Climate Change and Economic Growth

Master Thesis
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2 Abstract

Since one of today's major political issues is how we reduce carbon emissions and their impact on both the climate and the economy, then this paper will examine *'how will the global economy be affected by climate change'*. To analyze the problem, a simple climate-Solow model is used, which is the simplest Integrated Assessment Model (IAM). The paper will look at some of the main criticism of the DICE model such as the value of damages and determining the discount rate. The analysis shows why critics would like to value damages more, and the importance of a discount rate on the decision of what climate policy initiatives are more profitable. In comparison to the DICE model, the simple climate-Solow model gives an okay prediction and understanding of how the global economy will be affected by climate change, and what impact climate policy initiatives have.

Contents

3 Intro

Global climate change is not a new phenomenon and has been a big problem for the last many years and involves many people around the world - not just nationally or locally but globally. The climate is a global public good or an externality with negative spillovers/ negative externalities in the form of greenhouse-gas emissions that affects the whole world. Climate change is a consequence of greenhouse-gas emissions. Moreover, it is difficult for each individual to do something about it [Nordhaus, 2019] even though, there might be lots of people who are thinking about it and would like to make a change in their own way.

The human activity of daily life affects the climate by emitting a lot of greenhouse gases such as CO_2, H_2O, O_2, CH_4, and N_2O [Olsen, nd], which occurs, among other things, through the combustion of coal, oil, and natural gases, as well as through the deforestation and intensive cultivation of agriculture. As a result, an unnatural amount of greenhouse gasses is released into the atmosphere than what is 'natural'. In other words, greenhouse gases are released faster than nature can absorb them again [Videnskab, nd]. The greenhouse effect, which is the ability of the atmosphere to retain the sun's radiation, is reinforced and leads to an increase in the temperature on Earth over time. This is referred to as global warming with climate change as a consequence. The consequences of climate change are drought, rising water levels, extreme storms, floods, etc. [Landbrug and Fødevarer, nd]. For example in the last two centuries, the world had a big tsunami in Southeast Asia in 2004, an extreme drought in 2011, and again from 2020 to 2022 in West Africa, extreme forest fires in the Amazons, USA, and Australia, flooding in Pakistan in 2022, and many more extreme weather catastrophes [Nødhjælp, nd]. Besides all the extreme weather changes that come with climate changes and global warming, around 4 percent of the total area in the world is expected to have a change in the ecosystem at a 1° Celsius degree temperature increase, and a 13 percent chance at 2° Celsius degree temperature increase [Kommissionen, 2018].

From an economic perspective, in 2017 weather-related catastrophes cost Europe around 283 billion EUR and affected around 5 percent of the population in Europe. Climate changes will also affect productivity and food, water- and heat availability which may lead to further conflicts and migration flows [Kommissionen, 2018].

As mentioned, climate change is a public good with negative spillovers and it is difficult for an individual or even a small nation to slow the changes. Therefore, other more global methods should be used. Countries should cooperate and make multinational climate change policies [Nordhaus, 2019].

3.1 Problem

How will the global economy be affected by climate change?

There are three sub-questions to this problem:

- Will a simple climate-Solow model be able to predict the future of the global economy in case of climate change?
- How sensitive is the model output to climate change in the form of damages?
- How sensitive is the model output to the discount rate?

3.2 Motivation

This thesis will be based on the study by [Tsigaris and Wood, 2016]: *'A simple climate-Solow model for introducing the economics of climate change to undergraduate students'* It can be seen that today's generation of people creates climate change when things are produced and developed. With this, today's generation benefits from emitting greenhouse gases without thinking about future costs and consequences. These are considered to be global negative externalities. A cost-benefit analysis is made to find the social costs of the release of greenhouse gases. To see the impact of climate change, an Integrated Assessment Model (IAM) is created. This model is used to integrate knowledge from economics, physics, and the environment [Tsigaris and Wood, 2016]. There are various IAM models, and this thesis will use a simple climate-Solow model, which, among other things, will be used to show the relationship between carbon emissions and expected temperature changes. This is used to predict the economy in the event of climate change. This model will be a simple climate model and will be compared to Nordhaus' more complicated DICE model. Finally, this thesis will look at what the governments will be able to do to reduce greenhouse gas emissions.

3.3 Delimitation

To answer the problem of *How will the global economy be affected by climate change?*, a simple climate-Solow model is used. Therefore, for this master thesis, there is no use of other models. The only other model described is the more advanced DICE model, which is used for comparison. Furthermore, the only greenhouse gas that is used to show the relationship between greenhouse gas (GHG) emissions and expected temperature changes is carbon (CO_2), since the model describes the economy where GDP gathers all goods and services, and therefore uses carbon to measure greenhouse gas. There are various opinions of the DICE model. This paper will focus on the critics about the sensitivity of the damages and the discount rate.

4 Integrated Assessment Model

An Integrated Assessment Model (IAM) is used to generate predictions of economic damages from climate change and contains components that map the economic output to carbon generation. This leads to the increase in global average temperature, which leads to the reduction in economic output via the damage function. One of the most popular IAM models is the Dynamic Integrated Climate Economy model of William Nordhaus - also known as the DICE model. The DICE model was one of the first of its kind and helps to determine climate change policies [Keen et al., 2021]. The DICE model is based on the Ramsey growth model that *' portrayed long-run economic growth as the product of optimal savings decisions by a highly stylized society'* [Keen et al., 2021].

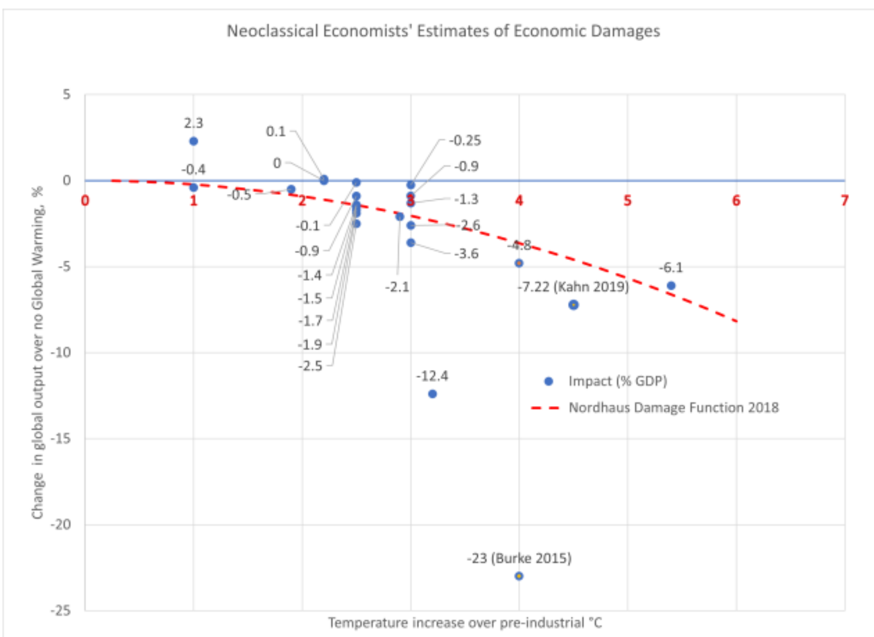
The advantages of an IAM model are that the models can project trends, calculate costs and benefits, assess policies, be internally consistent, and incorporate alternative assumptions. Internally consistent means that the IAM models keep track of different stocks and flow for all variables to make sure that nothing gets lost. Alternative assumptions mean that the model can handle if there is a change in output assumption, discounting, or pursuing a different policy, and still ensure that other parts in the model are consistent with the alternative changed assumption(s). Most experts agree on having all countries participate, have equalized marginal costs or carbon prices in all uses in a given year, and increase stringency over time. However, experts do not agree on the stringency of policies [Nordhaus, 2019].

4.1 Opinions of the use of IAM models

A problem with the DICE model is that the model does not take into account inefficiencies and externalities in the real-world economy. One example is the structure of the tax systems. The structure of the tax system is important when estimating an efficient level of carbon price or tax because there is a need of considering the interaction of the carbon price with the pre-existing tax and regulation structures in a given country. Another example is that the DICE model does not take into account carbon's impact on public health, monopoly and regulation in the energy sector, and technology changes. Moreover, the DICE model relies on the Cobb-Douglass production function to illustrate the production process. In some cases, there is an overestimated substitution, and in other cases, the substitution is underestimated [Nordhaus, 2023].

In the paper *'Economists' erroneous estimates of damages from climate change'* by [Keen et al., 2021] opinions of the use of IAM models are discussed. Scientists like Timothy Lenton have criticized economists in that they, in general, do not recognize and understand the climate tipping points, and they criticize economists' representation of climate change in IAM models [Keen et al., 2021]. A tipping point is when there is a point in a system where the system can no longer be in the changed system and shifts towards a new state [Learnz, nd]. Examples of a tipping point are the Greenland ice sheets collapse, the coral reef die-off, Amazon rain forest destruction, West African and Indian monsoon shift, and many more [TheGuardian, nd]. According to Lenton, tipping points could be triggered by global warming with temperature increase alone, hence keeping global warming below a certain level of temperature may reduce the risk of reaching a tipping point within this century. Nordhaus' assertion that *'no critical tipping elements with a time horizon less than 300 years until* *global temperatures have increased by at least* 3° *Celsius degree'* [Keen et al., 2021]. Furthermore, Nordhaus comments that the most important tipping point is the destruction of the Amazon rain forest, whereas Lenton says that the most important tipping point is the Arctic sea-ice ($0.5 - 2°$ Celsius degree warming) and the Greenland ice sheet ($1 - 2°$ Celsius degree warming) - and if the tipping point is not already passed, it will occur in this century. According to Lenton, this will have an impact on the economy through the impact on climate, biosphere, and suitability for human life. In response, Nordhaus means that the Greenland ice sheet has a time scale of at least 300 years.

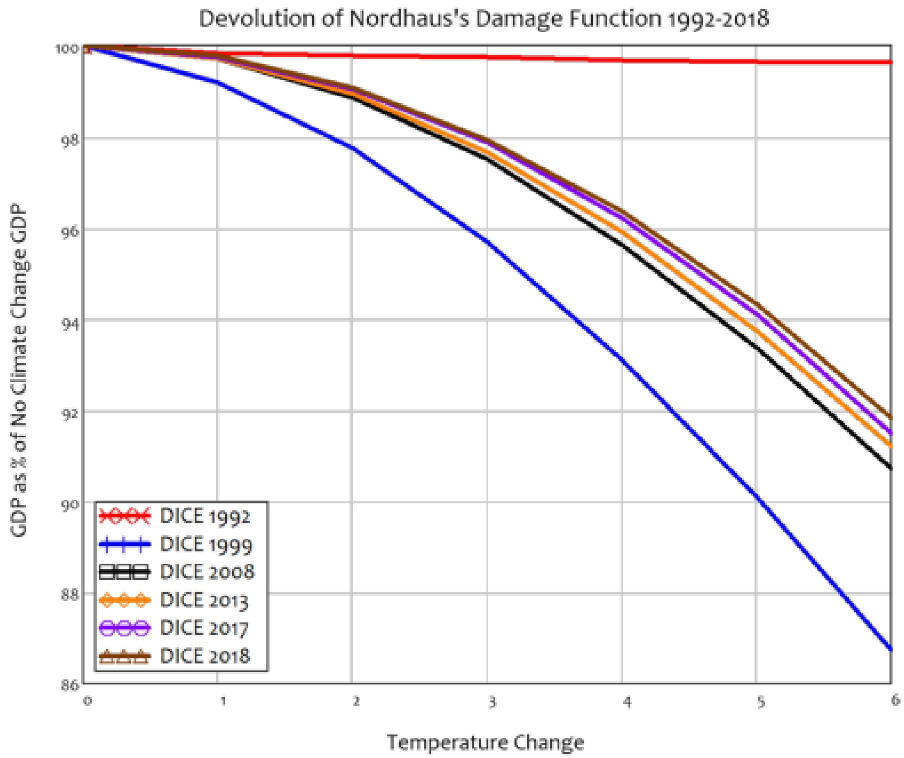
Lenton has calculated the Nordhaus DICE model and included the tipping point where Lenton's results will increase the social cost of carbon and proposed that a 2° Celsius degree will be a critical temperature level where the tipping point could occur. If Nordhaus would include the tipping point and all other assumptions in the DICE model, Nordhaus assigns the probability for a 3° Celsius degree warming scenario in the year 2090 to 1 percent, and a 7 percent probability for a 6° Celsius degree warming scenario in the year 2175. Therefore, estimated damage with the tipping point included in the DICE model will be higher [Keen et al., 2021]. For economists to see the economic consequence of climate change C. Field et. al. have in the 2014 IPCC report *"Climate Change 2014: Impacts, Adaptation, and Vulnerability Part A: Global and Sectoral Aspects"* made a scatter plot with global income change in percentage on the vertical axis and the temperature increase on the horizontal axis in Figure 1.



source: [Keen et al., 2021]

Figure 1: Neoclassical Economisis' Estimate of Economic Damages

Out of the 19 point estimates, it is shown that with a 1° Celsius degree increase in global temperature over pre-industrial levels, the global income will increase by 2.3 percent. Another point estimates that with a 5.4° Celsius degree increase in global temperature over pre-industrial levels, the global income will decrease by 6.1 percent. Economics still claims that the impact of climate change on economic sectors will be small relative to other drivers such as population, age, income, technology, relative prices, lifestyle, regulation, governance, and so on. The red line in Figure 1 shows the damage function from Nordhaus in 2018. Through the years, Nordhaus has used different functional forms of the damage function and made the function less convex, which is shown in Figure 2. The damage functions are plotted against the temperature increase, where the impact of each change in the damage function since the initial quadratic-based function from the year 1992 has been to reduce the predicted damages from climate change.



source: [Keen et al., 2021]

Figure 2: Devolution of Nordhaus's Damage Function 1992-2018

Again, scientists argue that the damages from climate change are higher than Nordhaus predicted damages from climate change. As an example climate change does affect humans' response to climate change - at some level of temperature, it will be too humid for humans [Keen et al., 2021].

According to Nordhaus, it is only sectors that are exposed to the weather, that are affected by climate change. Economic sectors that are exposed to the weather are for example agriculture, fisheries, and forestry and are hence affected by climate change. Unaffected sectors are those that occur indoors such as manufacturing and finance, and these sectors represent 87 percent of the economy. In [Keen et al., 2021], Nordhaus' assumption is rejected. Firstly, some consequences of climate change such as wildfires and floods will affect factories at least as much as consequences of climate change will affect the output from those factories. Secondly, some areas will be uninhabitable for people if the temperature increases too much. Factories placed in an uninhabitable area will produce zero output. And thirdly, some factories are dependent on non-manmade environmental inputs to production such as energy, agricultural, and mineral inputs [Keen et al., 2021].

Economists assume that *'climate-economy relation, for a specific region of Earth at a specific time, under the condition of a stable level of atmospheric CO_2, maps onto the climate-economy relation for the world as a whole as CO2 levels rise.'* [Keen et al., 2021]. This assumption has two errors. First, any current relationship between temperature and GDP must reflect regional climate changes that have developed over time. This is not true. For example, the two states Alaska and Maryland have similar GSP per capita but have different average temperatures, and therefore the climate is not a primary driver of income. But they forget that trade between regions changes with the climate. Global average temperature change will shift the climate suitable for growing crops to another place at a speed where new production will be created. Therefore, current productivity does not only depend on the current climate but also on the prior climate. Second, regional climate variability differs from global climate variability, which means that the economy should do the same. When global warming changes the average global temperature, it does not mean that the temperature is changed equally in all regions. While some regional climates are eliminated, other regional climates are introduced and therefore people will either stay and adapt to the new climate or they will migrate to other regions [Keen et al., 2021].

Overall [Keen et al., 2021] find some weaknesses in how economists estimate the damages from climate change. And according to [Keen et al., 2021], damages from climate change are higher than economic estimations.

5 A simple Climate-Solow Model

To illustrate the economic issues associated with climate change, a simple Climate-Solow model by Robert Solow is presented. A Solow model is an exogenous neoclassical growth model that is based on a production function and shows that every nation will converge to the same steady state. It shows how developing nations have faster economic growth - for example, the prediction of China's fast economic growth compared to Western countries. When all nations have reached a steady state, economic growth is at a constant rate. To continue economic growth, exogenous factors such as technology improvement, have to change to increase the quantity of output relative to the input in production. The Solow model is often used as a comparison model or base model to more advanced growth models [Vaidya, nd].

For this section, the simple climate-Solow model is presented to illustrate the economic issues associated with climate change. The model is based on a basic Solow model which is extended with climate changes. Furthermore, to compare the cost and benefits of a policy initiative, a cost-benefit analysis is made to show the importance of a discount rate. The discount rate is used to compare present values with future values. At the end of this section, the more advanced DICE model is presented to be used as a comparison model.

This theoretical part concerns the simple climate-Solow model and is primarily based on the paper: *'A simple climate-Solow model for introducing the economics of climate change to undergraduate students'* by [Tsigaris and Wood, 2016].

5.1 The impact of climate on economic growth

A standard Solow model is used as an exogenous growth model to see the long-run economic growth. According to Cobb-Douglass production function, the output Y_t is produced by capital K_t, labor L_t, and technology A_t:

$$Y_t = A_t K_t^{\alpha} L_t^{\alpha-1} \tag{1}$$

This can be rewritten as output per worker by dividing with $L_t^{1-\alpha}$:

$$y_t = A_t k_t^{\alpha} \tag{2}$$

To study the effect of climate change, the increase in temperature is added to the standard Solow model. Thus the production function is:

$$y_t = D_t A_t k_t^{\alpha} \tag{3}$$

where D_t is the damage function of climate changes:

$$D_t = \frac{1}{1+\theta_1 T_t^{\theta 2}} \leq 1 \tag{4}$$

The damage function affects the output per worker negatively throughout production. T_t is the temperature anomaly in year t. θ is the temperature parameter. T_t is measured by the increase in the average global temperature since the industrial revolution since 1700t and until today. The difference between a standard Cobb-Douglass production function in equation (1) and the production function in equation (3) is that output per worker in equation (3) is reduced by increased temperature. This means that the higher the temperature T_t is, the lower the output per worker y_t when all other variables are the same.

