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Evolution of the Dynamic Integrated Climate-Economy (DICE) Model: Decomposition of Changes Over Time

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Evolution of the Dynamic Integrated Climate-Economy (DICE) Model: Decomposition of Changes Over Time

by

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Report

Presented to the Faculty of the Graduate School of

The University of Texas at Austin

in Partial Fulfillment

of the Requirements

for the Degree of

Master of Science in Engineering

The University of Texas at Austin

May 2018

Abstract

Evolution of the Dynamic Integrated Climate-Economy (DICE) Model: Decomposition of Changes Over Time

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Global warming is one of the major environmental challenges of the modern era. Global temperature in 2005 has increased about 0.7°C (1.3°F) compare to 1900, also CO_2 concentrations increased by 100 parts per million (ppm). Estimated expense to decrease the CO_2 concentrations by 1 ppm is about $ 1 trillion (Pielke, 2009).

Overcoming global warming is difficult because it is interdisciplinary problem and involves many parts of society. Any proposed policies must balance the economic costs of operations today and future corresponding economic and environmental benefits. There are several studies and models which used economics and mathematical modeling to analyzed the efficiency of different approaches and policies to slowing global warming.

Dynamic Integrated model of Climate and the Economy (DICE) model uses economics and mathematical modeling to analyzed the efficiency of different approaches and policies to slow global warming (William D. Nordhaus, 1994, 2008, 2017, 2017a; William D. Nordhaus & Boyer, 2000). The main distinguishing feature of the DICE model is connecting economy and climate change factors including the carbon cycle, radiative

forcing equation, climate change equations, and climate damage relationship. DICE finds optimal emissions control rate by balancing abatement costs of reducing emissions, and economic growth due to avoiding future climate damages.

DICE-2016 shows following results under optimal emissions reduction policy, emissions reduction rate for CO_2 is increasing to 36 percent by 2050 and 84 percent by 2100 relative to the baseline. Corresponding, CO_2 concentrations is decreased and increase in global temperature relative to 1900 is decreased to 6.17°F (3.43°C) for 2100 and 6.96°F (3.87°C) for 2200. The net present value abatement cost and climate damages of the optimal policy is $42.6 trillion beneficial relative to no control. This includes $20.4 trillion of abatement costs and $63 trillion of reduced climatic damages. There is still $81.8 trillion climate damage even after taking optimal policy.

We compared the outputs of DICE-2016 and DICE-2007 to understand the economic effect of climate change and how climate changing is modeled in these two models. By comparing these models, we obtained estimated economical abatement costs to reduce emissions, social cost of carbon, and impact of climate change and global warming on the economy. We were trying to identify which changes have the most effect on the difference between these two models.

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Chapter 1: Introduction

Global warming is one of the major environmental challenges of the modern era. Overcoming global warming is difficult because it crosses many discipline and parts of society. Any proposed policies must level the economic costs of operations today and future corresponding economic and environmental benefits. However, there is no obvious answer on how fast governments should take actions to slow climate change.

CO_2 emissions change the Earth's carbon cycle which increase CO_2 concentration in atmosphere (IPCC, 2007a). Global temperature in 2005 has increased about 0.7°C (1.3°F) compare to 1900, also CO_2 concentrations increased by 100 parts per million (ppm). Intergovernmental Panel on Climate Change estimates the Earth is warmed from 1.8 to 4°C over coming century (IPCC, 2007a, 2007b, 2014). Estimated expense to decrease the CO_2 concentrations by 1 ppm is about $ 1 trillion (Pielke, 2009).

It is efficient to invest on more intensive emissions reductions since climate damages are estimated to increase relative to output in the coming decade(William D. Nordhaus, 2007). There are several studies and models which used economics and mathematical modeling to analyzed the efficiency of different approaches and policies to slowing global warming. One of these models which is comprehensive model of the economy and climate is called DICE, for Dynamic Integrated model of Climate and the Economy (William D. Nordhaus, 2017, 2017a). There are seven versions of modeling efforts, many of the equations and details have change among different versions, however the basic modeling philosophy remains same (William D. Nordhaus, 1994, 2008, 2017, 2017a; William D. Nordhaus & Boyer, 2000).

This report inspects the economic impact of climate change by using DICE-2016 model under proposed policies. Also, we compared the outputs of DICE-2016 and previous version DICE-2007 to understand the economic effect of climate change and how climate changing is modeled in these two models. By comparing these models, we obtained estimated economical abatement costs to reduce emissions, social cost of carbon, and impact of climate change and global warming on the economy. We were trying to identify which changes have the most effect on the difference between these two models. Chapter 2 describes the DICE model in detail, Chapter 3 presents the alternative policies and numerical results of these policies containing the economic impacts, the carbon prices, greenhouse gas concentrations, and temperature changes. Chapter 4 provides introductory results on the impacts of uncertainty on policies and outcomes. Chapter 5 compares the outputs of DICE-2016 and DICE-2007 and investigates the differences between these two versions of DICE model.

Chapter 2: Description of the DICE Model

DICE model was one of the integrated assessment models for climate changes, that published by Nordhaus(William D. Nordhaus, 1992, 1994). The latest version was published in 2016 (William D. Nordhaus, 2017, 2017a) with complete description of previous model (William D. Nordhaus & Sztorc, 2013). DICE series are models of economics of global warming, there are reginal models which called RICE (William D. Nordhaus, 2010; William D. Nordhaus & Yang, 1996). The DICE sees the climate change from economic growth theory perspective (William D Nordhaus, 2014).

Ramsey model is a standard optimal growth model that governments invest in capital goods, decreasing consumption today, in order to increasing consumption in future(Koopmans, 1965; Ramsey, 1928). The DICE model added climate investment to Ramsey model as capital investments in standard model. the model includes all components from economics through climate change to damages. The DICE model connects the economic growth factors, CO_2 emissions, the carbon cycle, climate change, climate damages, and climate change policies. Most of the variables in this model are endogenous including world output and capital stock, CO_2 emissions and concentrations, global temperature change, and climate damages. The decision variables in DICE-2016 are annual CO_2 emissions control rate and gross savings rate as fraction of gross world product.

The main distinguishing feature of the DICE model is connecting economy and climate change factors including the carbon cycle, radiative forcing equation, climate change equations, and climate damage relationship. DICE finds optimal emissions control by leveling emissions reduction, abatements costs, and economic growth. DICE can find optimal emissions control while we have limited temperature's increase to certain point. The DICE model just considers industrial CO_2 as endogenous GHG and other sources of

CO_2 emissions like land-use are included exogenously in radiative forcing part of model. Model assumes three reservoirs for carbon cycle: the atmosphere, upper oceans and the biosphere, and the deep oceans.

2.1 OBJECTIVE FUNCTION

The DICE model is designed to optimize the flow of consumption over time. Consumption includes market goods and services, and nonmarket items such as health status and leisure. We maximized a social welfare function which is the discounted sum of population-weighted utility of per capita consumption which represented in equation (1). Equation (2) shows utility function in one period, (3) represents average utility social discount rate, and (4) level of population and labor.

(1) $$welfare = scale2 + t * scale1 * \sum_{t=1}^{Tmax} PERIODU(t) * L(t) * rr(t)$$

(2) $$PERIODU(t) = \frac{\left(C(t)*\frac{1000}{L(t)}\right)^{1-elasmu} - 1}{1-elasmu} - 1$$

(3) $$rr(t) = \frac{1}{(1+prstp)^{(t-1)*tstep}}$$

(4) $$L(t+1) = L(t) * \left(\frac{popasym}{L(t)}\right)^{popadj}$$

t are time periods and $tstep$ is years per period in this report we assumed 5 years, $scale1$ is multiplicative scaling coefficient (0.0302), $scale2$ is additive scaling coefficient (-10993.704). $elasmu$ is elasticity of marginal utility of consumption 1.45, $prstp$ is Initial rate of social time preference per year 0.015, $popasym$ is asymptotic population (11500 million), $popadj$ is growth rate to calibrate to 2050 pop projection (0.134).

2.2 ECONOMIC VARIABLES

This set of equations provides the world output over time. Purchasing-power-parity (PPP) exchange rates is used to measure outputs. Equation (5) Output gross trillion 2005

USD, equation (8) output net of damages, (9) output net, (10) consumption, (11) per capita consumption, (12) saving rate, (13) capital balance.

(5) $$YGROSS(t) = \left(al(t) * \left(\frac{L(t)}{1000}\right)^{1-GAMA}\right) * (K(t)^{GAMA})$$

(6) $$al(t+1) = \frac{al(t)}{1-ga(t)}$$

(7) $$ga(t) = ga0 * \exp\big(-dela * 5 * (t-1)\big)$$

(8) $$YNET(t) = YGROSS(t) * \big(1 - DAMFRAC(t)\big)$$

(9) $$Y(t) = YNET(t) - ABATECOST(t)$$

(10) $$C(t) = Y(t) - I(t)$$

(11) $$CPC(t) = 1000 * \frac{C(t)}{L(t)}$$

(12) $$I(t) = S(t) * Y(t)$$

(13) $$K(t+1) = (1-dk)^{tstep} * K(t) + tstep * I(t)$$

$al(t)$ is level of total factor productivity, $ga(t)$ is growth rate of productivity, $GAMA$ is capital elasticity in production function (0.3), $ga0$ is an initial growth rate for TFP per 5 years (0.076), $dela$ is Decline rate of TFP per 5 years (0.005).

