicate thermal capacity of the atmosphere and the deep oceans, respectively.

$$\boldsymbol{T(t) = T(t-1) + \left(\frac{1}{R_1}\right)\{F(t) - \lambda T(t-1) - \left(\frac{R_2}{\tau_{12}}\right)[T(t-1) - T^*(t-1)]\}} \tag{1.13}$$

Temperature increase in the deep layer of the ocean is subject to the temperature of the previous period and the transfer of heat from the atmosphere. There is also a scaling factor $\frac{1}{R_2}$ to indicate the thermal capacity of the deep oceans.

$$\boldsymbol{T^*(t) = T^*(t-1) + \left(\frac{1}{R_2}\right)\{\left(\frac{R_2}{\tau_{12}}\right)[T(t-1) - T^*(t-1)]\}} \tag{1.14}$$

Radiative forcing is a term in atmospheric physics that represents the increase of Earth's surface warming, and is represented as a function of the CO_2-equivalent of greenhouse gas emissions. $M(t)$ is the atmospheric concentration of CO_2 and the exogenous $O(t)$ is the other greenhouse gas emissions, such as methane and nitrous dioxide, accumulating in the atmosphere during the same time period.

$$\boldsymbol{F(t) = 4.1\left\{\frac{\log\left[\frac{M(t)}{590}\right]}{\log(2)}\right\} + O(t)} \tag{1.15}$$

Atmospheric concentration of CO_2 is a function of greenhouse gas emissions retained in the atmosphere from the previous time period, $\beta E(t-1)$, and the emissions that are not transferred out of the atmosphere, $(1 - \delta_M)[M(t-1) - 590]$.

$$\boldsymbol{M(t) - 590 = \beta E(t-1) + (1 - \delta_M)[M(t-1) - 590]}$$

(1.16)

Total emissions in the current time period are determined by the policymaker using current GWP, adjusted by $\mu(t)$, the percentage of emissions reduced, and $\sigma(t)$, an emissions-to-output ratio.

$$\boldsymbol{E(t) = [1 - \mu(t)]\sigma(t)Q(t)} \tag{1.17}$$

DICE-2016

In 2013, Nordhaus extended the original DICE-1992 model by putting a price on greenhouse gas emissions (Nordhaus 2013). The social cost of carbon (SSC) designates the economic cost caused by one additional ton of greenhouse gas emissions in CO_2 equivalent. After obtaining the maximized discounted social welfare, $W(t)$, its partial derivatives with respect to emissions, $E(t)$, and total consumption, $C(t)$, define the SCC function.

$$\boldsymbol{SCC(t) = -\frac{\frac{\partial W}{\partial E(t)}}{\frac{\partial W}{\partial C(t)}}} \tag{1.18}$$

Mathematically, SCC is a ratio between the marginal impact of an additional unit of emissions and the marginal impact of an additional unit of total consumption. This result would provide policymakers with a regulatory tool for pricing greenhouse gas emissions in the present time. (Nordhaus 2017)

Additionally, with to two more decades of research in climate modelling, Nordhaus has been updating DICE-1992 continuously. The published update in 2016 (DICE-2016) references data published by the Intergovernmental Panel on Climate Change (IPCC) in 2014, which is used as the initial data for climate and economic projections in DICE (IPCC 2014). For the year 2015 in Table 1.1, DICE-1992 projects the model estimates for 2015 using IPCC data from 1990 while DICE-2016 uses data for 2015 as the initial data in the model for future projections (IPCC 1990). However, for the year 2100, both DICE models are projecting estimates, and their differences can be examined in Table 1.1.