In the simple Climate-Solow model s is the saving rate and is constant, which means that investment per worker in period t is sy_t. $g_{L,t}$ is the population growth rate over time where g_{L0} is the base year 2010. δ_K shows that the capital depreciates at a constant rate. And similarly, the parameters $\delta_L > 0$ and $\delta_A > 0$ show that the growth of the population and total factor productivity is decreasing over time. Thus, the population growth at a decreasing rate over time is:

$$g_{L,t} = \frac{g_{L,0}}{(1+\delta_L)^t}, \delta_L > 0 \tag{5}$$

And the total factor productivity does also grow at a decreasing rate is:

$$g_{A,t} = \frac{g_{A,0}}{(1+\delta_A)^t}, \delta_A > 0 \tag{6}$$

Thus, the difference equation shows the transitional dynamics in the model as:

$$k_{t+1} - k_t = sy_t - (\delta_K + g_{L,t})k_t \tag{7}$$

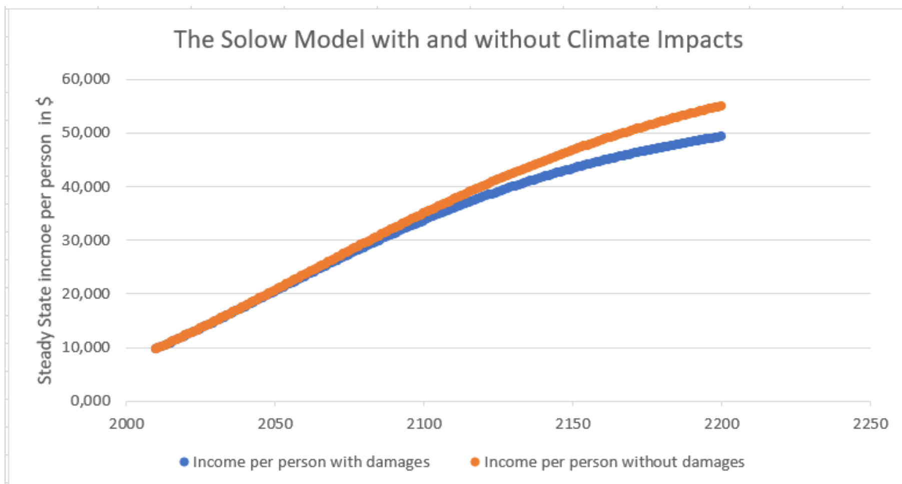
The transitional dynamics in the model show convergence to a steady state with a capital-labor ratio. For a given time period t, this capital-labor ratio is:

$$k_{ss,t} = [\frac{sA_tD_t}{\delta_K + g_{n,t}}]^{1/(1-\alpha)} \quad (8)$$

The steady state with a capital-labor ratio is increasing over time because the population is increasing and technology gets more advanced. Unfortunately, an increase in temperature T_t will reduce the increase of $k_{ss,t}$. By inserting equation (8) into equation (4). Equation (4) can be rewritten as output per worker at a rate that are depending on a change in temperature:

$$y_{ss,t} = D_tA_tk_{ss,t}^{\alpha} \quad (9)$$

where the total factor productivity does still grow with a decreasing rate, and the growth rate of the capital-labor ratio is weighted by the income share of capital and is denoted by α. Thus, when $D_t = 1$, then y_t grows faster. In other words, when there is no climate damage, the output per worker grows faster. In contrary to $D_t = 1$, $D_t < 1$ shows climate damages. Figure 3 shows the comparison between $D_t = 1$ and $D_t < 1$.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 3: The Solow Model with and without Climate Impacts

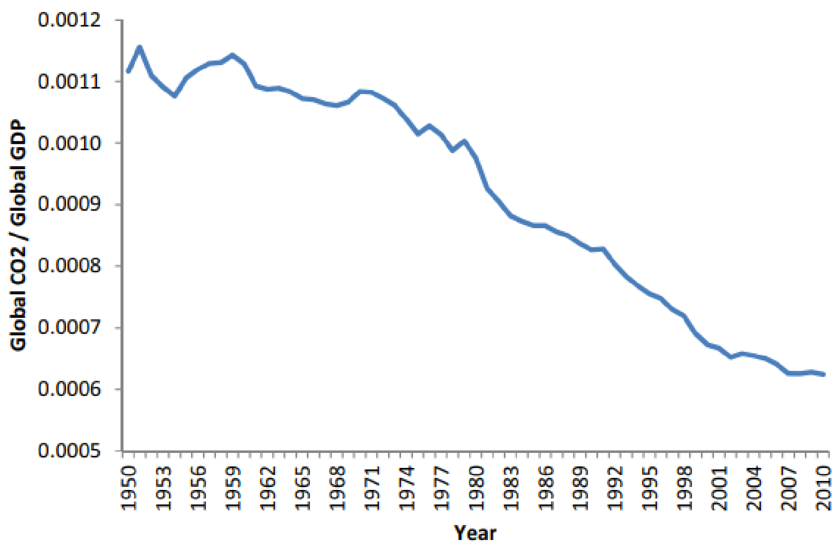
Figure 3 shows the simple climate-Solow model with and without climate changes and what impact climate changes have on output per worker measured in dollars. When there are no climate changes, $D_t = 1$, then in the future the income per person is higher than when there are climate changes, $D_t < 1$. The income per person is almost the same in the first few years from the base year 2010. In the year 2010, the income per person without climate changes, D_t, is \$9,653 dollars, and the income per person with climate changes, $D_t < 1$, is \$9,631 dollars. In the year 2200, the income per person without climate changes, $D_t = 1$, is \$55,000 dollars, and the income per person with climate changes, $D_t < 1$, is \$49,305 dollars. This is a difference of 5,695 dollars. This is around an 11 percent reduction in income per person when damage is added. The closer D_t is to 0, the reduction in income per person increases. Thus, the simple climate-Solow model shows the trade-off in the problem of climate change [Tsigaris and Wood, 2016].

5.2 Carbon emissions

To show how much emissions that are emitted per year measured by tonnes of carbon, the carbon emission function is:

$$E_t = \sigma_t Y_t \tag{10}$$

which shows that carbon emission E_t is dependent on how emission intensive the production is at time t, σ_t and shows how much emissions are released in production per unit of output. Therefore, carbon emission in year t equals emissions intensity in year t times output in year t.



source: [Tsigaris and Wood, 2016]

Figure 4: Global Emission Intensity, 1950-2010

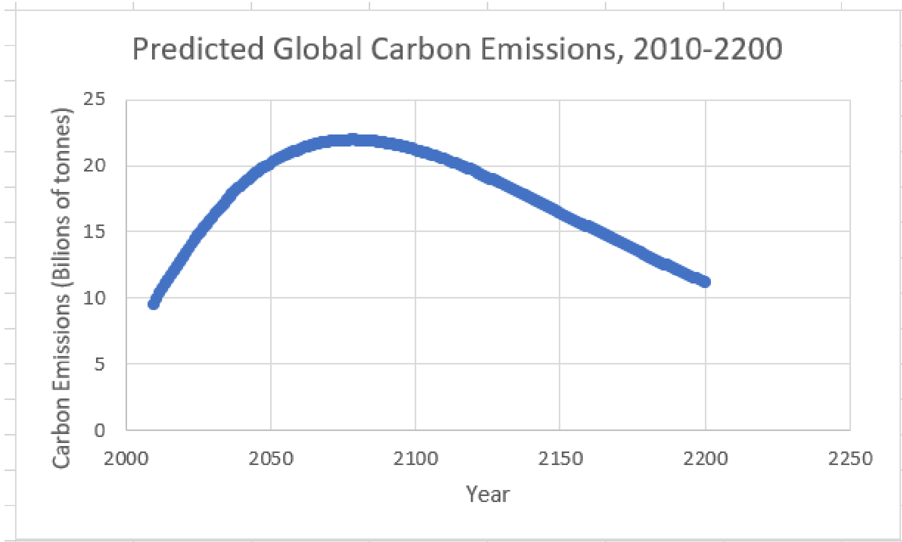
Figure 4 from [Tsigaris and Wood, 2016] shows the global emission intensity from 1950 to 2010. In 1950, the emission intensity was around 0.0011, and in 2010, the emission intensity was around 0.0006. The emission intensity has therefore declined over the years due to many factors like a change in energy source from coal towards fx natural gas, that rapidly growing companies are less energy intensive than slowly or stagnated growing companies, and technology has made it possible to use less energy in production. The formula for the decline in emission intensity is:

$$g_{\sigma,t} = \frac{g_{\sigma,t-1}}{1+\delta_\sigma}, g_{\sigma,t} < 0 \tag{11}$$

Where the value of emission intensity in year t is:

$$\sigma_t = \sigma_{t-1}(1 + g_{\sigma,t}) \tag{12}$$

To predict the global carbon emission, equation (10) is used, and is shown in Figure 5.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

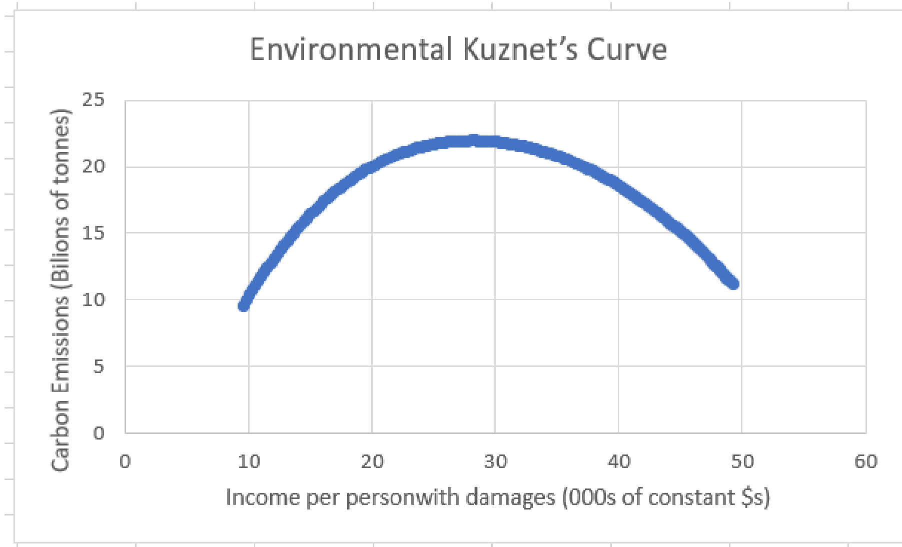
Figure 5: Predicted Global Carbon Emission, 2010-2200

Figure 5 shows that it is more difficult to reduce emissions in a growing economy alongside a steady population-, total factor productivity- and capital per worker growth. This can be shown as:

$$g_{Et} = g_{\sigma t} g_{Y t} \tag{13}$$

When the growth rate of output is higher, then $-g_{\sigma,t} < g_{Y,t}$. When the output reaches a certain level because of a diminishing total factor productivity and population growth, the emission growth will decrease, $-g_{\sigma,t} > g_{Y,t}$.

The relationship between climate and economic growth is according to [Dørs, 2015] often described as a bell-shaped environment Kuznets curve. Economic growth often gets linked to natural resources such as fossil fuels, metals, and minerals. Fossil fuels are used among other things to produce goods, electricity, and fuels. The earth has a limited amount of natural resources - and when it has been used, it cannot be reproduced. More production results in a reduction of fossil fuels and therefore, if the use of fossil fuels cannot be replaced, economic activities and economic growth will stop. Natural resources need to be substituted for man-made or alternative resources. To produce goods, fossil fuels get burned, which leads to climate change. Hence, there is also another interest in reducing the consumption of these resources. Social wealth fare does not only depend on GDP per capita, but also on social and environmental relationships such as education, health, and the condition of the environment. Again, natural resources need to be substituted for man-made or alternative resources. Some known alternative ways to produce energy are renewable energy sources such as the wind and the sun. Man-made or alternative resources can be costly in the short run but will benefit economic growth, in the long run [Dørs, 2015].



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 6: Environmental Kuznet's curve

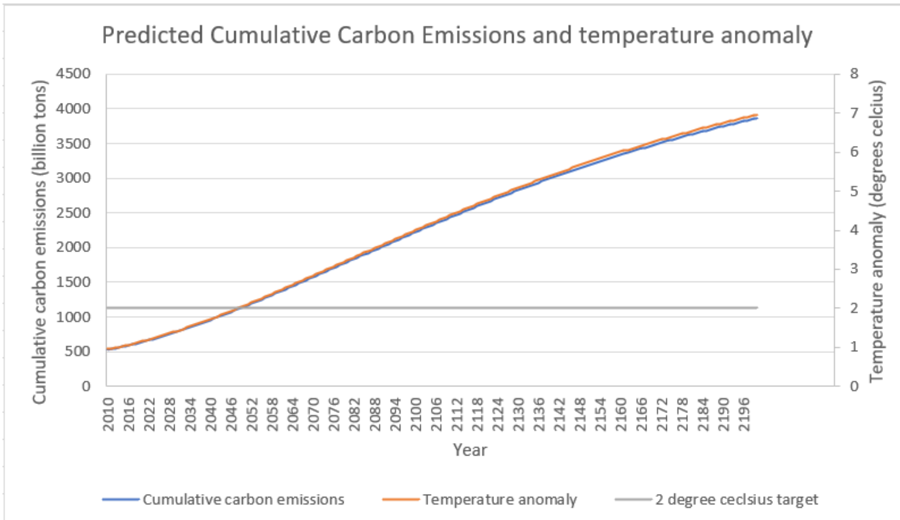
The relationship between climate and economic growth is described as a bell-shaped environment Kuznets curve because, in a society with a low GDP, the pollution is low too. When production increases, the GDP and pollution increase as well. At some point, the level of pollution will decrease because a clean environment is seen as a luxury good, and more strict policies are made to reduce the problem of more pollution. A luxury good is when the demand for the good increases more than proportionally with income. The predicted carbon is an inverse u-shape and follows the Environmental Kuznet's curve shown in Figure 6.

5.3 Carbon accumulation and temperature change

Now looking at the relationship between carbon cumulation and global temperature, it is shown that temperature increases independently from both time and the level of stabilization of atmospheric carbon concentration with around 1.8° Celsius degree per 1000 billion tons of carbon (1000 PgC) emitted. This made this simple climate-Solow model more simple. The function of global temperature change in relation to carbon accumulation in the future is:

$$T_t = \beta(C_0 + \sum_{i=1}^{t} E_i), t \geq 1 \tag{14}$$

where the cumulative emissions from pre-industrial levels to 2010 are summed up in C_0. Therefore, the term βC_0 shows the impact on global temperature change relative to the pre-industrial level. In the year 2010, the initial carbon billion of tonnes that already accumulated is 530 billion tons. The term $\beta \sum_{i=1}^{t} E_i$ then shows the impact on global temperature change at time t from 2010 onward with future emissions accumulation added. As the economy grows, emissions accumulation grow will continue, and thus will the temperature changes. The temperature will increase. When looking at temperature changes anomaly to below 2° relative to the pre-industrial level, the focus is on the cumulative carbon emission and the targeted budget. To follow that target, the cumulative carbon should not increase more than the budget of 1110 billion tons. With a 470 billion ton increase over the next 50 years from the year 2010, 1000 billion tons will be reached. Thus, there is a 1.8° temperature increase relative to the pre-industrial level. This will make β to be 0.0018 billion tons of cumulative carbon emitted [Tsigaris and Wood, 2016]. This is shown in Figure 7



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 7: Predicted Cumulative Carbon Emissions and temperature anomaly

Figure 7 shows the cumulative carbon emissions with its responding temperature anomaly and the 2° budget at time t. It is shown that the temperature anomaly passes the 2° degree around the year 2050. Moreover, the cumulative carbon emission passes the budget of 1110 billion tons around the same time.

5.4 Cost-Benefit analysis and 2° Celsius degree target

Carbon emissions remain in the atmosphere for a long time. The higher atmospheric concentration of carbon leads to the greenhouse effect where the surface temperature of land and sea increases. Increasing temperatures lead to more extreme weather phenomena and affect all lives that are climate sensitive. Climate models have predicted that the average warming of the globe will be around $3° - 5°$ Celsius degrees by 2100 and even higher after that [Nordhaus, 2019]. Therefore, [Nordhaus, 2019] describes that scientists have focused on three strategies to slow climate change.

- Strategy A is "abatement," or reducing emissions of CO_2 and other GHGs primarily by reducing combustion of carbon fuels
- Strategy B is "carbon removal," or removal of CO_2 from the emissions stream or from the atmosphere
- Strategy C is "geoengineering," or more precisely solar-radiation management, which would offset global warming by increasing the reflectivity of the earth

Doing Strategy C by geoengineering, the earth is going to be more reflective so less sunlight will reach the surface of the earth. Geoengineering is untested and will not reduce climate changes in all regions, and will not deal with ocean acidification. Moreover, it will be difficult to have all countries cooperate. Doing Strategy B by carbon removal where it runs combustion in reverse. Even though this is an attractive option, it is also very costly, and no technology can do this at an affordable cost. Doing Strategy A by abatement is also an expensive option, but not as expensive as Strategy B. Studies have also shown that the policy in Strategy B may be more efficient and have all countries participate [Nordhaus, 2019].