2.3 EMISSIONS AND DAMAGES

Equation (14) shows emissions ($GtCO_2$ per year), (15) industrial emissions ($GtCO_2$ per year), (16) radiative forcing equation (watts per m^2 from 1900), (17) equation for damages as fraction of gross output, (18) damage equation (trillion 2005 USD per year), (19) cost of emissions reductions (trillion 2005 USD per year) which is proportional to global output and to a polynomial function of reduction rate, (20) carbon price equation from abatement (2005$ per ton of CO2).

(14) $$E(t) = EIND(t) + etree(t)$$

(15) $$EIND(t) = sigma(t) * YGROSS(t) * \big(1 - MIU(t)\big)$$

(16) $$FORC(t) = fco22x * \left(\left(\frac{\log\left(\left(\frac{MAT(t)}{588} \right) \right)}{\log(2)} \right) \right) + forcoth(t)$$

(17) $$DAMFRAC(t) = \left(a1 * TATM(t)\right) + (a2 * TATM(t)^{a3})$$

(18) $$DAMAGES(t) = YGROSS(t) * DAMFRAC(t)$$

(19) $$ABATECOST(t) = YGROSS(t) * cost1(t) * (MIU(t)^{expcost2})$$

(20) $$CPRICE(t) = pbacktime(t) * (MIU(T)^{expcost2-1})$$

(21) $$sigma(t+1) = sigma(t) * \exp(gsig(t) * tstep)$$

(22) $$gsig(t+1) = gsig(t) * ((1 + dsig)^{tstep})$$

(23) $$etree(t) = eland0 * (1 - deland)^{t-1}$$

(24) $$forcoth(t) = fex0 + \left(\frac{1}{17}\right) * (fex1 - fex0) * (t-1)I(t < 18) + (fex1 - fex0)I(t \geq 18)$$

(25) $$cost1(t) = pbacktime(t) * \frac{\frac{sigma(t)}{expcost2}}{1000}$$

(26) $$pbacktime(t) = pback * (1 - gback)^{t-1}$$

$etree(t)$ is emissions from deforestation, $MIU(t)$ is emission control rate GHGs, $sigma(t)$ is CO2-equivalent-emissions output ratio, $fco22x$ is forcing of equilibrium CO2 doubling (Wm-2) (3.6813), $forcoth(t)$ is exogenous forcing for other greenhouse gases, $a1, a2, a3$ are damage intercept, quadratic term, and exponent (0,0.00236,2), $expcost2$ is exponent of control cost function (2.6), $cost1$ is adjusted cost for backstop , $gsig(t)$ is change in sigma (cumulative improvement of energy efficiency), $dsig$ is decline rate of decarbonization (per period) (-0.001), $eland0$ is carbon emissions from land 2015 (GtCO2 per year) (2.6), $deland$ is decline rate of land emissions (per period) (0.115), $fex0$ is 2015 forcing of non-CO2 GHG (Wm-2) (0.5), $fex1$ is 2100 forcing of non-CO2 GHG (Wm-2) (1), $pbacktime(t)$ is backstop price which is a technology can replace all fossil fuels. The backstop technology can remove carbon from atmosphere and starts zero carbon energy technology. It could be solar or nuclear power even as-yet undiscovered source. $pback$ is cost of backstop 2010$ per tCO2 2015 (550), $gback$ is initial cost decline backstop cost per period (0.025).

2.4 CLIMATE AND CARBON CYCLE

This set of equations connect economic and greenhouse gas emissions to carbon cycle. Equation (27) shows atmospheric concentration, (28) lower ocean concentration, (29) shallow ocean concentration, (30) temperature-climate equation for atmosphere, (31) temperature-climate equation for lower oceans.

(27) $$MAT(t+1) = MAT(t) * b11 + MU(t) * b21 + \left(E(t) * \left(\frac{5}{3.666}\right)\right)$$

(28) $$ML(t+1) = ML(t) * b33 + MU(t) * b23$$

(29) $$MU(t+1) = MAT(t) * b12 + MU(t) * b22 + ML(t) * b32$$

(30) $$TATM(t+1) = TATM(t) + c1 * \left(\left(FORC(t+1) - \left(\frac{fco22x}{t2xco2}\right) * TATM(t)\right) - \left(c3 * \left(TATM(t) - TOCEAN(t)\right)\right)\right)$$

(31) $$TOCEAN(t+1) = TOCEAN(t) + c4\left(TATM(t) - TOCEAN(t)\right)$$

$b11$ is the carbon fraction that will be remained in atmosphere between two periods (0.88), $b12$ is fraction of carbon goes from atmosphere to upper ocean between two periods (0.12), $b22$ is the carbon fraction that will be remained in upper ocean between two periods (0.797), $b21$ is fraction of carbon goes from upper ocean to atmosphere between two periods (0.196), $b23$ is fraction of carbon goes from upper ocean to lower ocean between two periods (0.007), $b33$ is the carbon fraction that will be remained in lower ocean between two periods (0.999), $b32$ is fraction of carbon goes from lower ocean to upper ocean between two periods (0.001), $c1$ is climate equation coefficient for upper level

(0.1005), $c3$ is transfer coefficient upper to lower stratum (0.088), $c4$ is transfer coefficient for lower level (0.025).

Chapter 3: Alternative Policies and Their Results

3.1 POLICIES

We investigated alternative policies in the DICE model. The baseline policy is a world in which there are no control over time. The next policy is the economic optimal, in which we maximized the discounted value of utility which is welfare. The next three have limitation on global temperature increases.

No policies or actions are taken to slow or reverse global warming and emissions in the first policy. Governments take no actions to prevent greenhouse gas emissions. Optimal case tries to find the economically efficient to slow climate change, no noneconomic constraints are considered in this case. This case fins the emission reduction which levels current abatement costs opposed to future damages from global warming. We can use this model as benchmark since it is the best solution for emissions reduction given assumed climate, economy and technology.

Climate constraints cases are similar to optimal case, only global temperature increasing is bounded to be less than a given upper limit. We consider three subcases: temperature increase is limited to 2.5, 3, and 3.5°C (from 1900 levels). These cases try to evaluate how costly it would be to add these temperature threshold constraints to economic optimal analysis. These cases focus on climate change against other policies such emissions and concentrations limits.

3.2 RESULTS

The overall results for all policies are shown in Table 1. The first column shows discounted value of the utility which is the present value of consumption under each policy. The next three columns show the present value of climate damages, abatement costs, and summation of the present value of climate damages and abatement costs (total cost).

Present value of climate damages under baseline policy is $144.8 trillion 2005 U.S. dollars. Economical optimal case causes $81.78 trillion for climate damages ($63 trillion reduce compare to baseline) and $20.38 trillion for abatement cost, so $102.2 trillion total cost. The fifth and sixth columns presents carbon price for each policy. The social coast of carbon is the present value of the stream of damages over time resulting from the emission of one ton of CO2 to the atmosphere. The last three columns present global mean temperature increase from 1900. The maximum temperature increase under baseline policy is 8.8°C (15.92°F) which happens in 2400. Maximum temperature change is 4°C (7.21°F) under optimal regime which occurs in 2165. Limited temperature to 2.5°C incurs $36.85 trillion less in climate damages and $102.92 trillion more in abatement cost compare to optimal regime. Limited temperature to 3°C increases climate damage by $13.51 trillion and decreases abatement cost by $60.96 trillion compare to 2.5°C.

The optimal case has considerable welfare 4456 . Table 2 presents added cost of adding climate constrains on top of optimal cases. Bounding the temperature to 2.5 degrees is extremely costly. This shows only specific policy of emissions reduction is economically acceptable, like limiting temperature to 3.5°C which has low added price, as shown in Table 2.

	Welfare	PV Climate Damages	PV Abatement Costs	PV Total Costs	Social Cost of Carbon		Global Temperature Change		
					2025	2100	2100	2200	Max
Policies		Trillion of 2005 U.S. $			2005 U.S, $/$TCO_2$		°F from 1900		
No Control	4405	$0	$145	$145	$0	$0	7.44	12.66	15.92
Optimal	4456	$82	$20	$102	$43	$268	6.17	6.96	7.21
L2.5°C	4392	$45	$123	$168	$229	$357	4.13	4	4.5
L3°C	4438	$58	$62	$120	$95	$357	4.95	4.98	5.4
L3.5°C	4453	$71	$35	$106	$57	$357	5.67	5.96	6.3

Table 1: Results of the DICE-2016 Model

	PV Climate Damages	PV Abatement Costs	PV Total Costs
Policy		Trillion of 2005 U.S. $	
L2.5C	-$36.85	$102.87	$66.02
L3C	-$23.33	$41.96	$18.63
L3.5C	-$10.99	$14.26	$3.27

Table 2: Incremental Costs Caused by adding Climate Constraints to Optimal

Table 3 presents the increasing abatement costs, damages, and benefit cost ratio for alternative policies. Any policy with ratio less than one has negative value against to no reduction policy. Figure 1 shows the social cost of carbon corresponding to alternative policies. Optimal case postpones the high carbon price to the future. Emissions control rate for alternative policies are shown in Figure 2. DICE-2016 shows we need to reach 100% emissions rate before 2110 in all policies, whereas we needed to reach 44% for optimal and 54% for limit temperature to 3°C policy in DICE-2007. Optimal case starts with 18.5 percent and climb slowly over next periods. Climate constraints cases begin with low rate then increase sharply between 40 and 100 percent by midcentury.