VARIABLES AND PARAMETERS CHANGED	**DICE-1992**	**DICE-2016**
PROJECTIONS FOR 2015		
$\boldsymbol{L(t)}$	6.868 billion	7.403 billion
$\boldsymbol{Q(t)/L(t)^{1-\gamma}}$	\$11293 (2010 USD)	\$14183 (2010 USD)
$\boldsymbol{c(t)}$	9195 (2010 USD)	10501 (2010 USD)
$\boldsymbol{O(t)}$	0.89 W/m^2	0.50 W/m^2
$\boldsymbol{\sigma(t)}$	0.607 (tons of CO_2 per thousand 2010 USD)	0.350 (tons of CO_2 per thousand 2010 USD)
$\boldsymbol{Industrial\ Emissions\ (t)}$	42.3 (gigatons of CO_2 per year)	35.7 (gigatons of CO_2 per year)
$\boldsymbol{Q(t)}$	77.6 (trillions of 2010 USD)	105.0 (trillions of 2010 USD)
$\boldsymbol{Atmospheric\ Concentration\ of\ CO_2}$	849 (gigatons of CO_2)	851 (gigatons of CO_2)
$\boldsymbol{T(t)}$	1.16 (degrees Celsius)	0.85 (degrees Celsius)
$\boldsymbol{F(t)}$	3.04 (W/m^2)	2.46 (W/m^2)
PROJECTIONS FOR 2100		
$\boldsymbol{\rho(t)}$	0.034	0.035
$\boldsymbol{L(t)}$	9.812 billion	11.126 billion
$\boldsymbol{S(t)}$	0.17	0.24
$\boldsymbol{Q(t)/L(t)^{1-\gamma}}$	22272 (2010 USD)	72367 (2010 USD)
$\boldsymbol{\theta_2}$	0.013	0.021
$\boldsymbol{c(t)}$	18536 (2010 USD)	55825 (2010 USD)

$\boldsymbol{O(t)}$	1.42 W/m^2	1 W/m^2
$\boldsymbol{\sigma(t)}$	0.113 (tons of CO_2 per thousand 2010 USD)	0.094 (tons of CO_2 per thousand 2010 USD)
$\boldsymbol{Industrial\ Emissions\ (t)}$	78.7 (gigatons of CO_2 per year)	70.8 (gigatons of CO_2 per year)
$\boldsymbol{Q(t)}$	218.5 (trillions of 2010 USD)	816.3 (trillions of 2010 USD)
$\boldsymbol{Atmospheric\ Concentration\ of\ CO_2}$	1428 (gigatons of CO_2)	1820 (gigatons of CO_2)
$\boldsymbol{D(t)/Q(t)}$	0.015	0.043
$\boldsymbol{T(t)}$	3.2 (degrees Celsius)	4.29 (degrees Celsius)
$\boldsymbol{F(t)}$	6.65 (W/m^2)	7 (W/m^2)

Table 1.1 *Comparisons of DICE-1992 and DICE-2016 for the years 2015 and 2100 (Nordhaus 2017)*

Social Cost of Carbon under Multiple Policy Scenarios

Given that $W(t)$, maximized social welfare at the present time, depends on optimized rate of greenhouse gas emissions control, $\mu(t)$, and optimized savings rate, $\boldsymbol{S(t)}$**,** which are chosen by the policymaker, there could be multiple other policy scenarios based on the results of historical international climate negotiations but are not necessarily beneficial for reaching Pareto efficiency in society. Each different scenario would result in different social cost of carbon over time, and provide policymakers with different regulatory guidelines for pricing greenhouse gas emissions.

1. *Baseline:* The policymaker does not slow or reverse greenhouse gas emissions. Most governments have been following this policy scenario since the publication of DICE-1992. (Nordhaus 1994)
2. *Optimal Policy:* This run maximizes social welfare or total utility in a society at the present time. Governments around the world all agree to internalize the global costs of their own greenhouse gas emissions decisions. Full participation of all nations is assumed to start in year 2025. (Barrage and Nordhaus, 2023)
3. *Paris Agreement:* At the UNFCCC's 21st Conference of Parties (COP21), nations agreed to collaborate to limit climate change to 2°C above pre-industrial levels, resulting in the Paris Agreement. This requires that national climate policy for each country to reduce greenhouse gas emissions by 2030. From 2015 to 2030, emissions control rate $\mu(t)$ in DICE increases by 1 percentage point per year. Afterwards, $\mu(t)$ will increase by under 0.5 percentage point per year. (Barrage and Nordhaus, 2023)

Results

Using R programming, the social cost of carbon over the next 500 years for each respective policy scenario will be calculated using DICE-2016 based on the initial values listed in Table 1.1. The code can be accessed in the Appendix.

Running each of the policy scenarios with DICE-2016, the social cost of carbon (SCC) for the years 2015, 2100 and 2395 are as follows.

Policy Scenarios	*2015 (2010 USD)*	*2100 (2010 USD)*	*2395 (2010 USD)*
No Control	30.3900	244.6129	2836.3601
Optimal Policy	32.6155	255.8205	1805.5812
Paris Agreement	32.6164	209.1216	2004.1699

Table 1.2 *Social Cost of Carbon for Each Policy Scenario*

For all policy scenarios, SCC peaks in the 76th time period, which corresponds to the year 2395. In the short term, optimal policy will result in the highest SCC, and over time, optimal policy will result in the lowest SCC.