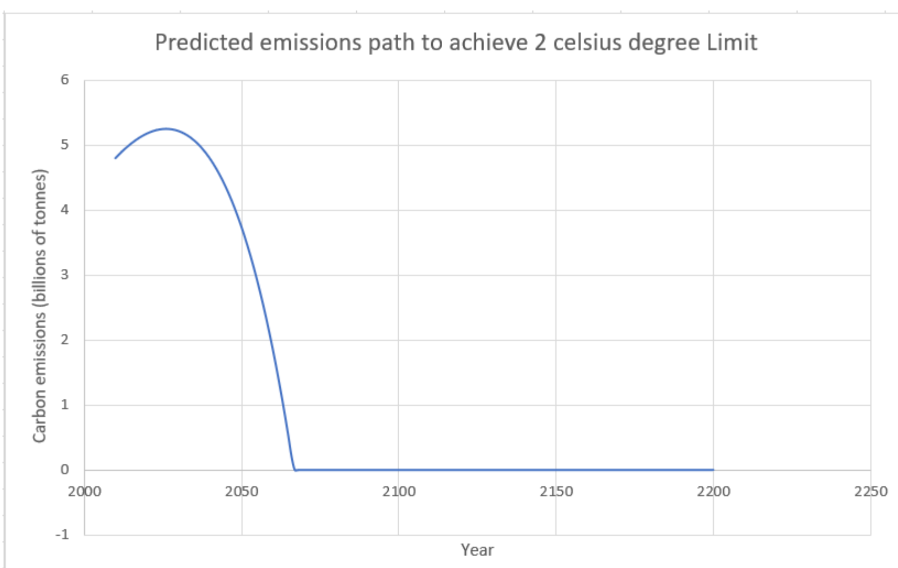
It is good to set a climate policy goal or target from which politicians can work. If the target is too low, there might be costs, such as a reduction in living standards, that are not taken account for. A cost-benefit analysis is made to balance costs and benefits [Nordhaus, 2019]. In 2010 at COP16, the 2° Celsius degree target was agreed on. This means that the average increase in temperature should be below 2° Celsius degree. Since there has already been emitted 530 billion tons of carbon by 2010, the carbon budget is at 580 billion tons, because the global cumulative carbon emission should be at 1.111 trillion tons. Otherwise, there is a 50 percent chance of passing the 2° Celsius degree target. To keep below the 2° Celsius degree target, there is a need for some restrictions from the government to reduce the emission - in [Tsigaris and Wood, 2016] this will be the control rate M_t.The control rate M_t increases at a constant rate m. The growth rate is:

$$M_t = M_{t-1}(1 + m) \tag{15}$$

By adding the control rate to equation 10, it is shown how emissions control enters the model:

$$E_t = (1 - M_t)\sigma_t Y_t \tag{16}$$

Assume the parameters to be $M_t = 0.09$ and $m = 0,04267$ [Tsigaris and Wood, 2016], the predictive emission path to achieve the 2° Celsius degree target is shown in Figure 8:



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 8: Example: Predicted emissions path to achieve 2° Celsius degree limit

It is shown in Figure 8 that the emissions increase until the year 2026 when it peaks at $5,243012$ billion of tonnes of carbon emissions. After the peak, emissions decline to zero around the year 2067. In Figure 5 the peak of emission was in the year 2072 with $7,773667$ billion of tonnes of carbon emissions. Thus, in Figure 8 the peak of carbon emissions is around $\frac{1}{3}$ less than in Figure 5.

Reducing carbon emissions is not costless and therefore a cost-benefit analysis is made to achieve the 2° Celsius degree target. To see the cost of reducing emissions, a convex abatement cost function is made:

$$AC_t = \Omega_t M_t^2 \tag{17}$$

where $\Omega = 0.06$ and is the abatement cost coefficient [Tsigaris and Wood, 2016]. Ω declines with at rate $-g_{A,t}$. In other words, the abatement cost coefficient declines over time at the same rate as the total factor productivity grows. Thus, the total income per capita net of abatement cost in year t is:

$$cy_t = (1 - AC) D_t A_t k_t^{\alpha} \tag{18}$$

To show the reduction in per capita income by reducing emissions, the net present value is used with different discount rates. The aim to show the reduction in per capita income of reducing emissions is to see which policy action will be most profitable. Therefore, a cost-benefit analysis is made to convert future costs and benefits into present value by applying a discount rate [Thomas and Chindarkar, 2019]. Or in other words, the discount rate makes it possible to compare present and future values [Finansministeriet, 2021]. The net present value (NPV) is:

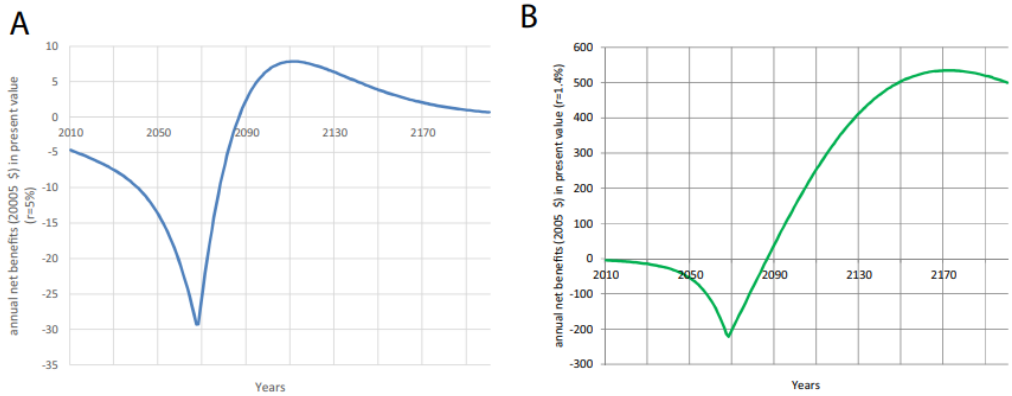
$$NPV = \sum_{t=0}^{n} \frac{NB_t}{(1+r)^t} \tag{19}$$

where NB is the annual net benefit in year t and r is the discount rate. Thus, the net present value is the sum of the annual net benefits, which is converted to the present value. The net benefits can also be divided into costs and benefits, so the net present value formula is:

$$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t} \tag{20}$$

The benefits are the output per worker shown in Equation 3, and the costs are the total income per capita net of abatement cost shown in Equation 18. If the net present value is positive, the policy action is profitable because the benefits overweight the costs. On the other hand, if the net present value is negative, the policy action will never pay itself. The discount rate is the cash flow that helps to convert the future stream of annual net benefits to the present. The discount rate is raised to the power t because it is the number of periods between the present and the moments every cash flow will take place [Merritt, nd].

Therefore, the discount rate plays an important role in policy-making. To illustrate the importance of the discount rate, the discount rate in [Tsigaris and Wood, 2016] is set to be first at 5 percent at first and then set to 1.4 percent. The illustration is shown in Figure 9.



source: [Tsigaris and Wood, 2016]

Figure 9: (A) Annual Net Benefits in Present Value using 5 percent Discount Rate. (B) Annual Net Benefits in Present Value using 1.4 percent Discount Rate.

Figure 9A shows the annual benefits in present value with a 5 percent discount rate, while Figure 9B shows the same but with a 1.4 percent discount rate. The total net present value with a 5 percent discount rate is $\$ - 499$ dollars per capita, while the total net present value with a 1.4 percent discount rate is $\$40,655$ dollars per capita. Even thought the cost are higher in the option with 1.4 percent discount rate than the option with a 5 percent discount rate, it is still more profitable to take the option with 1.4 percent discount rate, because the future benefits weights more than the costs - and thus the net benefits are positive.

5.5 Determination of the discount rate

As shown in Figure 9, the determination of the discount rate is important if a policy action will be chosen or not - if the policy initiative is profitable or not. As shown, if the discount rate is high, fewer policy initiatives will not be determined as profitable, and if the discount rate is low, more policy initiatives will be determined as profitable.

The discount rate is seen as a weight that reflects society's view of how future values are weighted against present values. Or in other words, the discount rate makes it possible to compare present and future values [Finansministeriet, 2021]. It is assumed that society weights costs and benefits over a shorter time, which means that society prefers taking 100 dollars today instead of in a year. So for example, if there are two policy initiatives A and B that is identical in costs and benefits and the only difference between policy initiative A and B is that A occurs earlier than B, then policy initiative A will be chosen as long as the discount rate is positive. Therefore, for policy initiatives involving climate change, the discount rate has importance, since the benefits are further into the future, while the costs are in the near future. Thus, climate initiative benefits weights more than the costs [Finansministeriet, 2018].

In other words, a policy initiative to reduce carbon emissions could be done by developing alternative energy sources and develop more efficient technologies. This is costly in the present and will continue to cost money in the future. The discount rate helps to value or translate future costs at a present time - future costs into a present value [Bice, nd].

A way to calculate what the discount rate could be is with the Ramsey formula.

$$r = \rho + \eta g \tag{21}$$

where r is the discount rate, ρ is the social rate of time preference (to discount future utility), η is the elasticity of the marginal utility of consumption, and g is the rate at which consumption is expected to grow. Thus, the Ramsey formula shows how much the consumer gets compensated for giving up consumption today [Finansministeriet, 2021].

The Organisation for Economic Co-operation and Development (OECD), looks at two methods to determine the discount rate: 1) the normative method and 2) the descriptive method. The normative method is based on how the weight between the present and the future should be, and the deceptive method is based on how the weight between the present and the future actually is [Finansministeriet, 2018].

The European Union's benchmark for a discount rate is 5 percent for Cohesion Member States, and 3 percent for other members [Komissionen, 2015], while other countries have either higher or lower discount rates shown in Figure 10. As shown, the higher discount rate is used in developing countries like the Philippines with a 15 percent discount rate and both India and Pakistan with a 12 percent discount rate each [Harrison, 2010].

International

Country	*Agency*	*Discount rate (per cent)*
Philippines		15[a]
India		12[a]
Pakistan		12[a]
International Multi-lateral Development Banks	World Bank	10–12[a]
	Asia Development Bank	10–12[a]
	Inter-American Development Bank	12[a]
	European Bank for Reconstruction and Development	10[a]
	African Development Bank	10–12[a]
New Zealand	Treasury and Finance Ministry	8[g]. From 1982 to 2008 it was 10[abf]
Canada	Treasury Board	8[c]. From 1976-2007 was 10 (and test 8–12 per cent)[ab]
China (People's Republic)		8[a]
South Africa		8 (and test 3 and 12 per cent)[d]
United States	Office of Management and Budget	7 (and test 3 per cent). Used 10 per cent until 1992.[a]
European Union	European Commission	5 From 2001–2006 was 6 per cent[a]
Italy	Central Guidance to Regional Authorities	5[a]
The Netherlands	Ministry of Finance	4 (risk free rate).e
France	Commissariat General du Plan	4. From 1985-2005 used 8 per cent[ab]
United Kingdom	HM Treasury	3.5 (declining to 1 per cent for costs and benefits received more than 300 years in the future) from 2003.[a] From 1969–78 used 10 per cent[a]
Norway		3.5. From 1978–98 used 7 per cent[ab]
Germany	Federal Finance Ministry	3. From 1999–2004 used 4 per cent[ab]
United States	Environmental Protection Agency	2–3 (and test 7 per cent)[a]

source: [Harrison, 2010]

Figure 10: 2010 real discount rates in practice in different countries

In Denmark, the determination of the discount rate is using both methods from the OECD. The Ministry of Finance in Denmark suggests a decreasing discount rate. In 2018 they suggested a discount rate of 4 percent for the first 35 years, a 3 percent discount rate from year 36 to year 70, and then a 2 percent discount rate from year 70 [Finansministeriet, 2018]. In the year 2021, The Ministry of Finance in Denmark updated its discount rate suggestion to a discount rate of 3.5 percent for the first 35 years, 2.5 percent from year 36 to year 70, and after year 70, the discount rate was suggested to be 1.5 percent. The discount rate got updated because of the publication of *DK2025 - policy initiatives that are realized between year 0 to year 35 will have a discount rate of 3.5 percent.* By lowering the discount rate by 0.5 percent, Denmark has a very fast declining discount rate, which is expected to have a positive influence on for example climate policy [Finansministeriet, 2021].

The Stern Review on the Economics of Climate Change suggested a 1.4 percent discount rate [Goulder and Williams, 2012]. , while Nordhaus suggested a 3.5 percent discount rate [Nordhaus, 2019].

5.6 Summary of a simple climate-Solow model

The purpose of the simple climate-Solow model is to introduce the economics of climate change and how damages from increased temperatures enter the model. Furthermore, the model looks at the 2° Celsius degree and illustrates the importance of the discount rate.

The simple climate-Solow model Figure 3 shows that the income per person in the future is almost the same in the first few years from the base year in 2010 with and without the impact of climate changes. Adding damages to the model decreases income per person by 11 percent in year 2200. Figure 5 shows that it is difficult to reduce emissions in a growing economy alongside growth in production, total factor productivity and capital per worker. Carbon emissions increases up until year 2072 and decreases slowly thereafter. Moreover, looking at the global temperature change in relation to carbon accumulation in the future, it is shown that the temperature anomaly passes the 2° Celsius degree around the year 2050, and the cumulative carbon emission passes the budget on 1110 billion tons around the same time. To reach the 2° Celsius degree target, a restriction from the government should be imposed. Assuming the control rate $M_t = 0.09$ and the constant rate $m = 0.04267$ Figure 8 shows that the carbon emission increases until the year 2026 and declines to zero around the year 2067, which is around $\frac{1}{3}$ less than in Figure 5. The cost-benefit analysis shows the annual net benefits in present value using both a 5 percent and a 1.4 percent discount rate. It is shown that the higher the discount rate is, the less profitable the policy initiative is, thus setting a low discount rate is important for climate change policies to be favored.

6 The DICE-model

The Dynamic Integrated Climate Economy (DICE) model was developed by William Nordhaus and is a member of the Integrated Assessment Models (IAM) family - just like the neoclassical simple climate-Solow model. Like the simple Solow model, the DICE model combines natural science with an economic insight into economic growth. The DICE model describes how economic activities lead to carbon emissions, which leads to a rise in the global temperature, which leads to damage costs that will lower the consumption possibilities in the future [Sørensen, 2018]. In other words, the DICE model is a neoclassic optimal growth model known as the Ramsey model, where society invests in capital to reduce consumption today in order to increase consumption in the future. In comparison to the Ramsey model, the DICE model includes climate investments. The DICE model includes economic activity, emissions through climate change, damages, and policy [Nordhaus, 2023]. Thus, the DICE model is 'just' a bit more complex than the simple Solow model

- the output is also dependent on the combination of capital, labor, and technology. One of the differences between the simple climate-Solow model and the DICE model is that in the simple climate-Solow model, the saving rate s is an exogenous constant, whereas the DICE model has an endogenous saving rate. The saving rate is endogenous because of the assumption that households maximize consumption through a utility function [Sørensen, 2018].

Policy initiatives may be costly in different aspects. It can be costly to reduce carbon emissions, but also costly for the global climate system if there are no carbon emission regulations. The DICE model includes a global capital reservoir, abatement costs, climate damages, relative climate costs, consumption, population, productivity factor, social utility, discount rate, and emissions [Bice, nd].

In the present context the global capital reservoir is in this context all the goods and services of the global economic system. Abatement costs are the cost of reducing carbon emissions, where the abatement costs are zero if there is no reduction of carbon emissions. Climate damages are the costs of rising global temperature. Relative climate costs are ways to compare abatement costs and climate damages. Consumption is spending money on goods and services and a way to measure the quality of life since services include things like education and health care. Both population and productivity factors will increase until a certain level - after that, both will decrease. Social utility is the accumulated sum of the social utility function which depends on the global population size, the per capita consumption, and the social time preference factor. The social time preference factor includes a discount rate and the parameter α, which shows the society's aversion to inequality [Bice, nd].

The social utility function is a function of the per capita consumption and the assumption of a discount rate that are discounting future costs and benefits. The DICE model seeks to maximize the social utility function to make it as big as possible [Bice, nd].

Thus, the social utility function of the DICE model is a non-linear dynamic optimization model with an infinite horizon [Nordhaus, 2019] - this is due to that the social utility function increases in the per capita consumption of a generation. The generation's consumption per capita is depended on the size of the population [Nordhaus, 2023]. The DICE model optimizes the consumption, emissions, and climate changes and can be written as followed:

$$\max_{c(t)} W = \max_{c(t)} [\int_0^\infty U[c(t)]e^{-\rho t} dt] \tag{22}$$

where the DICE model is the maximum discounted sum of the utility per capita consumption. With the consumption limits, the model can be written as:

$$c(t) = M(y(t); z(t); \alpha; \epsilon(t)) \tag{23}$$

where $c(t)$ is consumption, $y(t)$ are other endogenous variables such as global temperature, $z(t)$ are exogenous variables such as population, α are parameters such as climate sensitivity, ρ is the rate of time preference, and $\epsilon(t)$ are random variables in the stochastic versions of the model [Nordhaus, 2019]. With this, the DICE model is designed to optimize the consumption flow over time in both economic and climate policies [Nordhaus, 2023].

Optimization of linear models has a problem in that it produces both a primary variable and dual variables or shadow prices. The primary variable is in this case emissions, and the dual variable is in this case the impact on the objective function of a unit change in emission. An example of a dual variable is that the byproduct of the DICE-model is an extra ton of emissions will lower the consumption by $40 dollars because output per worker decreases. This is referred to as the carbon price or carbon tax to define the carbon externality. It is also referred to as *'the social cost of carbon'*. [Nordhaus, 2019].