	Benefit (Reduced Damages Costs)	Abatement Costs	Benefit-Cost Ratio
Policy	Trillion of 2005 U.S. $		
Optimal	63.0	20.4	3.1
Limit to 2.5°C	99.8	123.3	0.8
Limit to 3°C	86.3	62.3	1.4
Limit to 3.5°C	74.0	34.6	2.1

Table 3: Abatement Costs and Damages Compare to Baseline, and Benefit-Cost Ratio

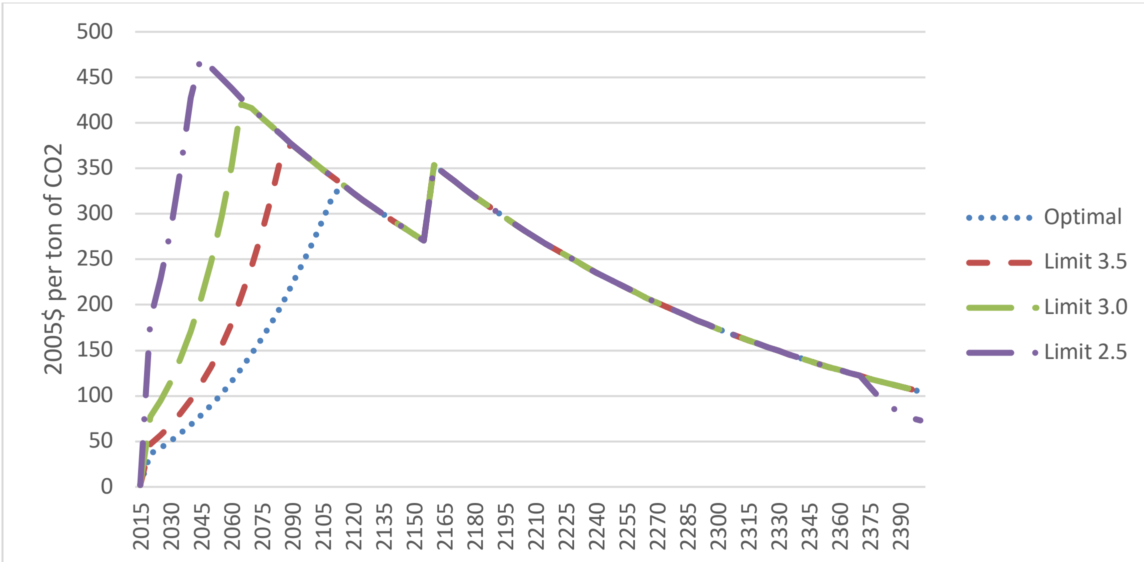

Figure 1: Social Cost of Carbon for different Policies

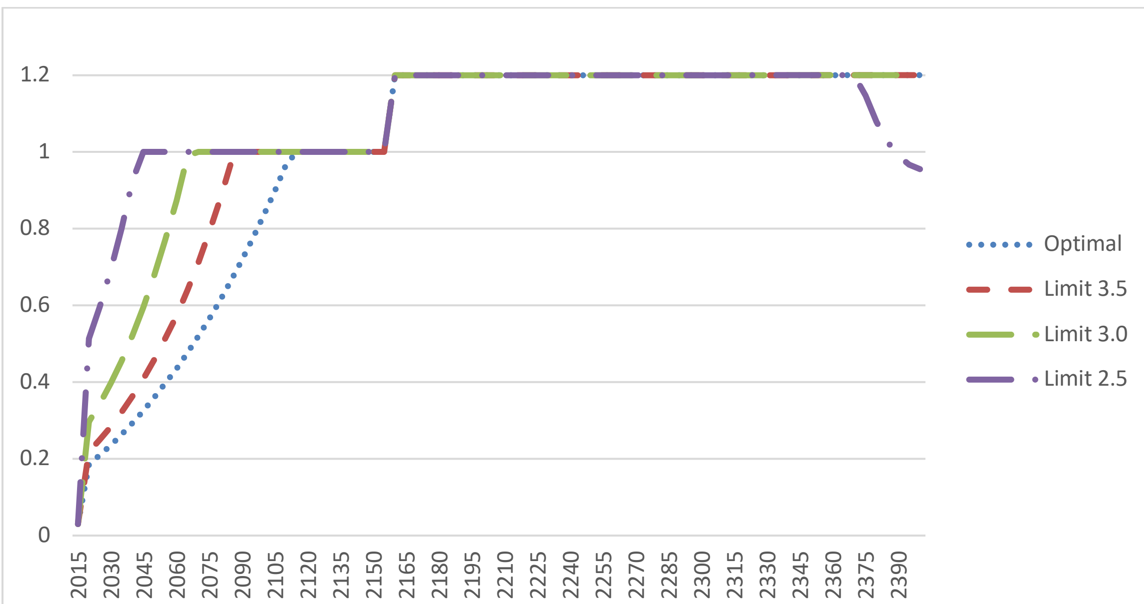

Figure 2: Emissions Control Rates for Alternative Polices

Figure 3 and 4 show CO_2 emissions and atmospheric concentrations of CO_2 respectively. Global temperature increase in atmosphere is shown in Figure 5.