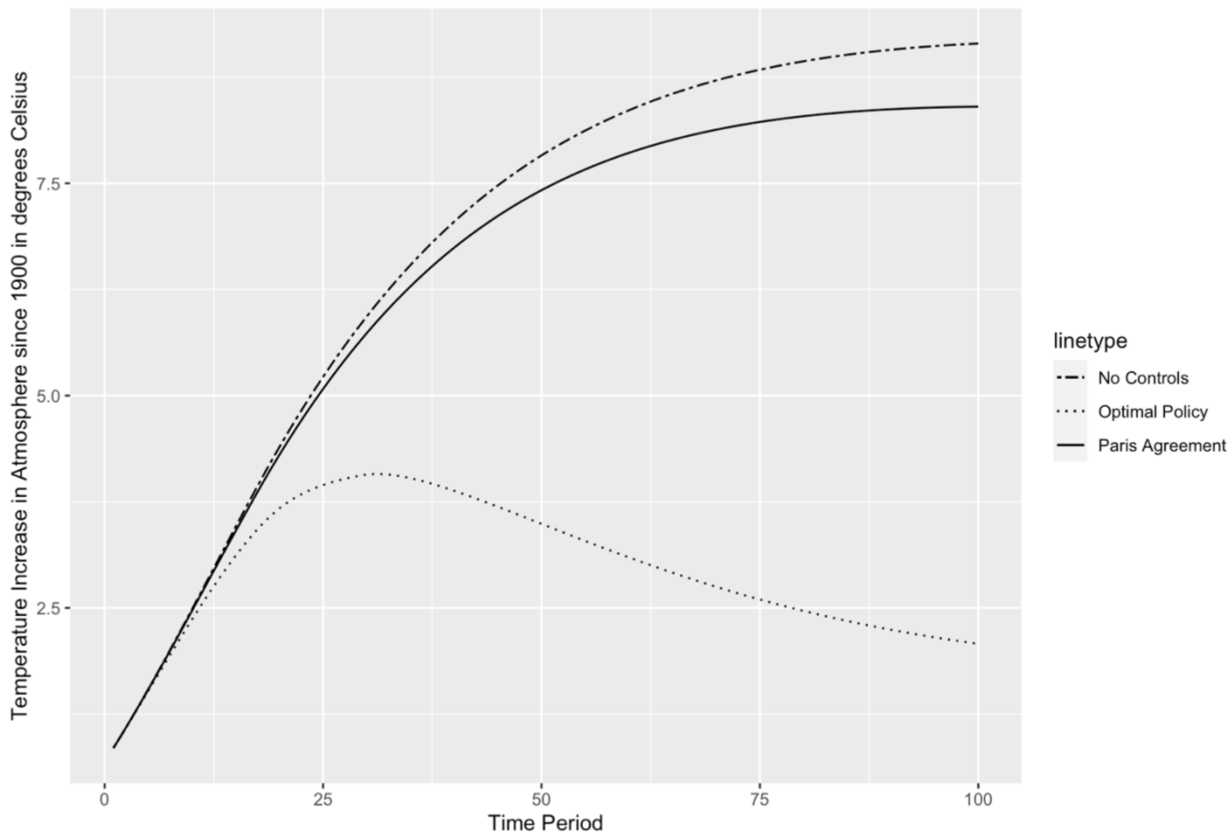

Figure 1.1 Temperature increase in the atmosphere (in degrees Celsius) since 1900 over several policy scenarios.