The production function of the DICE model is assumed to take the form of a Cobb-Douglas function and is the gross output reduced by damages and mitigation costs:

$$Q(t) = \Omega(t)[1 - \wedge(t)]Y(t) \tag{24}$$

Thus $Q(t)$ is the output of damages and abatement. $\Omega(t)$ is the damage cost function:

$$\Omega(t) = \frac{1}{[1 + \psi_1 T_t + \psi_2 T_t^2]} \tag{25}$$

where ψ_1 and ψ_2 are parameters in the damage cost function and T_t is the global average temperature change. The damage cost function shows how the economy is damaged by climate changes. In comparison to the simple climate-Solow model, the part '$1 + \psi_1 T_t$' is added to the damage function in the DICE model, and makes the damage line more convex than in the simple climate-Solow model. By adding '$1 + \psi_1 T_t$' indicates that the temperature damage the output more than valued in the simple climate-Solow model. $\wedge(t)$ is the abatement cost function:

$$\wedge(t) = \pi_t \Theta_1 \mu_t^{\Theta 2} \tag{26}$$

where π_t is the parameter for the carbon cycle, μ_t is the emission control rate. Θ_1 and Θ_2 are parameters in the abatement cost function. $Y(t)$ is the Cobb-Douglass production function:

$$Y(t) = A_t K_t^{\gamma} L_t^{1-\gamma} \tag{27}$$

Total carbon emissions, $E(t)$, are equal to uncontrolled emissions, $\sigma(t)$ reduced by the emissions reduction rate, $\mu(t)$, plus exogenous land-use emissions [Nordhaus, 2017]:

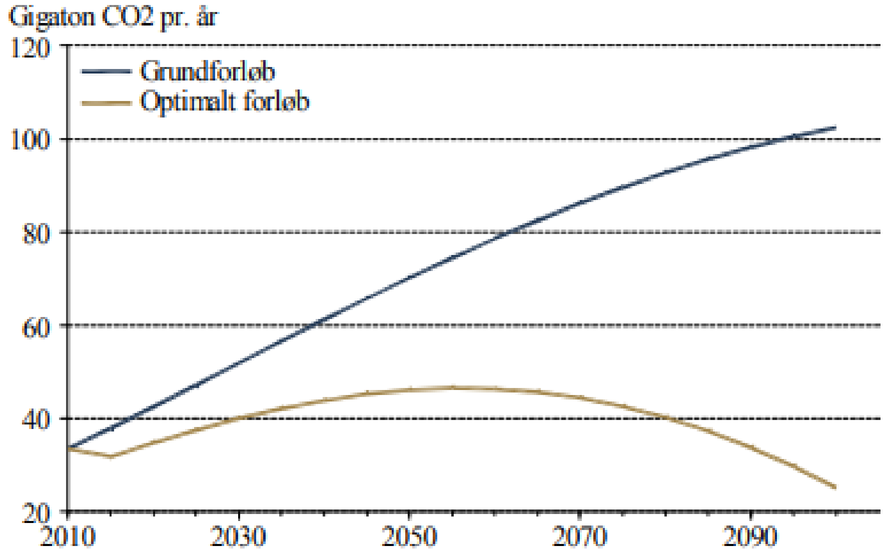
$$E(t) = \sigma(t)[1 - \mu(t)]Y(t) + E_{Land}(t) \tag{28}$$

'Business-As-Usual' (BAU) scenario or the baseline is a comparison line to show how the growth would be with no policy to slow down the climate change [Nordhaus, 2023].

6.1 Results from the DICE model

In Denmark, 'De Økonomiske Råd' (DØRS) has reproduced the results from the DICE 2013 model. In all figures from [Dørs, 2015] there are shown two scenarios. The blue line shows the 'Business-As-Usual' (BAU) scenario, and the brown line shows the DICE model scenario with an optimal climate policy (optimal scenario).

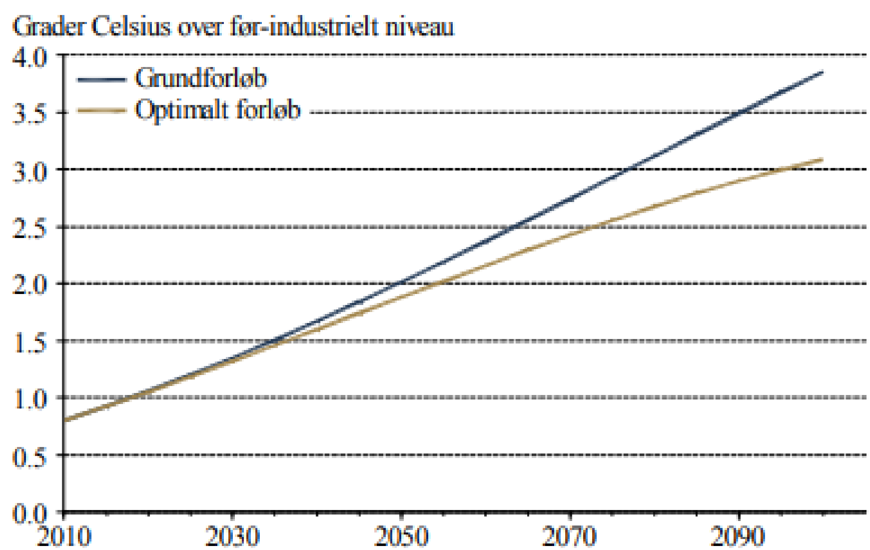
In Figure 11 the industrial emissions are shown. The billion of tonnes carbon emission is shown in the vertical axis, and the years are shown in the horizontal axis. In the BAU scenario, the industrial emissions continue to increase, while in the optimal scenario the carbon emission increases until around the year 2060, after which the emissions decreases to a lower level than in 2010 [Dørs, 2015].



source: [Dørs, 2015]

Figure 11: Industrial emissions

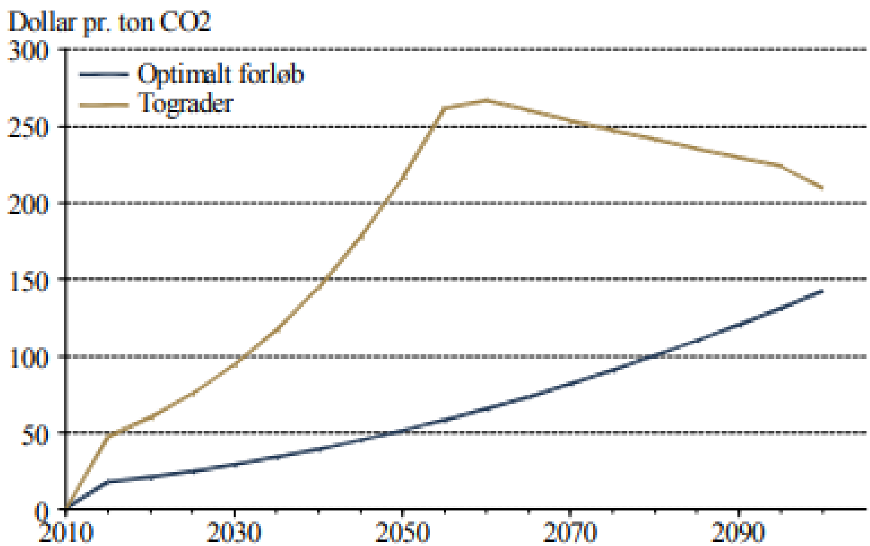
In Figure 12, the global average temperature is shown. The Celsius degree above the pre-industrial level is shown in the vertical axis, and the years are shown in the horizontal axis. In the BAU scenario, the temperature continues to increase and the average temperature is around 4° Celsius degree above the pre-industrial level in the year 2100. In the optimal scenario, the average temperature also continues to increase and is around 3° Celsius degree above the pre-industrial level in the year 2100 [Dørs, 2015].



source: [Dørs, 2015]

Figure 12: Global average temperature

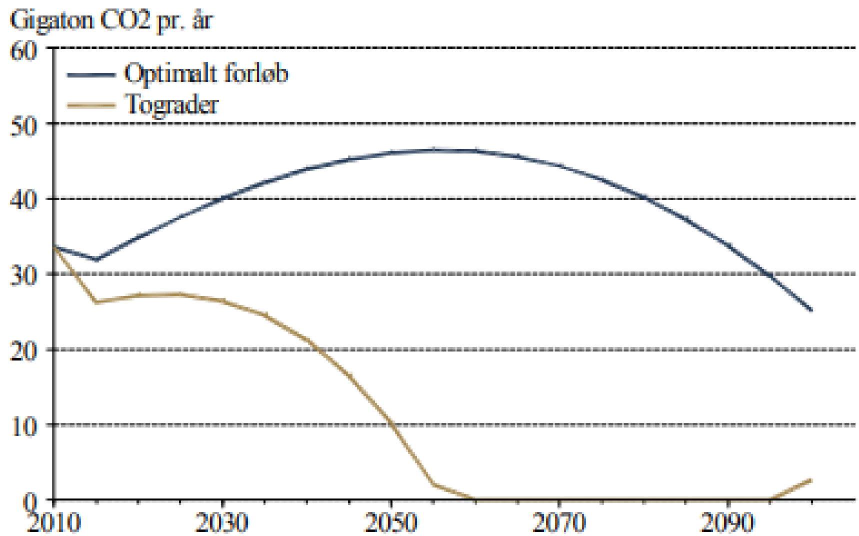
In both scenarios, the global average temperature is still above 2° Celsius degree. By having a climate policy with a 2° Celsius degree target, there is a possibility that climate change would not be out of control. As a climate policy initiative example to reach the 2° Celsius degree target, a carbon tax could be added to around 50 dollars per ton carbon. By adding a carbon tax, the price of carbon emission increases. The level of the carbon tax will increase until the year 2060 where the level of carbon emission will be zero, after which the tax level will decrease. Thus, by adding a carbon tax, the carbon emission will reduce to zero in the year 2060. This is shown in Figure 13 where the dollars per ton carbon is shown in the vertical axis, and the years are shown in the horizontal axis. The carbon tax level is shown for the optimal scenario in the blue graph and the two degree-scenario in the brown graph [Dørs, 2015].



source: [Dørs, 2015]

Figure 13: Carbon emissions tax-level

With a 2° Celsius degree target climate policy, carbon emissions will drop to zero in the year 2060. This is shown in Figure 14 where the blue graph shows the optimal scenario just like the brown graph in Figure 11. The two degree-scenario is shown in the brown graph. The billion of tonnes carbon emission is shown in the vertical axis, and the years are shown in the horizontal axis [Dørs, 2015]. The same behavior of carbon emissions is also shown in Figure 8 in the simple climate-Solow model.



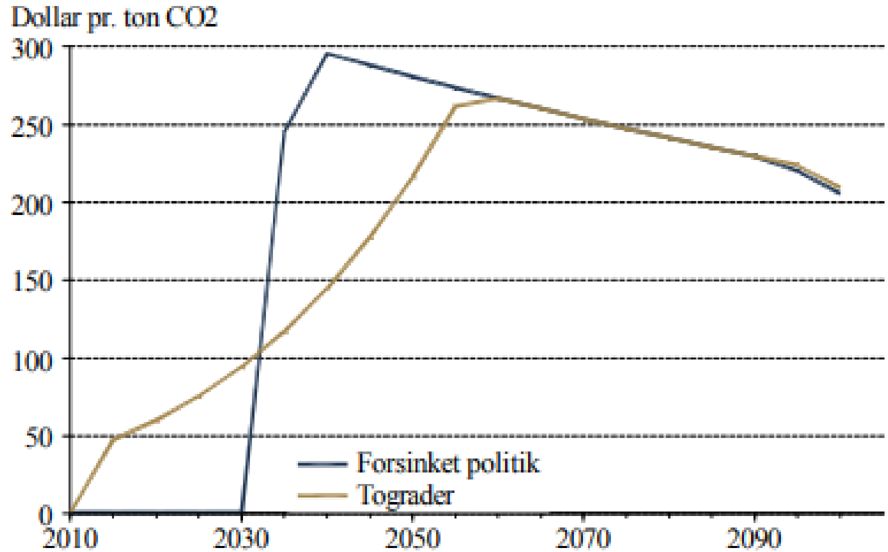
source: [Dørs, 2015]

Figure 14: Industrial emissions

Reducing carbon emissions to reach the 2° Celsius degree target can be costly. The production per capita around the year 2050 is approximately 2.5 percent lower in the two degree-scenario than in the optimal scenario. The two degree-scenario GDP per capita will be 130 percent higher in the year 2050 than in the year 2010, while the GDP in the optimal scenario will be 150 percent higher in the year 2050 than in the year 2010. However, from the year 2100 and further, the GDP per capita (minus climate damages), will be permanently higher in the two degree-scenario than in the optimal scenario [Dørs, 2015].

If the 2° Celsius degree target must be observed, but the world has a 20-year delay[1] on implementing the climate policy of a carbon tax to reach the 2° Celsius degree target. then the 2° Celsius degree target will be reached by a strong reduction in carbon emissions from 2035.

[1] a 20-year delay from 2015

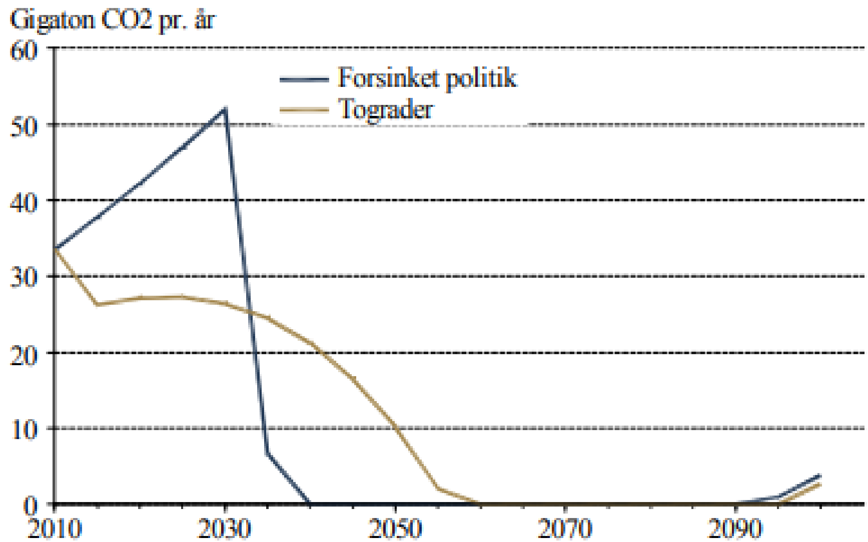


source: [Dørs, 2015]

Figure 15: Carbon tax-level - delayed climate policy

Figure 15 shows this 20 years delay of climate policy, where the dollars per ton carbon is shown in the vertical axis, and the years are shown in the horizontal axis. The blue graph shows the delayed climate policy compared with the two degree-scenario in the brown graph. When the 2° Celsius degree target climate policy is delayed, the annual emissions increase until the year 2035 to a level of 50 billion of tonnes carbon. In order to avoid temperature increases, there is an immediate need of phasing out fossil fuels, and the world needs to avoid industrial emissions from the year 2040. This scenario is impossible, and the two degree-scenario in a DICE model is not optimal. It is therefore optimal to let the temperature increase to flatten out over time. To do so, a discount rate is set.

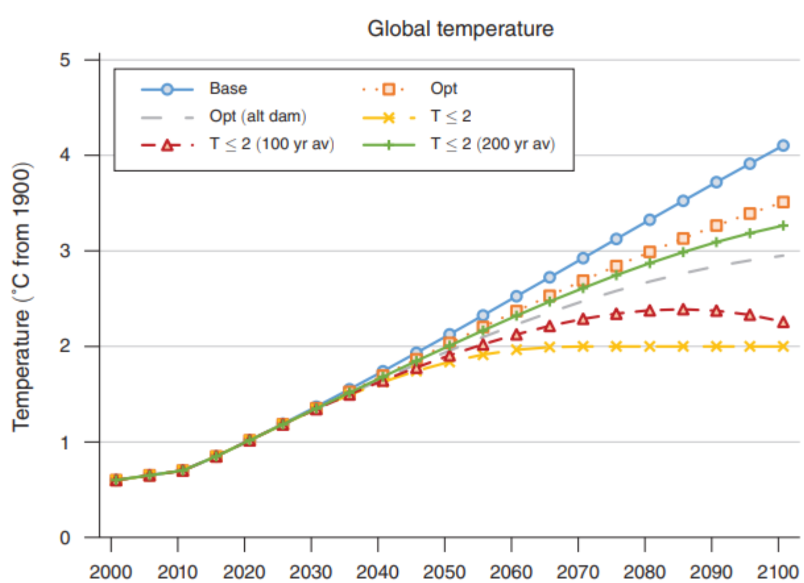
The two degree-scenario is shown in Figure 16 in the brown graph, and the delayed climate policy is shown in the blue graph. The billion of tonnes carbon emission is shown in the vertical axis, and the years are shown in the horizontal axis [Dørs, 2015]. The more delayed a climate policy is, the more strict is the climate policy to reach the same goal.



source: [Dørs, 2015]

Figure 16: Industrial emissions - delayed climate policy

In [Nordhaus, 2019] some results from the DICE 2016 model are shown. In the shown simulations of the DICE model, there are six scenarios: (1) no policy (business as usual (BAU or in this case Base)), (2) a cost-benefit optimum with standard damages (Opt), (3) a cost-benefit optimum with alternative damages ((Opt(alt dam)) where the weight of the damages less than the one with the standard damages, and scenario (4), (5) and (6) are three temperature-limiting strategies where the limit is 2° Celsius degree - and with a 100 years and a 200 years averaging period. The results are shown in Figure 17



source: [Nordhaus, 2019]

Figure 17: Temperature trajectories for different objectives

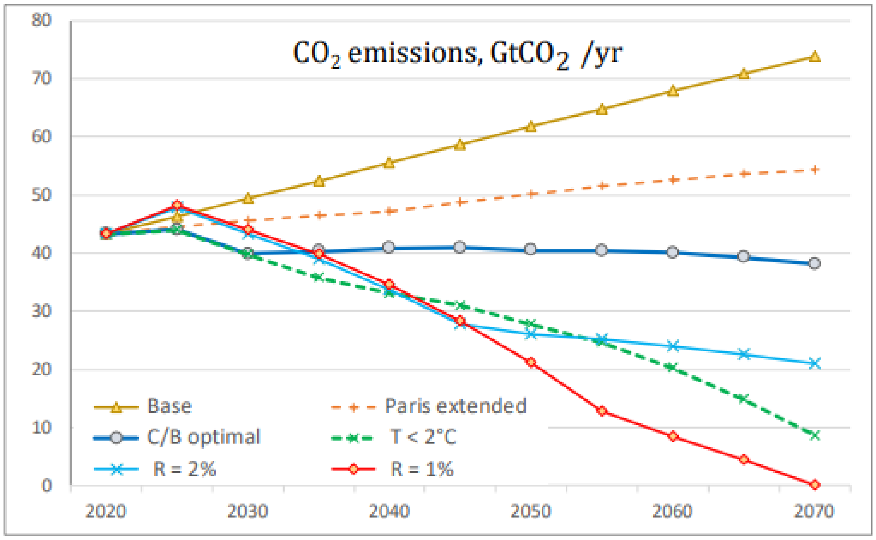
With no policy implemented in scenario (1), the temperature will pass 4° Celsius degree in the year 2100. A 1.5° Celsius degree target is impossible to reach, and a 2° Celsius degree requires negative emissions in the near future. In scenario (2) where a cost-benefit optimum with standard damages with a 3.5 percent discount rate is shown, the temperature increase will surpass 3° Celsius degree in the year 2100. And the same is shown in scenario (3) where the cost-benefit optimum has alternative damages - in this scenario, the temperature rises to 3° Celsius degree in the year 2100. Both scenarios exceed the international policy target. When looking at the average temperature instead of the peak temperature, the standard cost-benefit optimum in scenario (2) follows the path where the 200-year average is limited to 2° Celsius degree. How? Because the temperature is limited to a 2° Celsius degree for each 100-year period [Nordhaus, 2019].