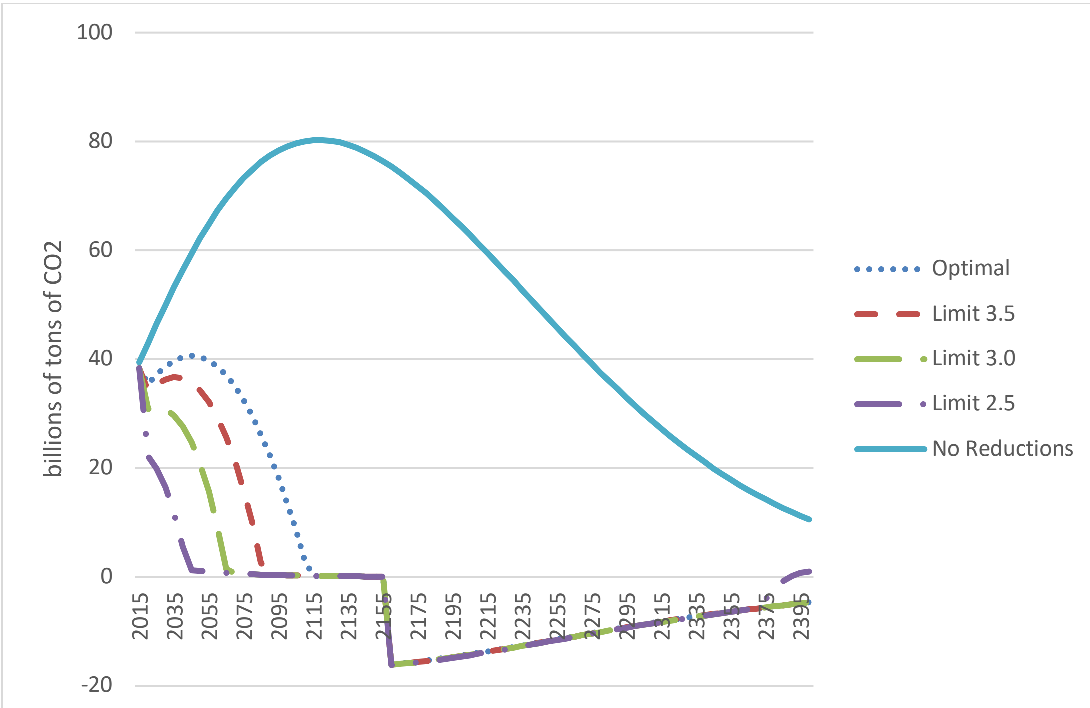

Figure 3: CO2 Emissions for Alternative Policies

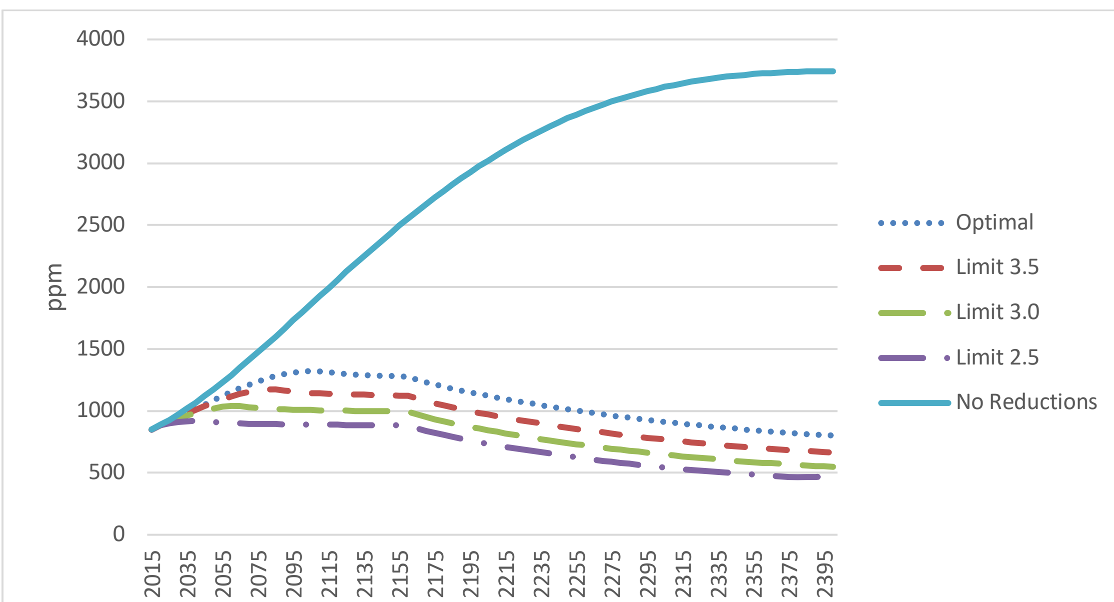

Figure 4: Atmospheric CO2 Concentrations for Different Policies

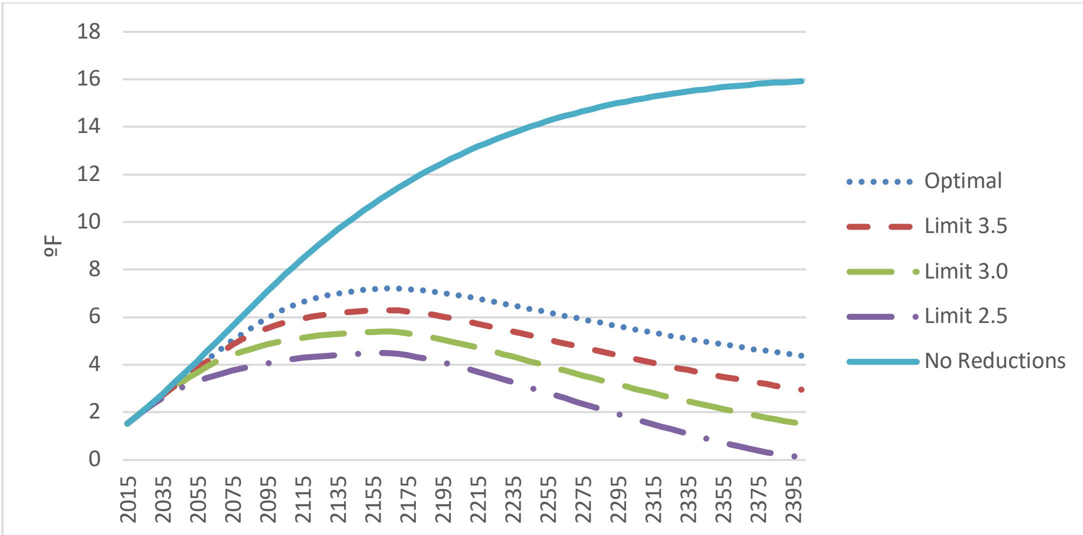

Figure 5: Global Temperature Increase for Alternative Policies

Chapter 4: Uncertainty in Policies

The uncertainty is stemmed from incomplete knowledge of exogenous variables and system. Recognizing the manageable parameters, estimating the distribution of each parameter, and evaluating the impact of each parameter are the main purpose of uncertainty analysis. We have chosen seven major parameters in the DICE model for applying uncertainty analysis based on previous studies (Eric Bickel, 2013; William D. Nordhaus, 2008). Previous studies showed following parameter have the major effect on outcomes: the growth rate of total factor productivity, rate of decarbonization, asymptotic population, initial cost of backstop technology, retention rate of CO_2 in atmosphere, climate sensitivity, quadratic damage parameter. We have assumed the independent probability distribution for each parameter which are shown in Table 4. All the parameter has independent normal distribution except climate sensitivity. IPCC estimated that climate sensitivity is between 2°C and 4°C by 66% probability and less than 1.5°C by only 10% probability, so we assumed climate sensitivity has lognormal distribution with mean 3.1°C and standard deviation of 1.5°C. P10 and P90 in Table 4 show the value for each variable such that probability of input be above the showed value is 10% and 90% respectively.

Parameters	Units	Mean	Standard deviation	P90	P10
Growth rate of factor productivity	Per year	0.076	0.004	0.0709	0.0811
Rate of decarbonization	Per year	-0.001	0.00027	-0.0013	-0.0007
Asymptotic population	Million	11500	1892	9075	13925
Initial cost of backstop technology	2005$ per ton of carbon	550	220	268	832
Retention rate of CO_2 in atmosphere	fraction	0.88	0.017	0.86	0.90
Climate sensitivity	°C per CO_2 doubling	3.1	1.5	3.25	5.02
Quadratic damage parameter	$trillion per square of °C	0.002	0.0013	0.0003	0.0037

Table 4: Assumption about Uncertainty

Figure 6 represents a tornado diagram of the effect of each uncertainty on total cost for optimal regime, low represents p10 and high represents p90. This diagram is centered at $102 trillion which equals to estimated total cost under optimal regime when all input parameters are set to original values. Figure 6 shows the impact on total cost by changing one variable at a time and hold the others constant. For example, if climate sensitivity is 3.25°C and other variables equal to base case then total cost is almost $60.09 trillion. If climate sensitivity is 5.02°C, total cost will be approximately $171.6 trillion which a range of $111 trillion. Therefore, the chance that climate sensitivity is between 3.25°C and

5.02°C is 80% and there is 80% chance that total cost is between $60 trillion and $171.6 trillion.

Figure 7 shows the sensitivity analysis of maximum temperature change under optimal regime, which is centered at 7.21°C. Climate sensitivity has main effect on uncertainty analysis then quadratic damage parameter and asymptotic population. moreover, cost of backstop technology and growth rate of total factor productivity have a very minor effect.

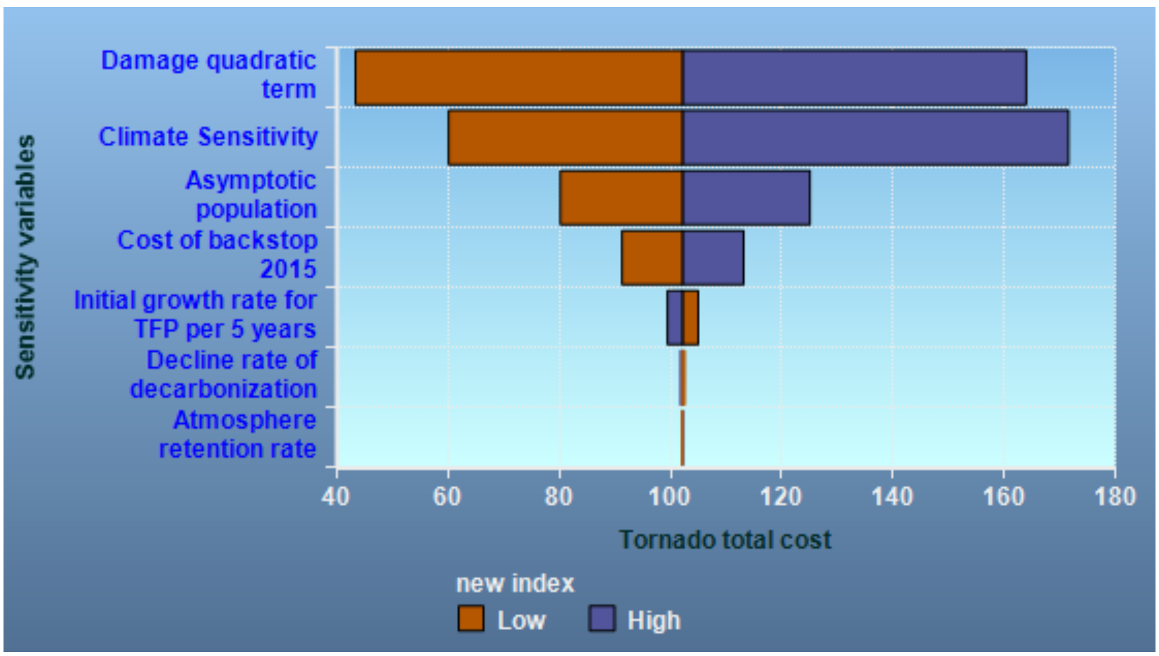

Figure 6: Sensitivity Analysis of Total Costs for Optimal Case

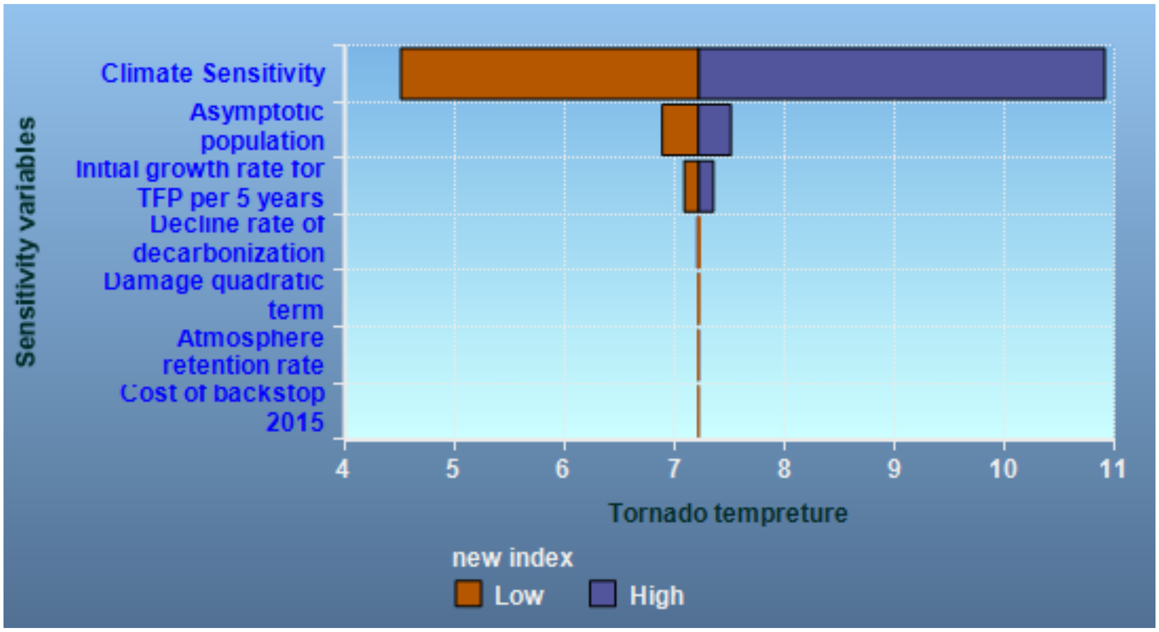

Figure 7: Sensitivity Analysis of Maximum Temperature Change for Optimal Case

Chapter 5: Comparing DICE-2016 and DICE-2007

We compared the outputs of DICE-2016 and DICE-2007 to understand the economic effect of climate change and how climate change is modeled in these two models. By comparing these models, we obtained estimated economical abatement costs to reduce emissions, social cost of carbon, and impact of climate change and global warming on the economy. We compared DICE-2007 and DICE-2016 under optimal controls and the no reduction policies. We were trying to identify which changes have the most effect on the difference between these two models.