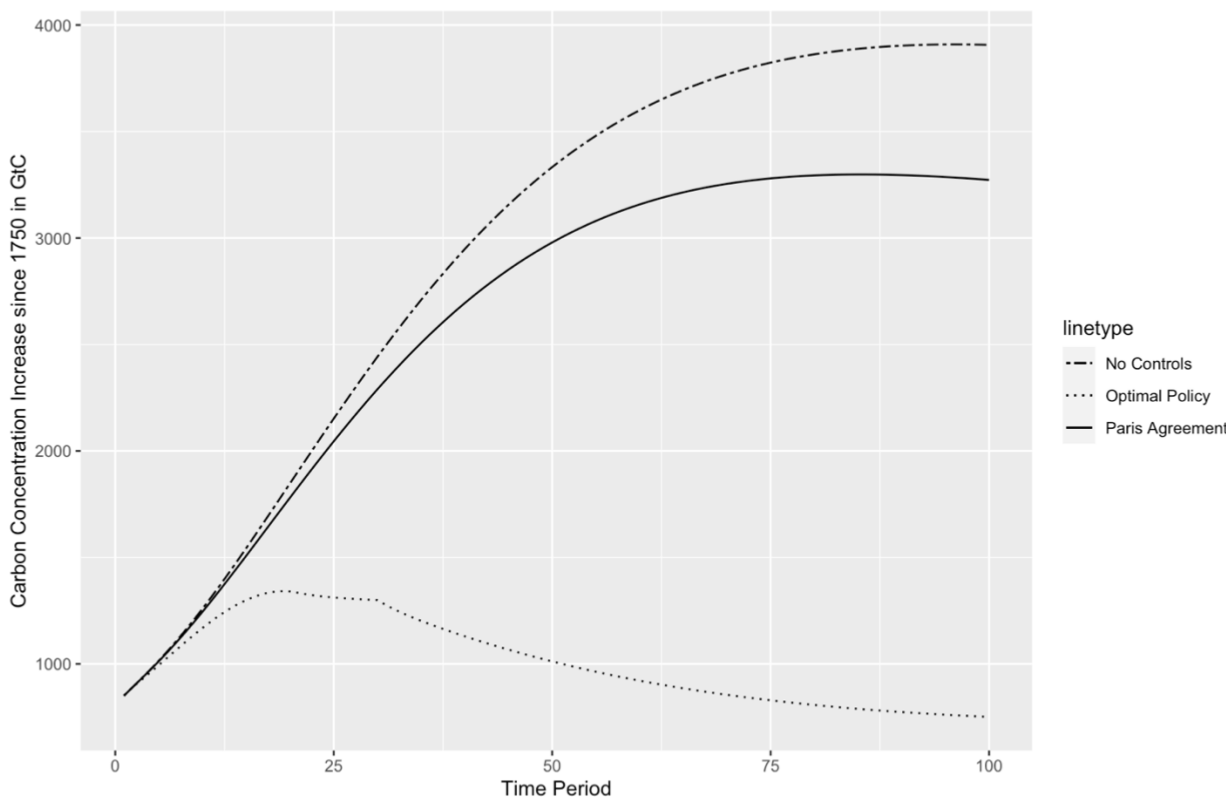

Figure 1.2 Carbon concentration increase (in GtC) since 1750.