6.2 DICE 2023 model

The above results are from the 2013 and 2016 DICE models. Marts 31 2023 results from the DICE 2023 model have been written in a paper from [Nordhaus, 2023]. The main difference between the DICE 2016 model and the DICE 2023 model is a lower level of optimal temperature change (cost-benefit balance), a lower cost of reaching the 2° Celsius degree target, and an increase in the estimated social cost of carbon [Nordhaus, 2023].

In the study from [Nordhaus, 2023] different scenarios are presented as: 1) *Baseline:* In the baseline scenario (Base), the current policies of 2023 are extended indefinitely. Furthermore, the average price of carbon emissions is about $6 dollars/$CO_2$ and foresees the carbon price to grow by 1 percent per year. 2) *No control:* In the no-controls scenario, there are zero carbon prices and is used as a reference to calculate variables. 3) *Cost-benefit optimal:* In the cost-benefit optimal scenario (C/B optimal), the policies maximize the economic welfare, there is full participation from all nations in 2025, and there are no climatic constraints. The cost-benefit optimal balance is the present value of the cost of abatement and the present value of the benefits of reduced climate damages. The cost-benefit optimal scenario is used as a benchmark to compare other policies. This is also referred to as *optimal* in DICE 2013 model and DICE 2016 model versions. In the DICE 2013 model and DICE 2016 model, the cost-benefit optimal relies on precautionary or threshold-avoidance principles, while the DICE 2023 model relies on monetized impacts and uses standard economic approaches to maximize welfare. 4) *Temperature-limited:* In the temperature-limited scenario ($T < 2°$C), [Nordhaus, 2023] take the cost-benefit optimal policies, but the temperature cannot exceed the target of 2° Celsius degree above the pre-industrial levels. 5) *Alternative discount rates:* The discount rate (R) is important when choosing a climate policy initiative. Therefore, the DICE 2023 model is calculated with different discount rates of 1 percent, 2, percent, 3 percent, 4 percent, and 5 percent per year. 6) *Alternative damage function:* The alternative damage function (Alt damage) has the same structure as the damage function from earlier DICE models. Since the damage function in earlier DICE models has been criticized for omitting several important damages, an alternative damage function is used for the DICE 2023 model that makes the damage more pessimistic. The alternative damage function has a damage/output ratio at a 3° Celsius degree increase, which means that the temperature-damage coefficient is 3 times larger than in earlier DICE models. And lastly, 7) in the Paris Accord scenario (Paris extended), policies are agreed on in 2015 to limit climate changes to 2° Celsius degree above pre-industrial levels. Countries need to meet this agreement, which this scenario assumes they do.

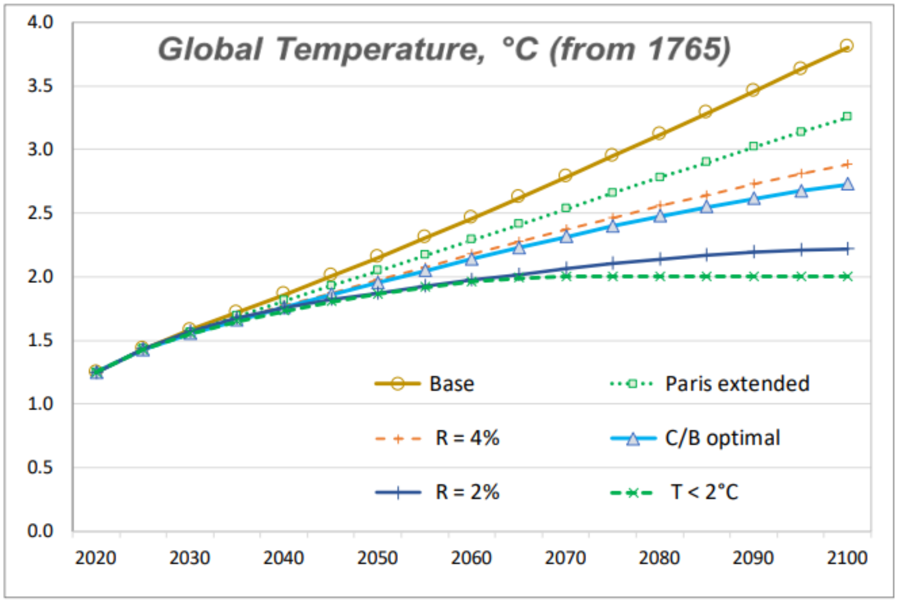
Now looking at the result, Figure 18 shows the carbon emissions in different scenarios where $GtCO_2/yr$ is shown on the vertical axis and the years are shown on the horizontal axis. Like the results in [Dørs, 2015] Figure 11, [Nordhaus, 2023] the base carbon emissions increase, and the C/B optimal carbon emissions increase until around the year 2045, where the emissions decrease to a lower level than in 2020.



source: [Nordhaus, 2023]

Figure 18: Carbon emissions

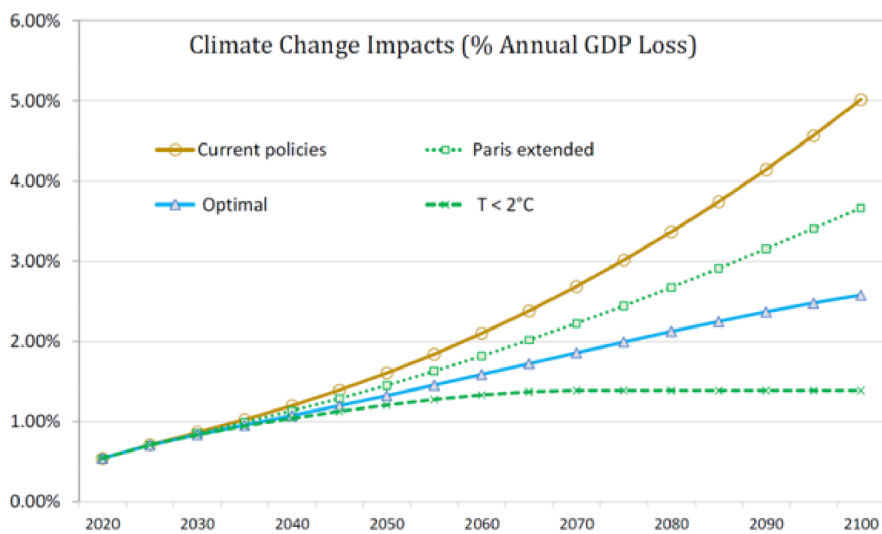
Figure 19 shows the global temperature increases under the different scenarios, where the temperature is shown on the vertical axis and the years on the horizontal axis. In the year 2100, the baseline temperature is 3.8° Celsius degree, the C/B optimal temperature is 2.7° Celsius degree, and the Paris extended is right at 2° Celsius degree. In comparison to [Dørs, 2015], the global temperature has decreased.



source: [Nordhaus, 2023]

Figure 19: Global temperature increase

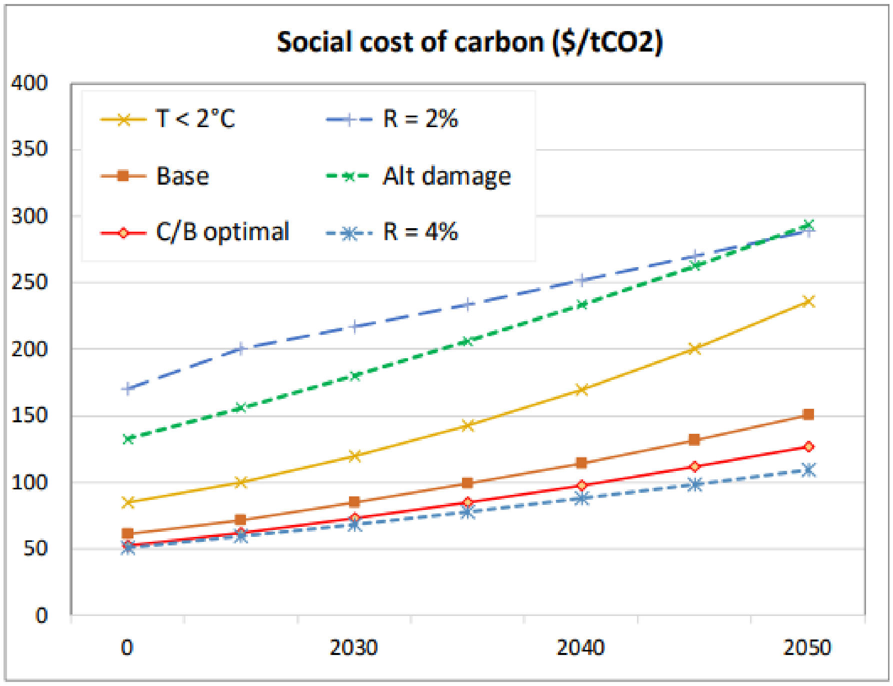
Figure 20 shows the climate change impact on annual GDP loss in percent on the vertical axis and the years on the horizontal axis. In the year 2100, the annual losses in the baseline scenario are 5 percent of output, the annual losses in the Paris extended scenario are 3.7 percent of output, the annual losses in the C/B optimal are 2.6 percent of output, and the annual losses in the $T < 2°C$ is 1.4 percent of output [Nordhaus, 2023].



source: [Nordhaus, 2023]

Figure 20: Climate change impacts (pct. annual GDP loss)

As mentioned, a byproduct of the DICE-model is that an extra ton of carbon emissions may lower the consumption by $40 dollars because the output per worker decreases when there is more carbon emission. This is referred to as *'the social cost of carbon'*. [Nordhaus, 2019]. In other words, the social cost of carbon is the discounted value of economic welfare from an additional unit of carbon emissions and is used to determine climate change policies. The social cost of carbon depends on the time since the marginal damage of carbon emissions changes over time.



source: [Nordhaus, 2023]

Figure 21: Social cost of carbon, alternative scenarios (2019$/$tCO_2$)

Figure 21 shows the social cost of carbon estimation on the vertical axis in 2019 international $, and the years on the horizontal axis. In the year 2020, the social cost of carbon estimation for the baseline is $61/$tCO_2$, $53/$tCO_2$ for the C/B optimal, and $85/$tCO_2$ for the 2° Celsius degree target. The bigger the damages are, the higher the social cost of carbon. In the graph of the 2° Celsius degree target, there is a sharp kink. This represents that the damage function is higher when the temperature exceeds this temperature limit. Furthermore, it is important to look at the discount rate for the social cost of carbon. In the year 2020, the social cost of carbon is $33/$tCO_2$ at a 5 percent discount rate, which is around 38 percent lower than the C/B optimal model. When the discount rate is 1 percent, the social cost of carbon is $429/$tCO_2$, which is more than 700 percent higher than the C/B optimal model. With a discount rate of 4 percent, the social cost of carbon is almost the same as the C/B optimal model at $51/$tCO_2$. This means, a low discount rate gives a higher social cost of carbon and therefore, the discount rate is important when determining the social cost of carbon [Nordhaus, 2023]. Note as mentioned, if the discount rate is high, fewer policy initiatives will be seen as profitable, and if the discount rate is low, more policy initiatives will be seen as profitable.

6.3 Summary of the DICE model

The DICE model is a more advanced IAM model than the simple climate-Solow model. The DICE model describes how economic and climate change affects each other, and helps policy taker to choose climate policy initiatives. In comparison to the simple climate-Solow model, the saving rate in the DICE model is endogenous and not an exogenous constant, because households maximize their consumption through a utility function. The results in the DICE model from [Dørs, 2015] show that in the optimal scenario, the carbon emissions will increase until the year 2060, and afterward will decrease. The global average temperature will still be above the 2° Celsius degree target. Therefore, a 2° Celsius degree target is set because there is a possibility that climate change would not be out of control. To comply with the 2° Celsius degree target, a carbon tax should be added per ton of carbon. The suggested carbon tax in the climate policy initiative will make carbon emissions drop to zero in the year 2060. If there is a 20-year delay in the climate policy, the carbon tax should increase. This scenario is impossible, and therefore it is important to look at the discount rate to make the temperature increase flatten over time [Dørs, 2015]. The results in the DICE model from [Nordhaus, 2019] show that when looking at the peak temperature, the optimal scenario (2) is above the 2° Celsius degree target. However, if the optimal scenario (2) takes the average temperature over a 200-year period, where the temperature is limited to 2° Celsius degree for each 100-year period, the average temperature is 2° Celsius degree [Nordhaus, 2019]. The results in the DICE 2023 model from [Nordhaus, 2023], show that the global temperature decreased in comparison to the [Dørs, 2015] DICE model, but the global temperature is still above the 2° Celsius degree target. Moreover, the DICE model 2023 shows that the climate change impact on GDP annual losses is less when following the 2° Celsius degree target with 1.4 percent of output. The DICE 2023 model does also show the importance of a rightful discount rate for the social cost of carbon and what impact damages have on the social cost of carbon. The bigger the damages are, the higher the social cost of carbon and a lower discount rate gives a higher social cost of carbon. When introducing policy initiatives, it is more likely that a low discount rate will make more policy initiatives profitable compared to a higher discount rate.

7 Analysis of the simulated results

To answer the problem of this paper: *'How will the global economy be affected by climate change?'*, the analysis will be based on the simple climate-Solow model. Since the DICE model is complex, then the simple climate-Solow model is used to understand the economics of climate change.

The parameters used in this paper are the same as in [Tsigaris and Wood, 2016] and is shown below in Figure 37

		Column		
		A	B	C
Row	1	Description	Symbol	Value
	2	Capital's share of income	α	0.3
	3	Savings rate	s	0.25
	4	Depreciation rate	δ_0	0.1
	5	Impact of temperature on depreciation rate	δ_1	0.01
	6			
	7	Initial 2010 population (in billions)	L_0	6.838
	8	Initial 2010 population growth rate	$g_{L,0}$	0.023
	9	Parameter affecting population growth	δ_L	0.052
	10			
	11	Initial 2010 total factor productivity	A_0	3.955
	12	Initial productivity growth rate	$g_{A,0}$	0.015
	13	Parameter affecting productivity growth	δ_A	0.011
	14	Temperature impact on productivity growth		0.001
	15			
	16	Initial world GDP (trillions of 2005 US $)	Y_0	63.69
	17	Initial world capital (trillion of 2005 US $s)	K_0	135
	18			
	19	Initial emission intensity	σ_0	0.549
	20	Initial 2010 growth of emissions intensity	$g_{\sigma,0}$	−0.01
	21	Parameter affecting emissions intensity growth	δ_σ	−0.0002
	23	Damage parameter	θ_1	0.002384
	24	Damage parameter	θ_2	2
	25	Damage parameter	θ_3	0.00000507
	26	Damage parameter	θ_4	6.754
	27			
	28	CCR per trillion tonnes	β	0.0018
	29	Initial Carbon (billions of tonnes)		530

source: [Tsigaris and Wood, 2016]

Figure 22: Variables, symbols, and values used for the simulated results

The parameters in Table 37 α, s, δ_0, L_0, Y_0, K_0, $g_{\sigma,0}$ and Σ are determined from Nordhaus DICE 2013 model, and the rest of the values are estimated by [Tsigaris and Wood, 2016]. The same values are used, so it is easier to compare this paper's results with the results from [Tsigaris and Wood, 2016], and the results from the Nordhaus DICE model. The period of the theoretical simulated results is from the year 2010 until the year 2200. In the analysis of the simulated results, there will be a simulation of the three most central parameters: average global temperature, carbon emission, and the output per worker. It is important to note that the values in this analysis differ by a few decimals from the values in [Tsigaris and Wood, 2016], which especially have an impact on the cost-benefit analysis. Therefore, as in [Tsigaris and Wood, 2016] this analysis is just to show theoretically what consequences production has on the climate, and cannot reflect real-life development.

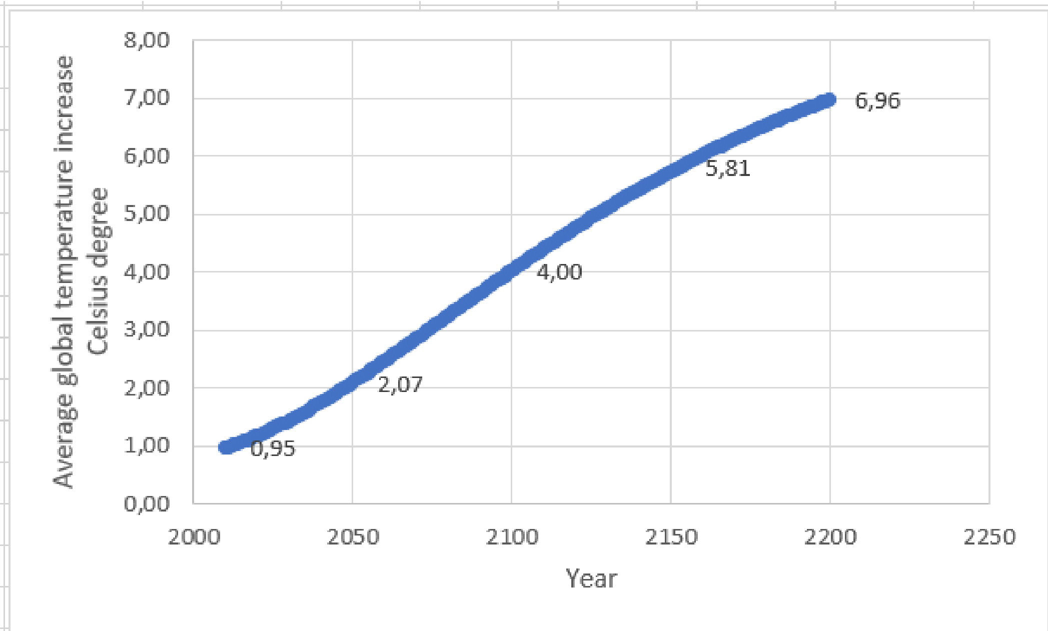
The analysis will compare a few scenarios against the Business-as-usual (BAU) scenario. Therefore, this analysis is sectioned into 5 sections. First, the analysis will look at the BAU scenario, then add a climate policy, a postponement of that climate policy, an optimal scenario with a different discount rate, and then in the end look at the damages.