5.1 DICE MODEL CHANGES

Some of the equations and details have changed between these two versions of DICE to align model with improved understanding of the economics of the climate change. However the basic modeling philosophy remains same. These changes include two types of changes parameters and structural changes.

5.1.1 Parameters Changes

In DICE-2007 the elasticity of consumption was 2.0 instead of 1.45, which is used in DICE-2016. DICE-2016 used 7403 million for world population in 2015 and 11500 million as the asymptotic population, while DICE-2007 estimated 2015 population for 7130 million and 8600 million for the asymptotic population. 2015 factor productivity is 5.115 in DICE-2016 and is estimated for 0.03 in DICE-2007. 2015 factor productivity growth rate and decrease in factor productivity growth rate are 0.076 and 0.005 in DICE-2016 and are estimated for 0.091 and 0.001 in DICE-2007. Rate of decarburization is 0.001 in 2016 model and 0.073 in 2007 model. The rest of the parameter changes are shown in

Table 5 which represents DICE-2016 and DICE-2007 values and how much DICE-2007 would be changed if we feed 2016 inputs.

5.1.2 Structural Changes

Structural equations that changed from DICE-2007 include population, CO2-equivalent-emissions output ratio, backstop price, exogenous forcing for other greenhouse gases, carbon concentration increase in atmosphere, gross world product GROSS of abatement and damages, damages, cost of emissions reductions, output net of damages equation, and investment. DICE-2007 formulas for these variables are shown as follows.

pop_{05} is population in 2005 and $pop_g(t)$ is population growth rate. $sigma_g(t)$ is growth rate of CO2-equivalent-emissions output ratio. $backrat$ is ratio initial to final backstop cost. ext_F_05 is exogenous forcing for other greenhouse gases in 2005. ext_F_max is maximum exogenous forcing. ext_F_Time is decades to reach maximum exogenous forcing. $Abatement\_cost\_frac(t)$ is abatement cost as fraction of output. $saving\_r$ is saving rate of capital.

(32) $$L(t) = pop_{05} * \left(1 - pop_g(t)\right) + popasym * pop_g(t)$$

(33) $$sigma(t+1) = \frac{sigma(t)}{1 - sigma_g(t+1)}$$

(34) $$pbacktime(t) = pback * \left(\frac{\left(backrat - 1 + \exp\left(-gback * (T-1)\right)\right)}{backrat}\right)$$

(35) $$forcoth(t) = MIN(ext\_F\_05 + (ext\_F\_max - ext\_F\_05)/ext\_F\_Time * (T-1), ext\_F\_max)$$

(36) $$MAT(t+1) = MAT(t) * b11 + MU(t) * b21 + (E(t) * 5)$$

(37) $$YGROSS(t) = (al(t) * (L(t))^{1-GAMA}) * (K(t)^{GAMA})$$

(38) $$DAMAGES(t) = YGROSS(t) * (1 - \frac{1}{1 + DAMFRAC(t)})$$

(39) $$YNET(t) = YGROSS(t) - DAMAGES(t)$$

(40) $$ABATECOST(t) = YGROSS(t) * Abatement\_cost\_frac(t)$$

(41) $I(t) = saving\_r * Y(t)$

Table 5 shows how much PV total cost of DICE-2007 in optimal policy would be changed if we change the structural equations and parameter inputs according to DICE-2016 one at a time. We ordered them based on present value total cost. First row shows present value total damages (2005$ trillion) of DICE-2007 with original inputs and equations in optimal policy. We changed some parameters and equations together because they are aligned together.

5.2 COMPARING DICE-2016 AND DICE-2007 MODELS

We tried to compare the outputs of these two models and found the main differences between them. We chose 2015 through 2395 as time horizon to compare these two models. Related parameters and equations were divided to packages. Interaction between parameters and equations were considered by following this approach. Then, we changed one package at a time from 2007 to 2016 and evaluate the PV total cost in optimal regime. Then we picked the parameter or equation which has the most difference in total cost from original 2007 and kept it changed. At second step, we changed rest of packages one at a time and chose the most difference in total cost from previous changed model and kept it changed as second change. We kept going to find the order of importance of the packages.

This approach orders the packages from the most effective to the least effective. Figures 8 and 9 show how much total cost would be increased or decreased by changing packages sequentially in optimal and no reduction policy respectively. Parameters and equations with corresponding packages for this approach are shown in Table 6. MIU in these two figures are outputs of DICE-2016 as emissions control rate that added at the end of sequence. Unknown represents difference due to different time span 5 years versus 10 years, correlation between parameters and equations (we changed one parameter or equation at a time) or other reasons that we did not find.

Parameters and Equations	Parametric Structural	DICE- 2007	DICE- 2016	Changes (2005$trillion)	Order
2007		20.08			
CO2 Upper Ocean -> Atmosphere	Parametric	0.097	0.196	28.48	1
2015 Factor Productivity Gross Output	Parametric Structural	0.03 -	5.115 -	19.56	2
Elasticity of Consumption	Parametric	2	1.45	16.77	3
Decrease in Land Use Emissions	Parametric	90%	88.5%	-15.54	4
Sigma	Structural	-	-	15.37	5
CO2 Retention Rate: Atmosphere	Parametric	0.811	0.88	10.7	6
Asymptotic Population	Parametric	8600	11500	9.76	7
Concentration in Upper Ocean	Parametric	1255	460	-7.7	8
Initial Capital Stock	Parametric	137	223	7.2	9
Rate of Decarbonization	Parametric	0.003	-0.001	7.18	10
Coefficeint for Upper level	Parametric	0.22	0.101	-6.05	11
External Forcing Concentration Increase Atmosphere	Structural Structural	- -	- -	5.18	12
Quadratic Damage Parameter	Parametric	0.003	0.002	-3.05	13
Transfer Coefficient Upper to lower Stratum	Parametric	0.3	0.088	3.01	14
CO2 Retention Rate: Upper Ocean	Parametric	0.853	0.797	-2.81	15
Decrease in Factor Productivity Growth Rate	Parametric	0.001	0.005	2.53	16
Concentration in Lower Ocean	Parametric	18365	1740	-2.17	17
Population	Structural	-	-	-2.12	18
2015 Factor Productivity Growth Rate	Parametric	0.091	0.076	2.02	19
Initial Emissions from Land Use	Parametric	1.1	2.6	1.84	20
CO2 Lower Ocean -> Upper Ocean	Parametric	0.003	0.001	-1.29	21
Cost of Backstop Technology	Parametric	1.17	0.55	-1.25	22
Concentration in Atmosphere	Parametric	809	851	1.06	23
Investment	Structural	-	-	-1.02	24
Temp Change Atmosphere / Upper Ocean	Parametric	0.731	0.85	0.81	25
Exponent of control cost function	Parametric	2.8	2.6	0.72	26
Climate Sensitivity	Parametric	3	3.1	0.65	27

Table 5: DICE-2016 Changes from DICE-2007

Backstop price Initial cost decline backstop per period	Structural Parametric	- 0.05	- 0.025	-0.55	28
Transfer Coefficient for Lower Stratum	Parametric	0.05	0.025	-0.37	29
2015 World Population	Parametric	7130	7403	-0.36	30
CO2 Doubling Forcing	Parametric	3.8	3.681	-0.34	31
Climate Damages	Structural	-	-	0.26	32
Output net of damages	Structural	-	-	0.013	33
Abatement Cost	Structural	-	-	0	34

Table 5, Cont.

Fraction of carbon goes from upper ocean to atmosphere between two periods (CO2 Upper Ocean -> Atmosphere), 2015 factor productivity, and elasticity of consumption cause the largest changes between DICE-2007 and DICE-2016 as shown in Table 5. Therefore, the main changes between these two models are economical parameters and equations changes rather than climate changes.

Carbon cycle package is the most impactful changes in DICE model. Then, output and productivity are the second and third most effective packages which both are economic factors. As we see in Figure 8 most economical packages including output, productivity, capital accumulation, and population have increasing effect on total cost excluding damage function and abatement cost (connection between climate change and economy) under optimal policy. Economic factors cumulatively increase the total cost by $130.98 trillion from DICE-2007 to DICE-2016. However, climate packages including carbon stock-radiative forcing, carbon concentration, and climate model have decreasing impact on total cost excluding carbon cycle, carbon emissions. Climate factors cumulatively decrease the total cost by $78 trillion from DICE-2007 to DICE-2016.