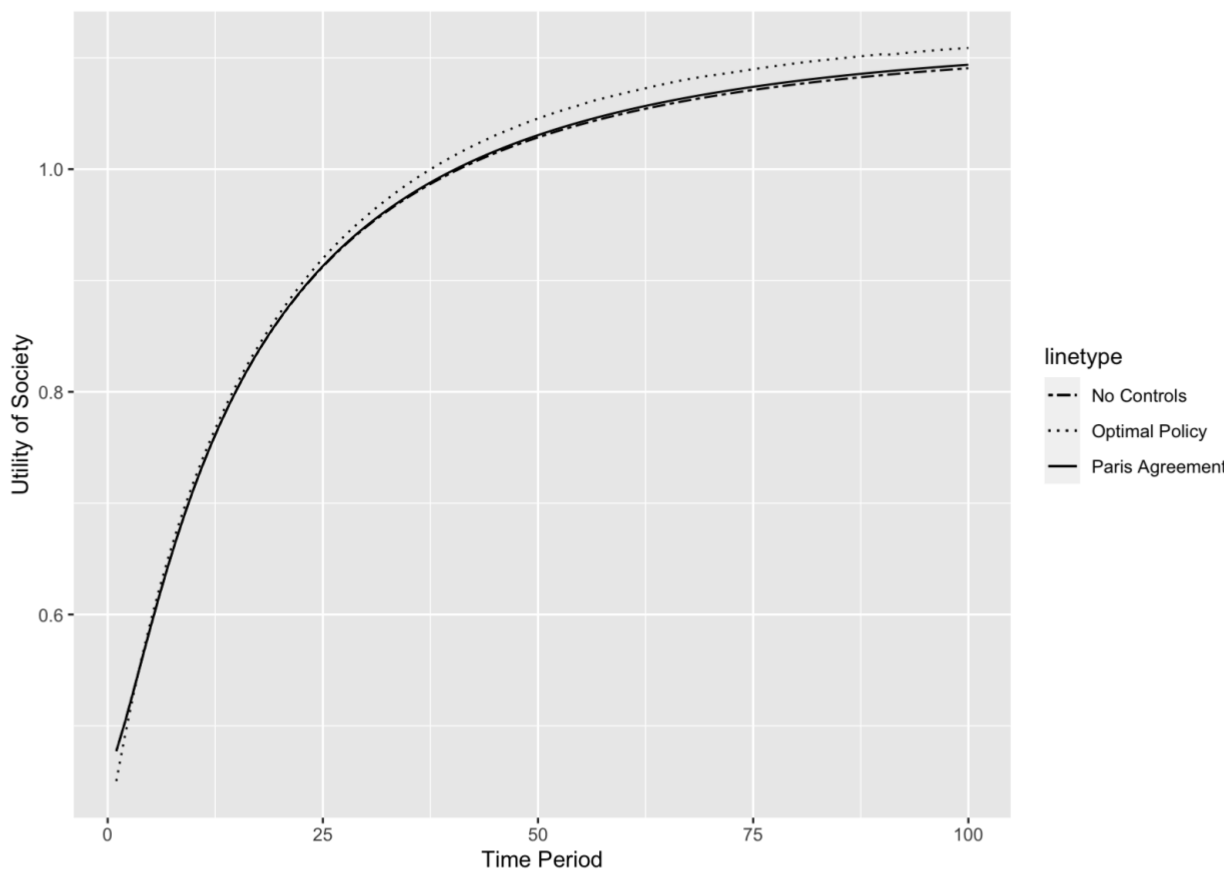

Figure 1.3 The utility of society over time.

References

Barrage, Lint and Nordhaus, William D. “Policies, Projections and the Social Cost of Carbon: Results from the DICE-2023 Model.” *National Bureau of Economic Research* no. 31112.

Goulder, Lawrence H. and Williams III, Roberton C. “The Choice of Discount Rate for Climate Change Policy Evaluation.” *National Bureau of Economic Research* Working Paper No. 18301 (2012)

Keen, Steve. “The Appallingly Bad Neoclassical Economics of Climate Change.” *Globalizations* 17, no. 8 (2020): 1303–1316.

Nordhaus, William D. *A Question of Balance: Weighing the Options on Global Warming Policies.* Yale University Press, 2007.

Nordhaus, William D. “An Optimal Path for Controlling Greenhouse Gases.” *Science* 258, no. 5086 (1992): 1315–1319.

Nordhaus, William D. “Climate Clubs: Overcoming Free-Riding in International Climate Policy.” *American Economic Review* 105, no. 4 (2015): 1339–1370.

Nordhaus, William D. “Economic Aspects of Global Warming in a Post-Copenhagen Environment.” *Proceedings of the National Academy of Sciences* 107, no. 26 (2010): 11721–11726.

Nordhaus, William D. “Economic Growth and Climate: The Carbon Dioxide Problem.” *American Economic Review* 67, no. 1 (1977): 341–346.

Nordhaus, William D. “Estimates of the Social Cost of Carbon: Concepts and Results from the DICE-2013R Model and Alternative Approaches.” *Journal of the Association of Environmental and Resource Economists* 1, no. ½ (2014): 273 – 312.

Nordhaus, William D. “Evolution of Assessments of the Economics of Global Warming: Changes in the DICE Model, 1992 – 2017.” *National Bureau of Economic Research* no. 23319 (2017).

Nordhaus, William D. *Managing the Global Commons: The Economics of Climate Change*. Cambridge, MA: The MIT Press, 1994.

Nordhaus, William D. “Global Warming Economics.” *Science* 294, no. 5545 (2001): 1283–1284.

Nordhaus, William D., and Boyer, Joseph G. “Requiem for Kyoto: An Economic Analysis of the Kyoto Protocol.” *The Energy Journal* (Special Issue) (1999): 93–130.

Nordhaus, William D., and Yang, Zili. “A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies.” *American Economic Review* 86, no. 4 (1996): 741–765.

Ramsey, Frank P. "A Mathematical Theory of Saving." *The Economic Journal* 38, no. 152 (1928): 543-559.

Solow, Robert M. *Growth Theory: An Exposition*. New York: Oxford University Press, 1970.

Stanton, Elizabeth A. “Negishi Welfare Weights: The Mathematics of Inequality.” Stockholm Environment Institute, 2009.

Stern, Nicholas, Stiglitz, Joseph, and Taylor, Charlotte. “The Economics of Immense Risk, Urgent Action and Radical Change: Towards New Approaches to the Economics of Climate Change.” *Journal of Economic Policy Reform* 25, no. 2 (2022): 136–156.