7.1 Business-as-usual - BAU

To compare the result from the analysis, a business-as-usual (BAU) case scenario is made. The BAU case scenario shows how the temperature, carbon emissions, and output per worker would be if the model does not follow any climate policies. The development of carbon emission is shown since it has a relevant role in the average global temperature. Production leads to carbon emissions. Output per worker shows if there are any economic benefits of climate policy initiatives.

Figure 23 shows the predicted development of the BAU average global temperature from the year

2010 to the year 2200.

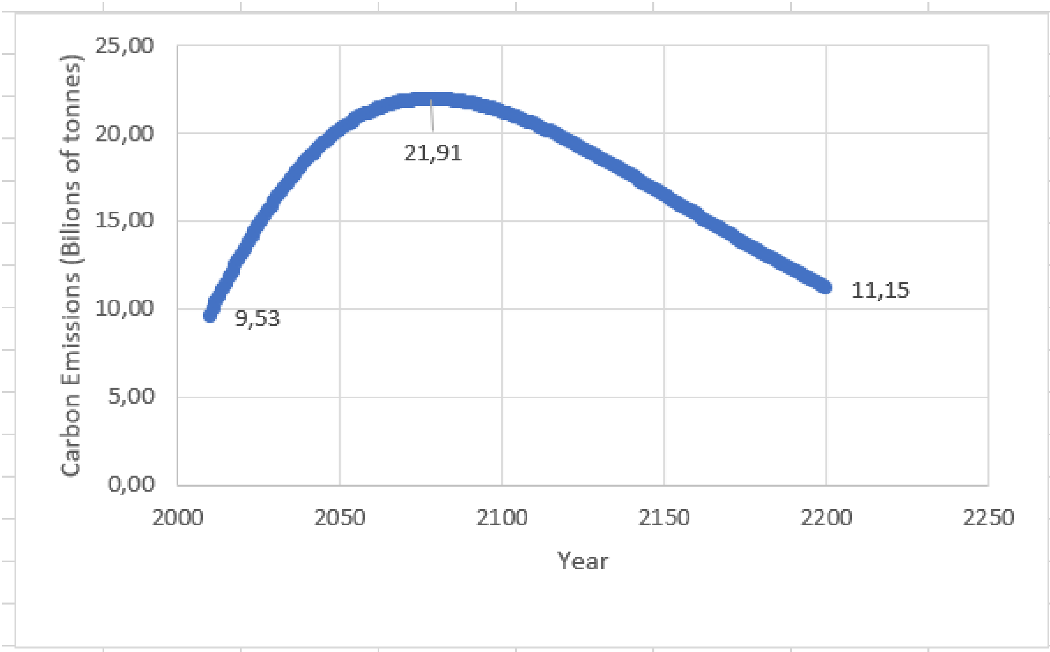


source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 23: Average global temperature (BAU)

In the BAU scenario, the global average temperature will increase from 0.95° Celsius degree in 2010 to 6.9° Celsius degree in 2200, which is an increase of 6.1° Celsius degree. In comparison to the DICE model, the prediction of the average global temperate is nearly the same. In the year 2100, the average global temperature is 4° Celsius degree in the BAU simulation, and in both DICE models seen in Figure 12 and Figure 17, the average global temperature is just around 4° Celsius degree.

Figure 24 shows the predicted development of the yearly predicted carbon emissions from the year 2010 to the year 2200.

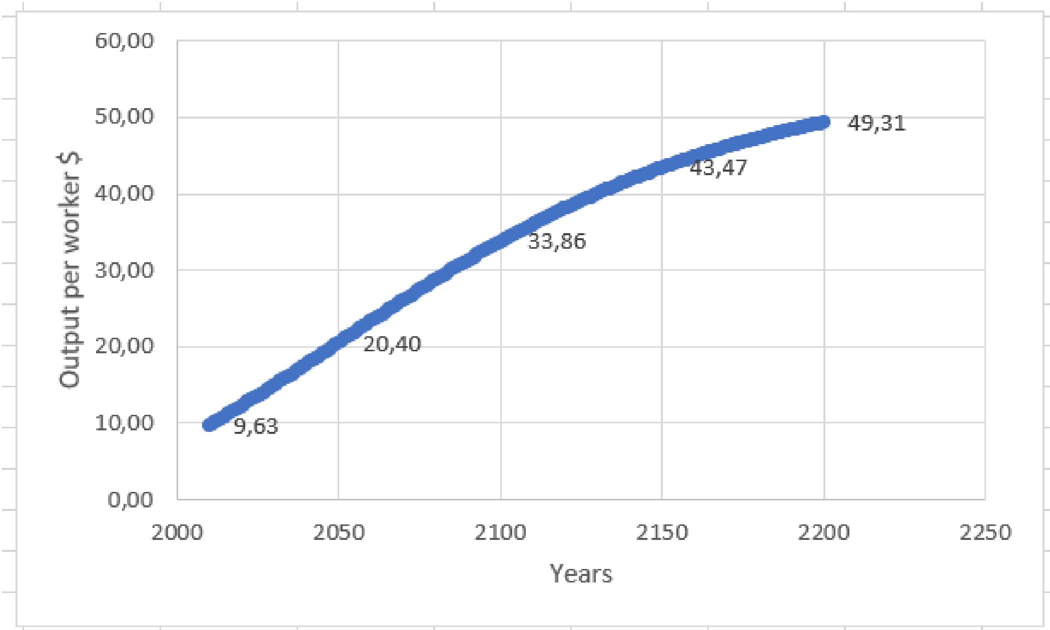


source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 24: Predicted carbon emissions (BAU)

The predicted carbon emissions in the BAU scenario are predicted to reach their peak in the year 2076 with 21.91 billion tonnes. From there, the carbon emissions will decrease because of technology, and in the year 2200, the carbon emission will be 11.15 billion tonnes, which is still higher than the starting point in the year 2010 when the carbon emission was 9.53 billion tonnes. The increase in carbon emissions, in the beginning, is an indication that the output of production grows faster than the carbon intensity. The carbon intensity shows how much carbon emissions there are in a given production.

Figure 25 shows the predicted development of output per worker from the year 2010 to the year 2200.



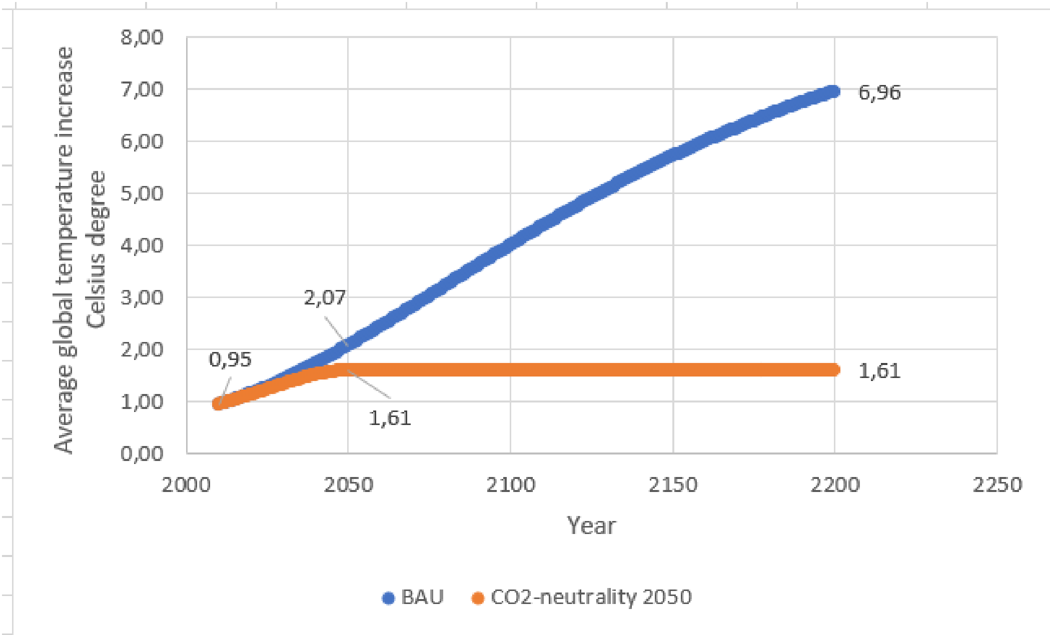
source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 25: Output per worker (BAU)

Figure 25 shows that in the BAU scenario, the output per worker in the year 2010 is $9.87 and will increase to $49.31 dollars in the year 2200. Even though the carbon emission will decrease at some point, the output per worker does not follow that same path and continues to increase. This comes from that there is a reduction in carbon emissions during production.

7.2 Climate policy: CO_2-neutrality in 2050

This section shows if it is theoretically possible to reach a global CO_2-neutrality in the year 2050 with the help of climate policies. To do so, the control rate M_t is used where the starting point in the year 2010 is $M_0 = 0.09$ - as the value of M_t in [Tsigaris and Wood, 2016]. This means that carbon emission is reduced by 9 percent without stopping production. The control rate M_t increases at a constant rate m, where $m = 0.04267$. This is shown in Equation 15. To achieve CO_2-neutrality in the year 2050 and thus a 100 percent reduction of carbon, then $M_{40} = 1$, and then m should be $m = 0.0621$ [Vandborg and Andresen, 2022]. When $M_{40} = 1$, there is no carbon emission in the year 2050, and when $m = 0.0621$ means that the control rate is increased by 6.2 percent each year to reach the goal of no carbon emission in the year 2050. Adding the control rate is shown in Equation 38.

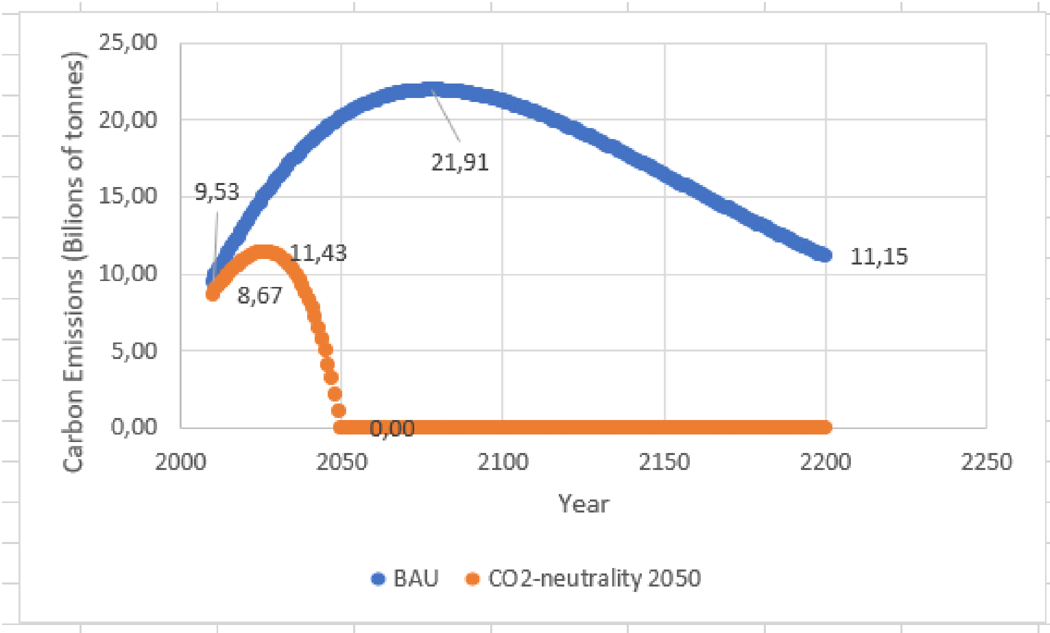


source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 26: Average global temperature (BAU and CO2-neutrality in 2050)

Even though the above scenario with a CO_2-neutrality in the year 2050, where carbon emission is reduced by 9 percent without stopping production, may not be realistic, Figure 26 shows the theoretical point of view of the effects to reduce carbon emissions. In the CO_2-neutrality scenario, the global average temperature will increase from 0.95° Celsius degree in 2010 to 1.6° Celsius degree in the year 2050, which is an increase of 0.66° Celsius degree. After the year 2050, the global average temperature will be stable at this temperature, because there is no more carbon emission, and the increase in the global temperature will be under 2° Celsius degree. The difference in the global average temperature between the BAU scenario and the CO_2-neutrality scenario is a 5.35° Celsius degree.

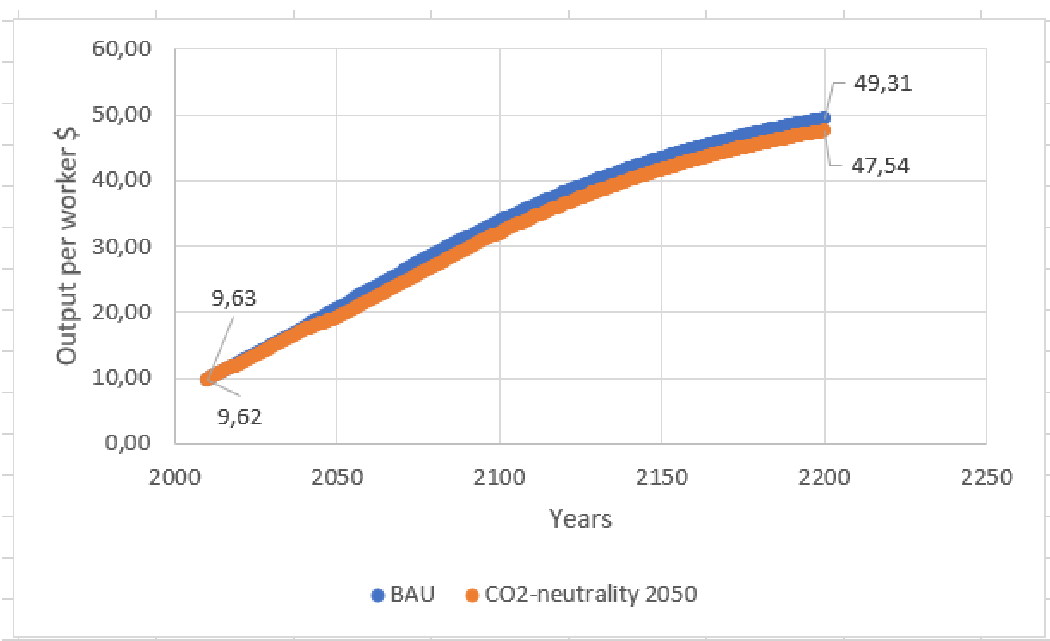
Figure 27 shows how the predicted development of the yearly carbon emissions gets affected by the CO_2-neutrality climate policy.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 27: Predicted carbon emissions (BAU and CO2-neutrality in 2050)

While the predicted carbon emissions in the BAU scenario are predicted to reach their peak in the year 2076 with 21.91 billion tonnes, the predicted CO_2-neutrally scenario is predicted to reach its peak in the year 2026 with 11.43 billion tonnes, after which the carbon emission declines until it reaches to zero in the year 2050 and will continue to do so. The result of the BAU scenario is higher in the year 2010 than the CO_2-neutrally scenario, because the climate policy comes into force in the year 2010, and is therefore 9 percent lower in the first year, $M_1 = 0.09$.

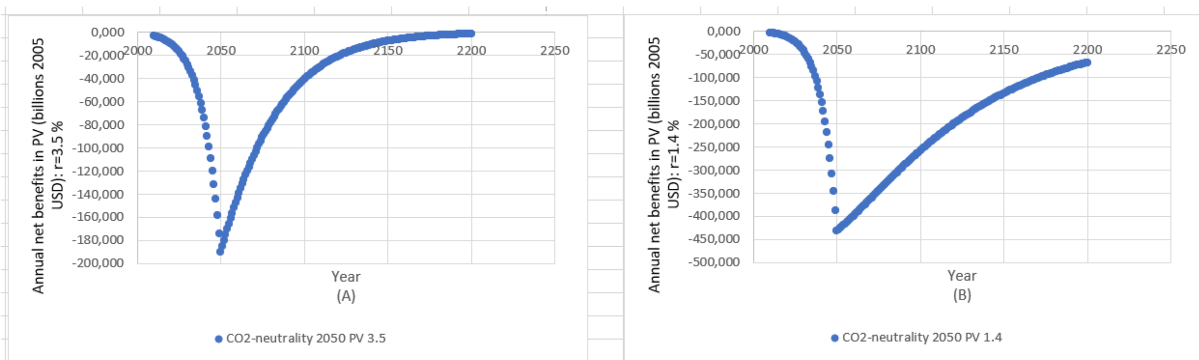


source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 28: Output per worker (BAU and CO2-neutrality in 2050)

Figure 28 shows how the predicted development of output per worker from the year 2010 to the year 2200 gets affected by the CO_2-neutrally climate policy. In the CO_2-neutrally scenario the output per worker is \$47.54 dollars. In comparison to the BAU scenario, this is a \$0.89 dollars loss. Compared to the development of the average global temperature in Figure 26 and the development of carbon emission in Figure 27 the difference between the BAU scenario and the CO_2-neutrally scenario in the development of output per worker in Figure 28 is not as large. The difference between the BAU scenario and the CO_2-neutrally scenario increases a little over time. In the simple climate-Solow model, it is the damage function that affects output per worker throughout production as seen in Equation 4.