Consequently, we can say economical packages increased the total cost and climate packages decreased the total cost. Therefore, climate damages have worse effect on economy in DICE-2016 compare to DICE-2007.

packages	Variable
Carbon Cycle	CO2 Retention Rate: Atmosphere - CO2 Upper Ocean -> Atmosphere - CO2 Retention Rate: Upper Ocean - CO2 Lower Ocean -> Upper Ocean
Carbon Emissions	Rate of Decarbonization - Initial Emissions from Land Use - Decrease in Land Use Emissions -Land Use Changes - Initial Rate - Carbon intensity 2010 - Cumulative efficiency improvement - Sigma
Output	Elasticity of Consumption -Climate Damages -Output net of damages - Abatement Cost - Adjusted cost for backstop
Productivity	2015 Factor Productivity Growth Rate - Decrease in Factor Productivity Growth Rate - 2015 Factor Productivity - Gross Output -productivity
Carbon Concentrations	Concentration in Atmosphere - Concentration in Upper Ocean - Concentration in Lower Ocean
Capital Accumulation	Investment - Savings Rate -Initial Capital Stock
Carbon Stocks -Radiative Forcing	External Forcing - Radiative Forcing - 2015 Forcing of non-CO2 GHG - 2100 Forcing of non-CO2 GHG - CO2 Doubling Forcing - Concentration Increase Atmosphere
Climate Model	Atmosphere / Upper Ocean - Coefficient for Upper level - Climate Sensitivity - Transfer Coefficient Upper to lower Stratum - Transfer Coefficient for Lower Stratum
Damage Function	Quadratic Damage Parameter
Population	2015 World Population - Asymptotic Population - Population - Growth rate to calibrate to 2050 pop projection
Abatement Cost	Cost of Backstop Technology - Exponent of control cost function -Backstop price - Initial cost decline backstop pc per decade

Table 6: Packages for Third Approach

Economic factors cumulatively increase the total cost by $210.9 trillion from DICE-2007 to DICE-2016 under no reduction policy as shown in figure 9. Moreover, Climate factors cumulatively decrease the total cost by $147.42 trillion from DICE-2007 to DICE-2016.

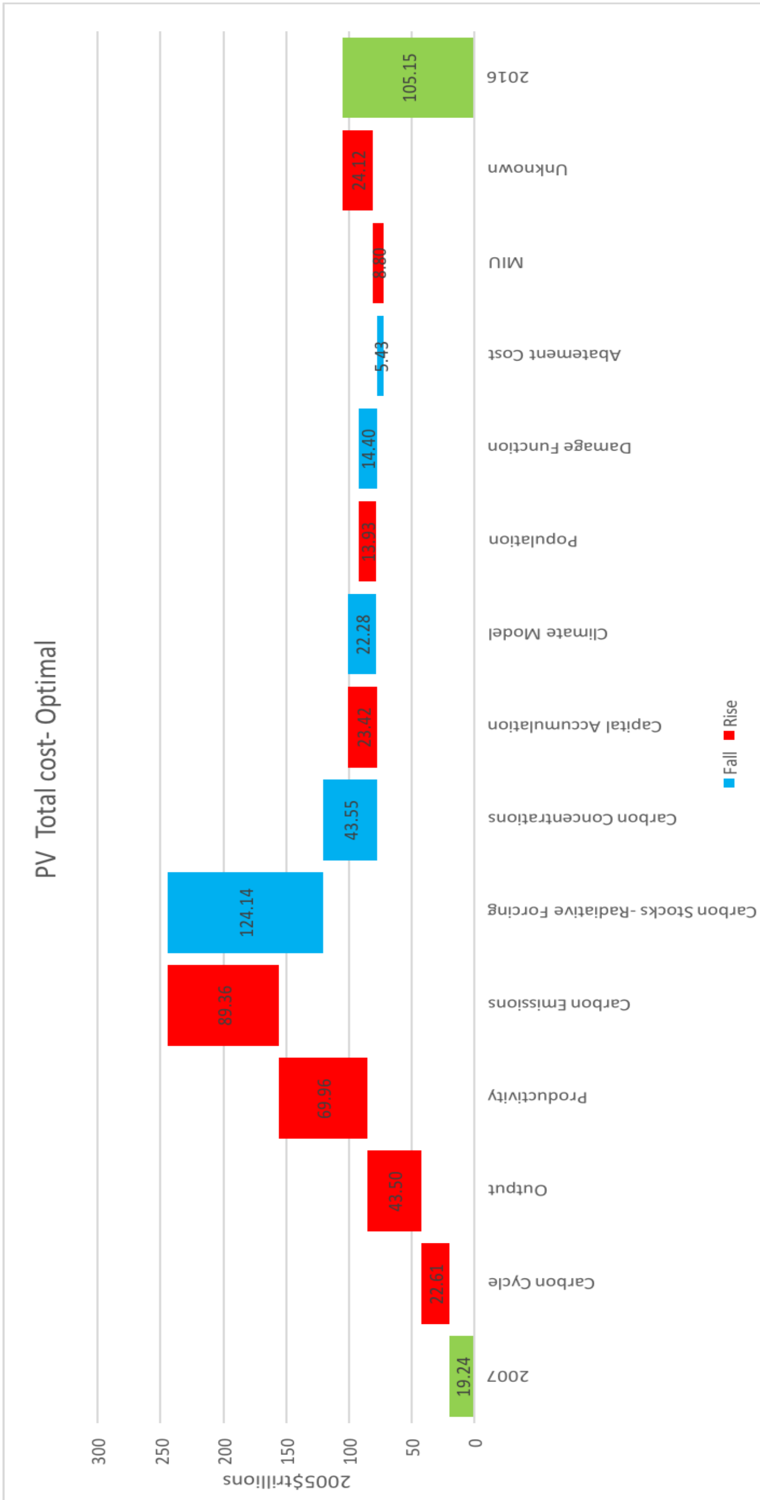

Figure 8: Waterfall of Packages - PV Total Cost of Optimal

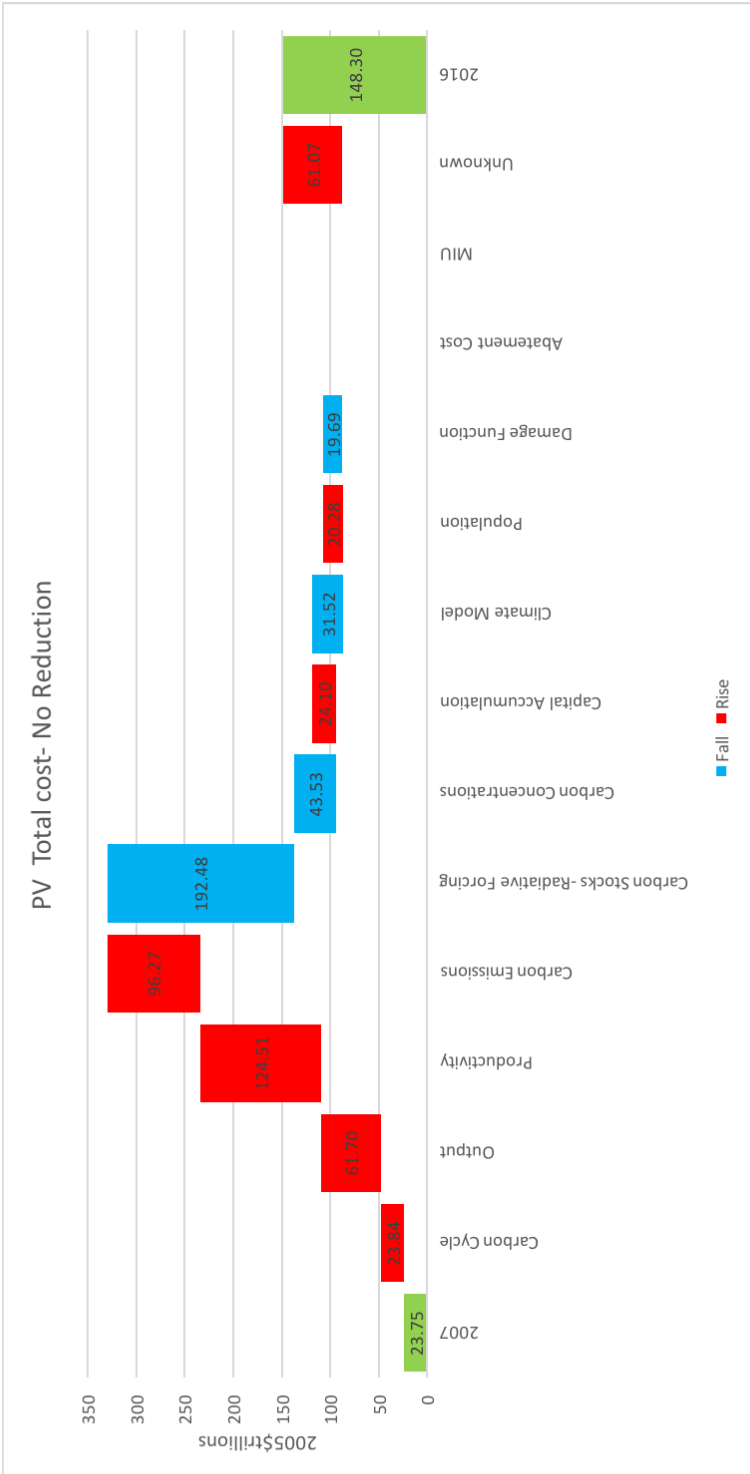

Figure 9: Waterfall of Packages - PV Total Cost of No Reduction

5.3 MODEL'S OUTPUTS DIFFERENCES

Figure 10 shows climate damages, abatement cost and total cost for DICE-2016 and DICE-2007 under optimal and no reduction regimes. Estimated values are obtained in time horizon 2015 through 2395. DICE-2007 estimated 88% of total cost is due to abatement cost as opposed to 80% in DICE-2016. Therefore, decreasing global temperature which represented by abatement cost is costlier in DICE-2007 rather than DICE-2016. Abatement cost is almost 7 times larger than climate damages in DICE-2007 compare to 4 times in DICE-2016. Therefore, we might can say decreasing global temperature which represented by abatement cost is costlier in DICE-2007 rather than DICE-2016 considering how much climate change will affect economy represented by climate damages.