Figure 29 shows the cost-benefit analysis in the CO_2-neutrally scenario. M_t and m is still set to be $M_t = 0.09$ and $m = 0.0621$.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

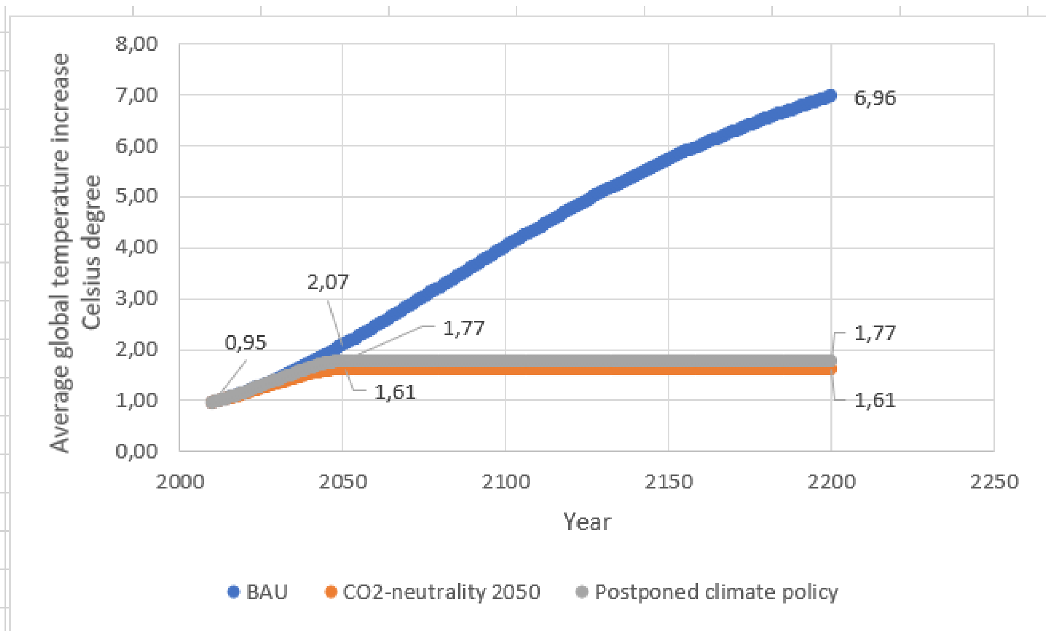
Figure 29: Cost-Benefit analysis (BAU and CO2-neutrality in 2050)

As mentioned, the values in the analysis differ by a few decimals from the values in [Tsigaris and Wood, 2016], which have an impact on the cost-benefit analysis. It means that in this analysis the values of cy_t in Equation 18 are not 'correct'. On the vertical axis, the annual net benefits shown in present value, PV, are shown, and the years are shown on the horizontal axis. Scenario (A) shows the cost-benefit analysis in the CO_2-neutrally scenario with a 3.5 discount rate, while scenario (B) shows the cost-benefit analysis in the CO_2-neutrally scenario with a 1.4 discount rate. In both scenario (A) and scenario (B), the present value peaks in the year 2050. This is also the year where the carbon emission reach to zero in Figure 27.

A cost-benefit analysis is made to see if a climate policy is profitable with a given discount rate. To see if a climate policy is profitable, then all the annual net benefits must be summed up - this means that each years net benefits are summed up to get the total net present value. In scenario (A), the discount rate is set to be 3.5 percent where the present value for the climate policy is $\$-8,093$ dollars. Whereas in scenario (B), the discount rate is set to be 1.4 percent where the present value for the climate policy is $\$-35,418$ dollars. According to this analysis, none of the climate policies are profitable, since the net benefits in both scenarios are negative. Looking at Figure 9, the option with a 1.4 percent discount rate has a positive present value and is therefore profitable. Even thought the cost is higher in the option with a 1.4 percent discount rate than the option with a 5 percent discount rate, it is still more profitable to take the option with a 1.4 percent discount rate because the future benefits weights more than the costs - and thus the net benefits are positive. This result will be the same as for Figure 29 if the values in cy_t were 'correct'.

7.3 Postponement of the climate policy

Often, when policymakers have chosen which climate policy initiative they would like to use, the climate policy does not come into effect immediately. Therefore, this section of the analysis shows if the climate policy is postponed until the year 2025, and shows the theoretical consequence of, if the climate policy is delayed. The climate policy is: *'CO_2-neutrality in 2050'*. Again, the Equation 15 and Equation 38 are used, and m is determined so $M_{40} = 1$. Thus, $m = 0.1011$ [Vandborg and Andresen, 2022]. Since the climate policy is postponed for 15 years, the starting point is at $M_{15} = 0.09$ and since the climate policy will first come into force in the year 2025, the climate policy must be more strict to reach its goal of CO_2-neutrality in 2050.

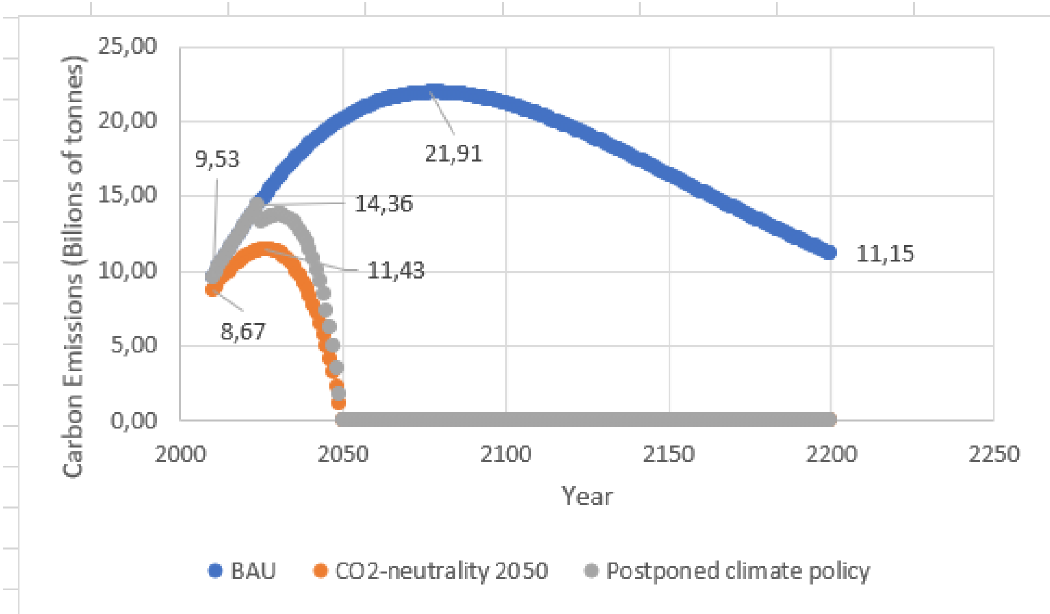


source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 30: Average global temperature (BAU, CO2-neutrality in 2050 and Postponed climate policy)

In comparison to the CO_2-neutrality scenario, when there is a postponement of the climate policy Figure 30 shows, that the average global temperature will increase to 1.77° Celsius degree in the year 2050, which is a 0.16° Celsius degree increase from the CO_2-neutrality scenario in the year 2050. Even though, the increase in the global temperature in the postponed CO_2-neutrality scenario will still be under 2° Celsius degree, the consequence of a postponed climate policy is a higher average global temperature in the year 2050. Therefore, the climate policy should not be postponed - or at least not be postponed any further.

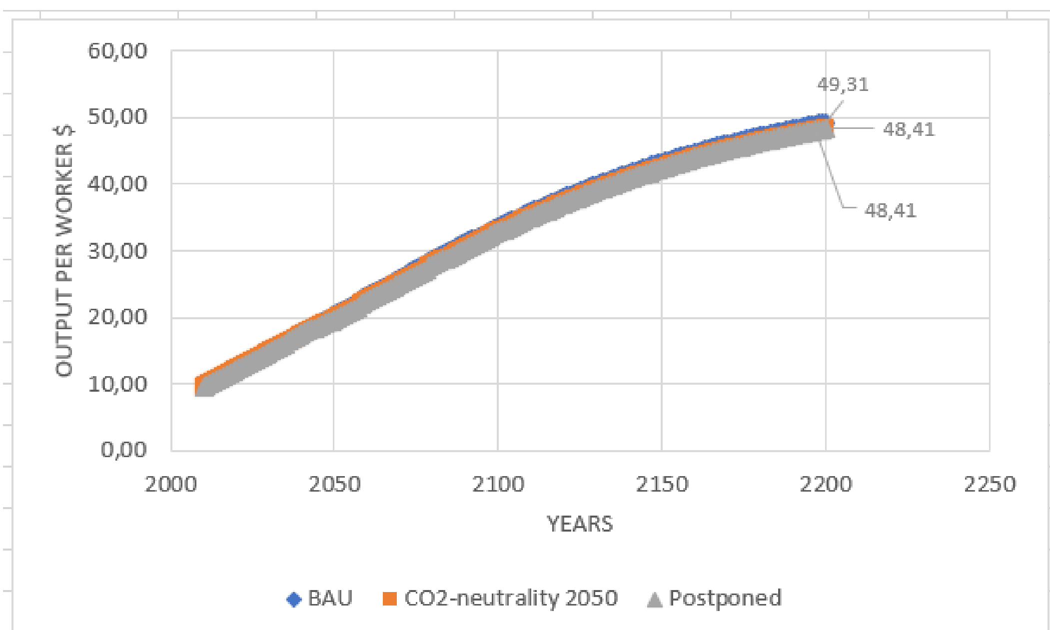
Figure 31 shows how a postponed climate policy affect carbon emission.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 31: Predicted carbon emissions (BAU, CO2-neutrality in 2050 and Postponed climate policy)

Once again, there are consequences of a postponed climate policy. In the postponed CO_2-neutrality scenario, the carbon emission peaks in the year 2024 with 14.36 billion tonnes of carbon emission. In comparison to the CO_2-neutrality scenario, this is 2.39 billion tonnes of carbon emission increase.



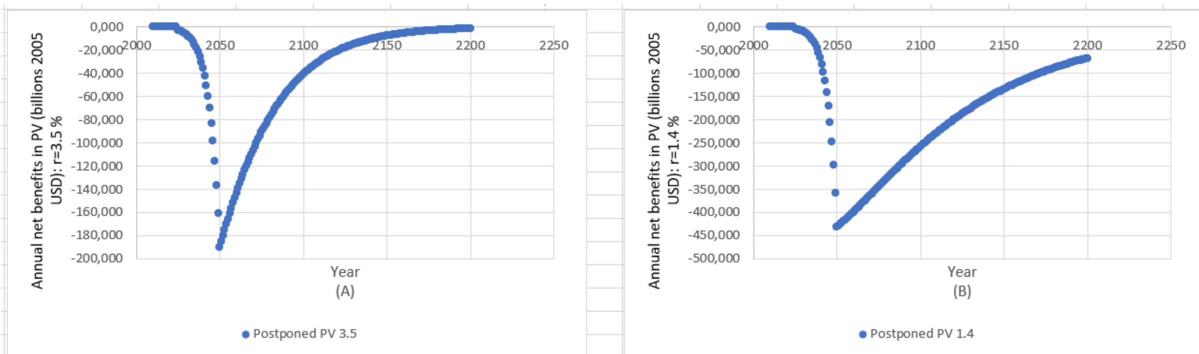
source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 32: Output per worker (BAU, CO2-neutrality in 2050 and Postponed climate policy)

Figure 32 shows how the postponed climate policy affects the output per worker. The result is nearly the same as shown in Figure 28. In the year 2050 and afterward, the postponed CO_2-

neutrality scenario follows the CO_2-neutrality scenario. This indicates that implementing a climate policy, whether it is postponed or not, the output per worker does not get much affected.

Figure 33 shows the cost-benefit analysis for the postponed CO_2-neutrally scenario.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 33: Cost-Benefit analysis (BAU and Postponed CO2-neutrality in 2050)

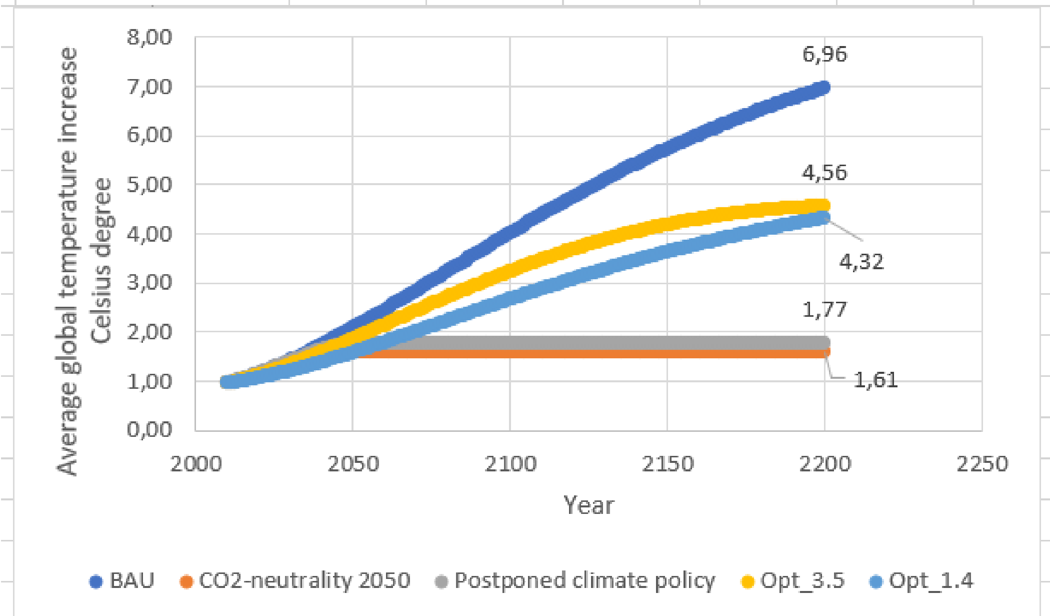
On the vertical axis, the annual net benefits are shown, and the years are shown on the horizontal axis. Scenario (A) shows the cost-benefit analysis in the postponed CO_2-neutrally scenario with a 3.5 discount rate, while scenario (B) shows the cost-benefit analysis in the postponed CO_2-neutrally scenario with a 1.4 discount rate.

In comparison to Figure 29, both scenarios in Figure 33 have an increased present value when the climate policy is postponed. In scenario (A) with a 3.5 discount rate, the present value has increased from $\$-8,093$ dollars to a present value of $\$-7,270$ dollars, and in scenario (B) with a 1.4 discount rate, the present value has increased from $\$-35,418$ dollars to a present value of $\$-34,009$ dollars. Since the present value will become less negative, there is an argument for that the climate policy should be postponed. According to [Vandborg and Andresen, 2022] the climate policy should not be postponed. They show that in scenario (B) with a 1.4 percent discount rate, the positive present value will be reduced, and reduced further the more the climate policy is postponed.

7.4 'Optimal' climate policy

For policymakers to find out what policies that should be invested in, they look at the climate-policy initiative that is most cost-effective. In other words, they choose the climate-policy imitative that will give some good results without costing a lot of money or as [Marks, 2022] noted *'Cost-effectiveness measures how well you are achieving your goals. It is the relationship between the resources consumed and the results achieved'*. Therefore, in a cost-benefit analysis, climate policies maximize economic welfare. The cost-benefit optimal scenario is balancing the present value of benefits of reduced climate damages and the present value of costs of abatement [Nordhaus, 2023]. The benefits of the net present value depend on the discount rate. In this section, the discount rate is set to be 1.4 percent as in The Stern Review, and 3.5 percent as in Nordhaus 2016. The 3.5 percent discount rate is chosen so it is compatible with Figure 17. To calculate the optimal scenarios with a control rate, Equation 38 is used. For the optimal climate policy with a 1.4 percent discount rate, the values of M_t and m are $M_0 = 0.44$ and $m = 0.000$. And the optimal climate policy with a 3.5 percent discount rate, the values of M_t and m are $M_0 = 0.16$ and $m = 0.009$ [Vandborg and Andresen, 2022]. These values may not be realistic, but are illustrated to show theoretical the importance of a discount rate.

Figure 34 shows the predicted development in average global temperature from the year 2010 to the year 2200 by using Equation 14.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 34: Average global temperature (BAU, CO2-neutrality in 2050, Postponed climate policy, Optimal climate policy with 3.5 discount rate and Optimal climate policy with 1.4 discount rate)

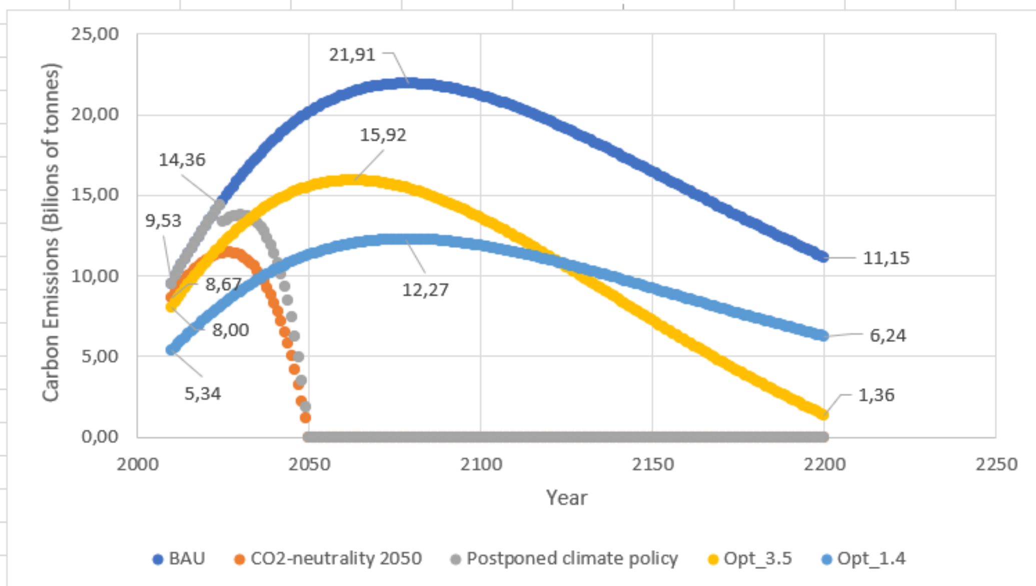
In the year 2010, the average global temperature starts at 0.95° Celsius degree for all scenarios. In the CO_2-neutrality scenario and the postponed CO_2-neutrality scenario average global temperature stops increasing as it reaches the year 2050, where the total annual carbon emission, E_t, is zero. In both scenarios, the average global temperature is below 2° Celsius degree. This means that each year, the average global temperature increases at a temperature level that is below the 2° Celsius degree target.