However, climate damages are increased almost 9 times in DICE-2016 compare to DICE-2007 and abatement cost is increased almost 5 times. Some main reasons for this drastically changes include, changing initial factor productivity from 0.03 in DICE-2007 to 5.115 in DICE-2016 and elasticity of consumption from 2 in DICE-2007 to 1.45 in DICE-2016. These two parameters have the most impact on difference between DICE-2007 and DICE-2016 as shown in Table 5. DICE-2016 assumed there is more productive economy rather than DICE-2007, so climate damage has worse effect on economy. Moreover, discount factors are increased by changing elasticity of consumption from 2 to 1.45. Therefore, discounted climate damages and abatement cost are higher in DICE-2016

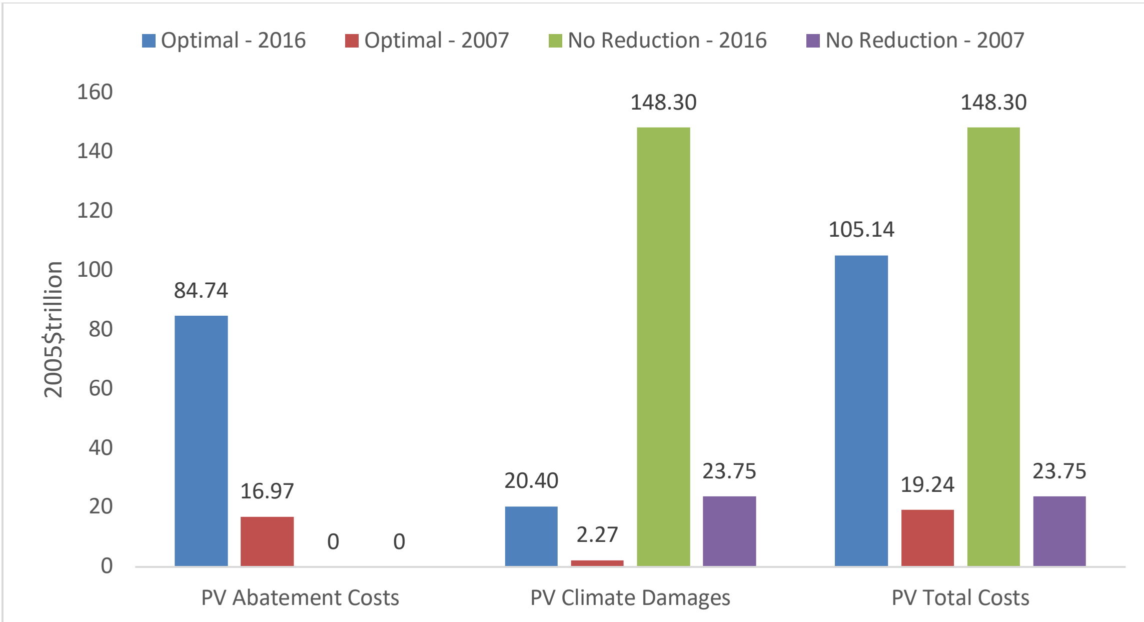

Figure 10: Changes of Cost Between DICE-2016 and DICE-2007

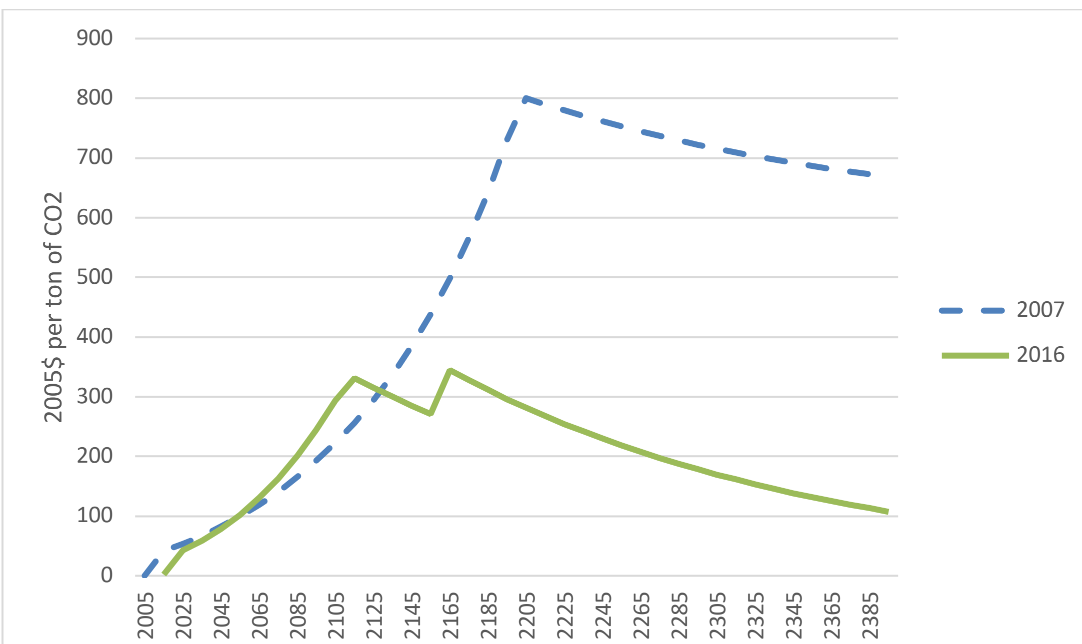

Figure 11: Changes of Social Cost of Carbon Between DICE-2016 and DICE-2007

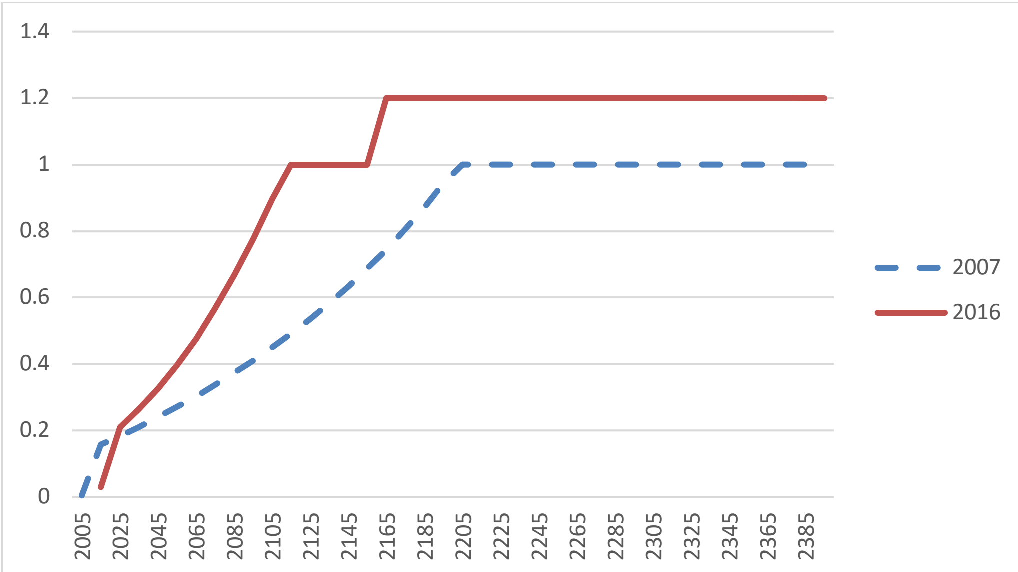

Figure 12: Changes of Emissions Control Rate Between DICE-2016 and DICE-2007 under Optimal Regime

Figure 11 represents social cost of carbon per ton of CO2 for DICE-2016 and DICE-2007. As we see DICE-2016 estimated lower carbon price, specifically carbon price of DICE-2007 is almost 4 times higher than DICE-2016 in year 2205. Moreover, carbon price was declined in both models, it is declined after year 2205 in DICE-2007 and year 2165 in DICE-2016. Figure 12 shows emissions control rate under optimal regime. DICE-2007 achieved the highest point which is 1 in year 2205, same year that carbon price started to decline, DICE-2016 achieved the highest point which is 1.2 in year 2165.

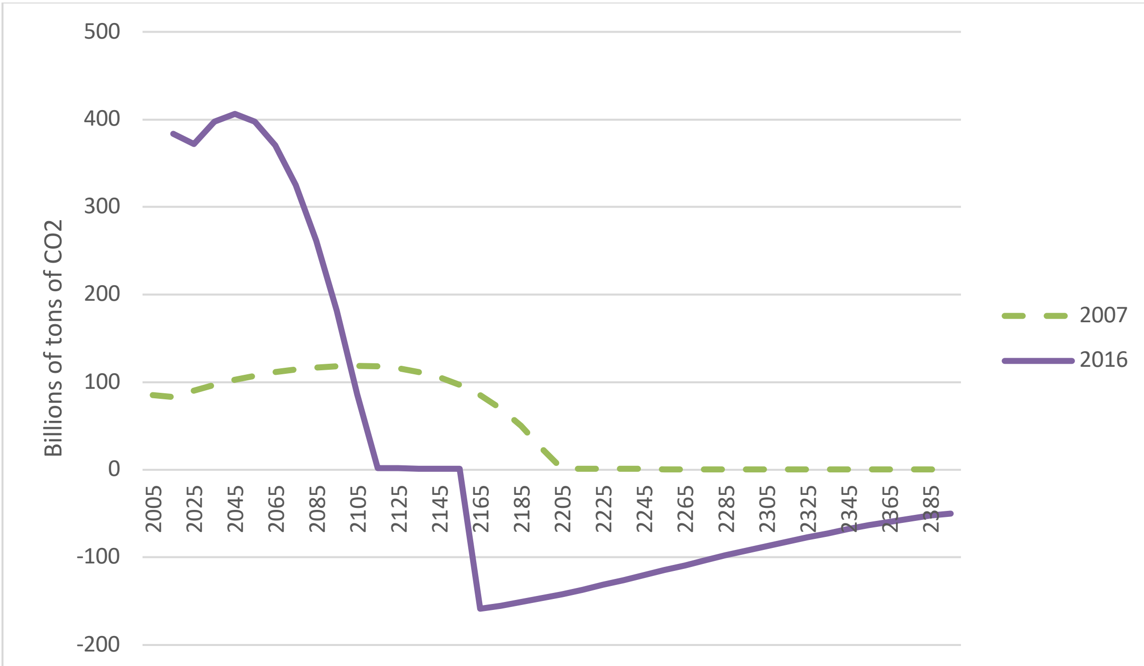

Figure 13: Changes of CO2 Emissions per Decade Between DICE-2016 and DICE-2007

Figure 13 represents the CO2 emissions under optimal policy, the lowest value in DICE-2007 is 0 because the maximum value of emissions control rate was 1 in this model. However, DICE-2016 has the emissions control rate more than 1 which means we can absorb the CO2 from atmosphere and eliminate them. Therefore, we can have negative value for CO2 emissions which means we will not produce the CO2 anymore after year 2165 and we wash out the existing CO2.

Figure 14 represents CO2 concentration at atmosphere, DICE-2007 can have infinity values in no reduction policy. However, DICE-2016 has kind of asymptote for CO2 concentration of atmosphere in no reduction policy and it has lower slope.

Figure 15 shows global temperature increase compare to 1900. DICE-2007 has sharper slope for no reduction policy compare to DICE-2016. Moreover, both models approach to the same point (4.4°F) in year 2395 under optimal policy.

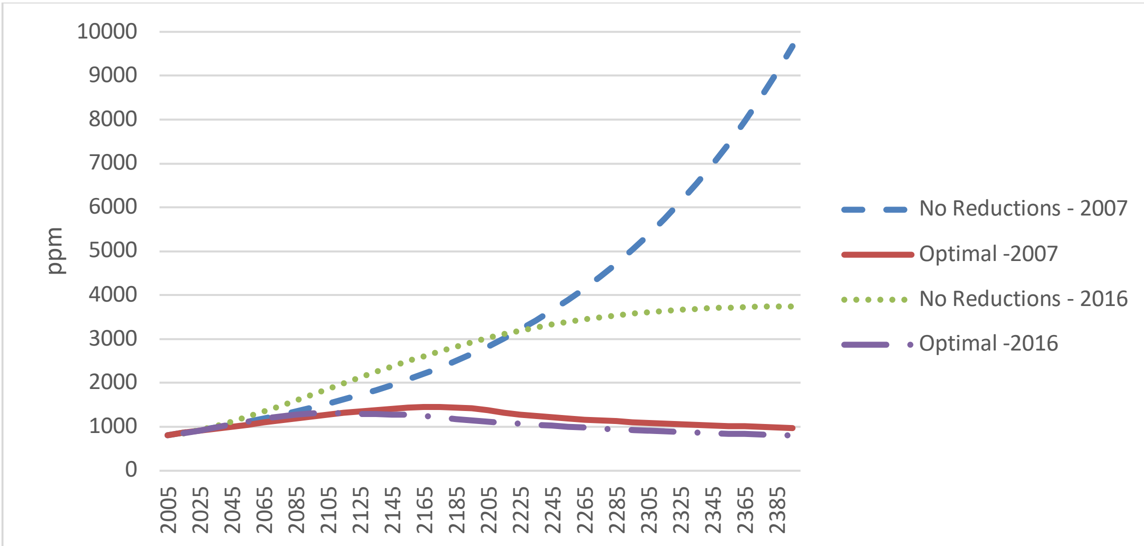

Figure 14: Changes of Atmospheric CO2 Concentrations Between DICE-2016 and DICE-2007

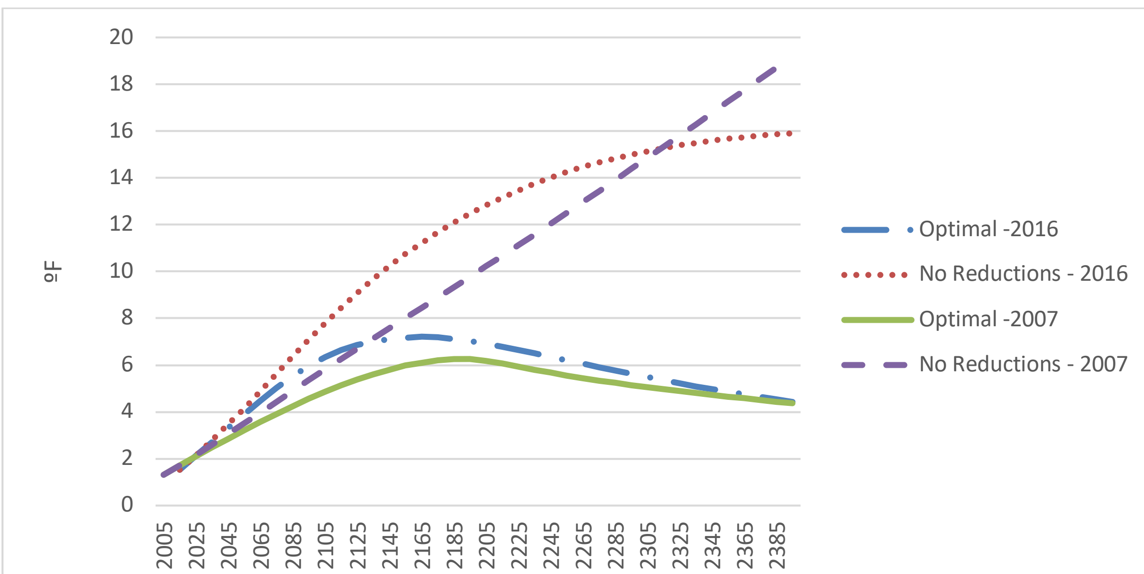

Figure 15: Changes of Global Temperature Increase Between DICE-2016 and DICE-2007

Chapter 6: Conclusions

The model shows following results under no emissions reduction policy (baseline case), fast increase in CO_2 emissions from 500 billion tons of carbon per year in 2015 to 2007 billion tons per year in 2100. Similarly, carbon emissions cause a fast increase in atmospheric concentrations of CO_2 from 280 parts per million (ppm) in preindustrial era to 851 ppm in 2015 and to 1795 ppm in 2100. Global temperature in 2005 has increased about 0.7°C (1.3°F), compare to 1900 and DICE model shows it will increase by 7.44 in 2100, and 12.66 in 2200. The climate damages associated with these temperatures are estimated by 4 percent of global gross output in 2100 and 11.7 percent of global gross output in 2200.

The model shows following results under optimal emissions reduction policy, emissions reduction rate for CO_2 is increasing to 36 percent by 2050 and 84 percent by 2100 relative to the baseline. Corresponding, CO_2 concentrations is decreased and increase in global temperature relative to 1900 is decreased to 6.17°F (3.43°C) for 2100 and 6.96°F (3.87°C) for 2200. The net present value abatement cost and climate damages of the optimal policy is $42.6trillion beneficial relative to no control. This includes $20.4 trillion of abatement costs and $63 trillion of reduced climatic damages. There is still $81.8 trillion climate damage even after taking optimal policy.

Some of the equations and details have change among these two versions DICE-2007 and DICE-2016 to catch the economics of the climate change and to include scientific knowledge. DICE-2007 estimated 88% of total cost is due to abatement cost as opposed to 80% in DICE-2016. Abatement cost is almost 7 times larger than climate damages in DICE-2007 compare to 4 times in DICE-2016. Therefore, we might can say decreasing global temperature which represented by abatement cost is costlier in DICE-2007 rather than DICE-2016 considering how much climate change will affect economy represented by climate damages. However, climate damages are increased almost 9 times in DICE-2016 compare to DICE-2007 and abatement cost is increased almost 5 times. Some main reasons for these drastic changes include, changing initial factor productivity from 0.03 in DICE-2007 to 5.115 in DICE-2016 and elasticity of consumption from 2 in DICE-2007 to 1.45 in DICE-2016. These two parameters have the most impact on difference between DICE-2007 and DICE-2016 as shown in Table 5. DICE-2016 assumed there is more productive economy rather than DICE-2007, so climate damage has worse effect on economy. Moreover, discount factors are increased by changing elasticity of consumption from 2 to 1.45. Therefore, discounted climate damages and abatement cost are higher in DICE-2016.

DICE-2007 achieved the highest point of emissions control rate which is 1 in year 2205, same year that carbon price started to decline, DICE-2016 achieved the highest point which is 1.2 and carbon price started to decrease in year 2165. The lowest value of CO2 emissions in DICE-2007 is 0 because the maximum value of emissions control rate was 1 in this model. However, DICE-2016 has the emissions control rate more than 1 which means we can absorb the CO2 from atmosphere and eliminate them. Therefore, we can have negative value for CO2 emissions which means we will not produce the CO2 anymore after year 2165 and we wash out the existing CO2. Moreover, both models approach to the same global temperature increase (4.4°F) in year 2395 under optimal policy.

(William D. Nordhaus & Sztorc, 2013)

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