The Opt-3.5 scenario and the Opt-1.4 scenario have on the other hand both an average global temperature in the year 2200 that is above 2° Celsius degree. The Opt-3.5 scenario average global temperature in the year 2200 is 4.56° Celsius degree, and the Opt-1.4 scenario average global temperature in the year 2200 is 4.32° Celsius degree. This implies that the higher the discount rate is, the higher the average global temperature. Both the Opt-3.5 scenario and the Opt-1.4 scenario have a lower average global temperature in the year 2200 than the BAU scenario has.

In comparison to Figure 12, where the optimal scenario has an average global temperature of 3° Celsius degree in the year 2100, the Opt-3.5 has an average global temperature at 3.23° Celsius degree, and the Opt-1.4 has an average global temperature at 2.66° Celsius degree. In Figure 17, the Opt average global temperature is between $3 - 4°$ Celsius degree in the year 2100.

The results in the Opt-3.5 scenario based on a simple climate-Solow model are almost the same as the Opt scenario in the DICE 2016 model in Figure 12, and therefore the simple climate-Solow model would give an okay prediction of the predicted average global temperature.

Figure 35 shows the predicted development of carbon emissions from the year 2010 to the year 2200 by using Equation 38.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 35: Predicted carbon emissions (BAU, CO2-neutrality in 2050, Postponed climate policy, Optimal climate policy with 3.5 discount rate and Optimal climate policy with 1.4 discount rate)

In the year 2010, the CO_2-neutrality scenario, the Opt-3.5 scenario, and the Opt-1.4 scenario start at a lower level of carbon emission than in the BAU scenario because of the start value of the control rate M_t. The CO_2-neutrality scenario starts 9 percent lower with 8.67 billion tonnes of carbon emission, the Opt-3.5 scenario starts 16 percent lower with 8 billion tonnes of carbon, and the Opt-1.4 scenario starts 44 percent lower with 5.34 billion tonnes of carbon emission than the BAU scenarios carbon emission starting with 9.53 billion tonnes of carbon in the year 2010.

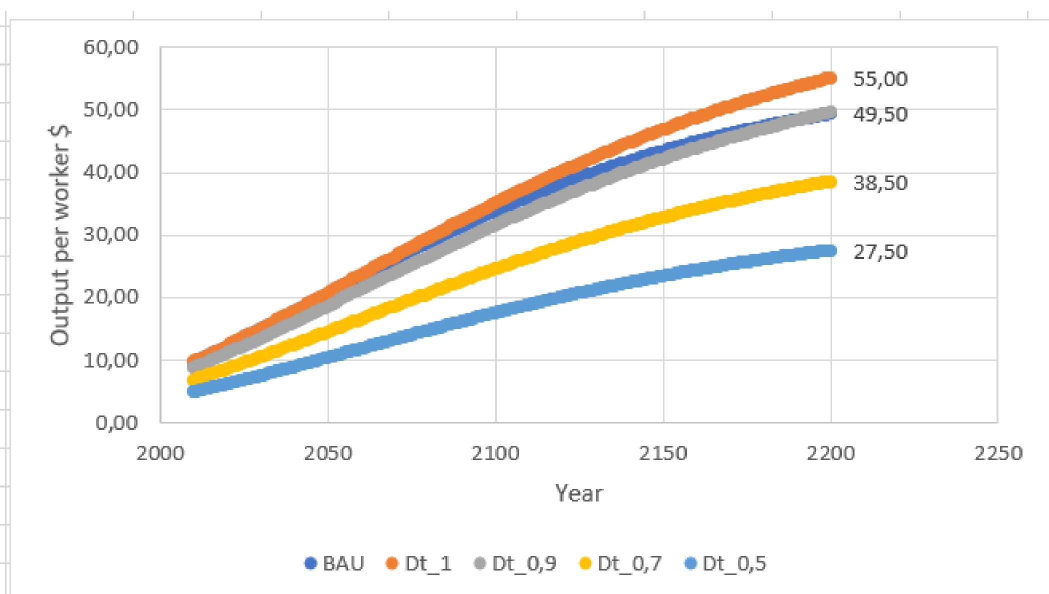
Both the CO_2-neutrality scenario and the postponed CO_2-neutrality scenario are underlying a climate policy, which makes it possible for both scenarios to have an outcome of zero carbon emission in the year 2050. And as in Figure 16, the postponed CO_2-neutrality scenario needs to be more strict to reach the same goal as the CO_2-neutrality scenario - CO_2-neutrality in the year 2050.

As in the BAU scenario, the Opt-3-5 scenario, and the Opt-1.4 scenario, the level of carbon emission increases until it reaches its peak, after which the level of carbon emission will decrease. The Opt-3.5 scenario peaks in the year 2062 with 15.92 billion tonnes of carbon emission, and the Opt-1.4 scenario peaks in the same year as the BAU scenario in 2078 with 12.27 billion tonnes of carbon emission. There are 9.64 billion tonnes of carbon emission between the BAU scenario and the Opt-

1.4 scenario in the year 2078. The level of carbon emission peaks earlier in the Opt-3.5 scenario and lies between the BAU scenario and the Opt-1.4 scenario. However, the level of carbon emission in the Opt-3.5 scenario is lower in the year 2200. The level of carbon emission in the ear 2200 is 1.36 billion tonnes in the Opt-3.5 scenario and is 6.24 billion tonnes in the Opt-1.4 scenario. The crossover happens around the year 2123, when the level of carbon emissions is around 10.80 billion tonnes. The reason why the Opt-3.5 scenario decreases more than the Opt-1.4 scenario is that the Opt-3.5 scenario has a climate policy that is tightened with the value m by 0.09 percent each year, and the Opt-1.4 scenario does not have a climate policy that is tightened over time. In both scenarios, they do not result in CO_2-neutrality in the year 2050. As in Figure 11 the Opt-3.5 scenario to a lower level of carbon emission than in 2010. Both the BAU scenario and the Opt-1.4 scenario end with a higher level of carbon emission than in 2010.

7.5 Damages

According to [Keen et al., 2021], economists does not recognize and understand the climate tipping points, and therefore is the damage function in the DICE model set to be too high. To meet some of the criticism of the DICE model, the analysis will look at different damage function values in the simple climate-Solow model. The damage function is defined in Equation 4 and affects output per worker negatively throughout production. In other words, the damage function is a value in y_t and depends on the average global temperature, which depends on the level of carbon emission. The value of the damage function is replaced by different values in Equation 3 in the case of the BAU scenario. When $D_t = 1$, then y_t grows at a faster rate than when $D_t < 1$ and thus, there is no climate damage when $D_t = 1$[Tsigaris and Wood, 2016]. Figure 36 shows how different values of D_t affects the output per worker, where the output per worker in $ is shown on the vertical axis and the years are shown on the horizontal axis.



source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 36: Output per worker with different damages

The different values of D_t is: $D_t = 1$, $D_t = 0.9$, $D_t = 0.7$, and $D_t = 0.5$. When $D_t = 1$, there are no climate changes that affect the output per worker, and thus the output per worker, y_t grows fast. In the year 2200, the output per worker is \$55 dollars when there are no climate changes. In comparison to the BAU scenario shown in Figure 25 where the output per worker is \$49, 31 dollars, there is a \$5.70 dollars difference between $D_t = 1$ scenario and the BAU scenario. The difference between the $D_t = 1$ scenario and the BAU scenario increases throughout the years. When D_t is 0.9, 0.7, and 0.5, the damages affect the output per worker such that the output per worker is \$49.50 dollars, \$38.50 dollars, and \$27.50 dollars. The closer the value D_t is to zero and hence more damages, the slower the growth of the output per worker. Again, the distance between the different values of D_t and $D_t = 1$ increases throughout the years.

7.6 Summary of the analysis of the simulated results

The analysis is based on simulated results of the simple climate-Solow model using the same values as in [Tsigaris and Wood, 2016]. The analysis first looks at the BAU scenario, then adds a climate policy, a postponement of that climate policy, an optimal scenario with a different discount rate, and then, in the end, looks at the damages. The climate policy is CO_2-neutrality in the year 2050. The average global temperature, carbon emission, and output per worker will be analyzed.

When looking at the average global temperature, it is shown that while in the BAU scenario, the average global temperature continues to increase each year, the CO_2-neutrality scenario stops increasing after the year 2050, and increases each year with a stable level at 1.61° Celsius degree, which is below the 2° Celsius degree target. If the climate policy is postponed, the average global temperature will increase to 1.77° Celsius degree in the year 2050, which is still below the 2° Celsius degree target. This indicated that the effect of a postponed climate policy is a higher average global temperature. The Opt-3.5 scenario and the Opt-1.4 scenario have on the other hand both an average global temperature in the year 2200 that is above the 2° Celsius degree target. Since the Opt-3.5 scenario has a higher average global temperature in the year 2200 at 4.56° Celsius degree than the Opt-1.4 scenario at 4.32° Celsius degree, then it implies that the higher the discount rate is, the higher is the average global temperature. As mentioned, the result in the Opt-3.5 scenario based on the simple climate-Solow model is almost the same result as the Opt scenario in the DICE 2016 model in Figure 12. In the case of predicting the average global temperature, the simple climate-Solow model will theoretically be an okay tool for this.

In the prediction of the yearly carbon emission, it is shown that the CO_2-neutrality scenario reach its peak in the year 2026 with 11.43 billion tonnes of carbon emission, after which the carbon emission declines until the year 2050, where it reaches zero carbon emission. The consequences of a postponed climate policy, the level of carbon emission when it peaks is higher than in the CO_2-neutrality scenario with 14.36 billion tonnes of carbon emission in the year 2024, and the climate policy is more tightened so it is able to reach CO_2-neutrality in the year 2050. Therefore, the climate policy should not be postponed. The two optimal scenarios, Opt-3.5 and Opt-1.4, do not result in a CO_2-neutrality before the year 2200. However, the Opt-3.5 scenario has a tightened climate policy which makes it decline more than the Opt-1.4 scenario. In contradiction to the Opt-1.4 scenario and the BAU scenario, the Opt-3.5 scenario has a lower level of carbon emission in the year 2200 than in the year 2010.

The predicted development of output per worker from the year 2010 to the year 2200, does not change much from the BAU scenario when comparing it to the CO_2-neutrality scenario and the postponed CO_2-neutrality scenario. Therefore, implementing a climate policy, whether it is postponed or not, the output per worker does not get much affected. However, the output per worker gets affected by the damage function. When the damage function is $D_t = 1$, there are no climate changes, which means that the lower the value of D_t is, the more damages are there. Thus, the closer the value D_t is to zero and hence more damages, the slower the growth of the output per worker, in which the output per worker gets more affected by the damages.

For this analysis, the cost-benefit analysis only looks at the theoretical points since the values of cy_t are 'incorrect'. In the CO_2-neutrality scenario, the present value in scenario (A) with a 3.5 percent discount rate is $\$-8,093$ dollars, and the present value in scenario (B) with a 1.4 percent discount rate is $\$-35,418$ dollars. Thus, none of the scenarios are profitable since the net benefits are negative. Taking the results from Figure 12, the option with a 1.4 percent discount rate has a positive present value and is therefore profitable. Options with lower discount rates are more costly but have higher future benefits which weights more than the costs. The same results are applied to the postponed CO_2-neutrality scenario. The difference is that in the postponed CO_2-neutrality scenario, the present values in both scenarios (A) and scenario (B) are less negative than the CO_2-neutrality scenario. But according to [Vandborg and Andresen, 2022], the climate policy should not be postponed. They show that in scenario (B) with a 1.4 percent discount rate, the positive present value will be reduced, and reduced further the more the climate policy is postponed.

Overall, this analysis of the simulated results shows, that a climate policy is needed to reduce the average global temperature and the carbon emission. The results also show that the more the climate policy is postponed, the higher will the average global temperature and the level of carbon emission be. Furthermore, it shows that implementing a climate policy does not affect the output per worker much. What affects the output per worker is among other things the damages. The more damages there are, the slower the growth of output per worker, and hence the level of output per worker will be lower, the more damages there are. Moreover, the discount rate does also have an impact on the decision of implementing a climate policy. The lower the discount rate is, the more profitable the net benefits. As with the average global temperature and the level of carbon emission, the climate policy should not be postponed, since the present value will decrease the further the climate policy is postponed.

8 Discussion

This section will discuss how the global economy will be affected by climate change. What model is chosen to illustrate this effect and the disadvantages of the model.

To analyze how the global economy will be affected by climate change, a Dynamic Integrated Climate Economy model by William Nordhaus can be chosen. The model is referred to as the DICE model and is a part of the Integrated Assessment Model family - IAM models. Since the DICE model is a more complex model, this paper has instead used a simple climate-Solow model, which is also an IAM model. The DICE model helps policymakers to decide whether to implement climate policy initiatives or not. By comparing the simple climate-Solow model with the DICE model, this paper will make it easier to understand the theoretical takeaways from the DICE model and help answer the problem of the paper.

The simple climate-Solow model will only be able to see the main takeaways from the DICE model and see how different parameters interacts with each other. Since it is a simple model, the temperature is only affected by the level of carbon emission. Therefore, the analysis excludes looking at other factors that affect the temperature such as other greenhouse gasses. The DICE model is more complex and takes among other things these factors into account. And lastly, the value of the control rate M_t is a political instrument that can be turned up and down to see how a climate policy affects the model's outcome. In this analysis, M_t is used to see how the climate policy of CO_2-neutrality in 2050 reduces the average global temperature, the level of carbon emission, and how the climate policy affects the output per worker. Thus, the control rate in the simple climate-Solow model is just a political instrument and does not tell how to achieve the climate policy of CO_2-neutrality in 2050.

There are no models without criticism, and the DICE model is not an exception. As pointed out in [Keen et al., 2021] a criticism of the DICE model is how economists value the damage function. In the paper from [Keen et al., 2021] the DICE model is criticized for not to recognized and understanding the climate tipping points, and therefore criticizing the representation of climate change in the DICE model. Tipping points are triggered by higher temperatures, and therefore they criticize the value of the damage function. On the other hand, Nordhaus claims that there are no critical tipping points within the next 300 years until the average global temperature has increased to 3° Celsius degree. Furthermore, they criticize the economists for not recognizing that climate have an impact on production - not only production that is directly affected by the climate such as agriculture, fisheries, and forestry but also other sectors. Economists claim that the weight climate change has on production is small relative to other factors like population, age, income, technology, relative prices, lifestyle, regulation, governance, and so on. [Keen et al., 2021] argue, that the consequences of climate change are wildfire and floods, and this will affect factories at least as much as the consequences of climate change will affect the output from those factories. Moreover, if the temperature in some areas is too high, then no one will live there, and factories placed in such a place will produce zero output. According to Nordhaus, it is only sectors that are exposed to the weather, that are affected by climate change. To understand why [Keen et al., 2021] criticizes how economists value the damage function, the analysis of this paper simulated results of output per worker with different values of the damage function as seen in Figure 36. It is said that climate change only causes loss in production through the damage function, and hence the impact of different values of the damage function on output per worker is analyzed [Tsigaris and Wood, 2016]. The lower the value of the damage function is, the more impact climate change has on the output per worker. Since economists look at how climate affects the output, by having a lower damage function, there is more focus on that climate has a bigger impact on the economy and thus economists and policymakers may set the discount rate lower to make more climate policies profitable, or in general accommodate climate policy initiatives.

In continuation with [Keen et al., 2021], climate change affects the output indirectly by affecting the durability and how long the capital stock will work. As mentioned, an example is that climate change causes extreme weather events such as wildfires, storms, sea level rise, and many more.

Extreme weather events can damage the capital stock and infrastructures, and therefore there is a need for maintenance [Tsigaris and Wood, 2016]. Moreover, as [Keen et al., 2021] mentions that extreme weather events can make people move away from areas where extreme weather events happen often, or where the temperature is too high for people to live there. In such cases, where the capital needs either replacement, maintenance, or climate adaptation, factories spend their money on covering the costs instead of new investments. This is needed to keep the capital-labor ratio constant. New investment is what keeps the economic growth. Furthermore, the output per hour of input may decrease if the inputs need more labor or capital to produce the same level of output as before getting exposed to an extreme weather event. Therefore there is a reduction in the growth rate of total factor productivity [Tsigaris and Wood, 2016].

Another thing the model must take into account is the discount rate. The discount rate is seen as a weight that reflects society's view of how future values are weighted against present value. There is no fixed discount rate and the discount rate is determined differently in each country. If the discount rate is high, fewer policy initiatives will not be determined as profitable, while with a lower discount rate, more policy initiatives will be determined as profitable. Moreover, a higher discount rate results in slower tightening of a climate policy. If a climate policy is tightened too slowly, costs may exceed the benefits, and therefore the discount rate might be set too high. The higher the discount rate is determined to be, the smaller value is the future income given, and therefore it may not be necessary to complete a tight and fast climate policy like they would do if the discount rate is low. In contradiction to a high discount rate, a low discount rate gives income in the future a higher value. A higher discount rate is shown in countries like the Philippines, Pakistan, and India, and thus income in the future is given a little value compared to countries like Denmark which starts with a discount rate of 3.5 percent and thus gives income in the future a higher value. The sensitivity of the discount rate is best shown in Figure 9. It is shown that a lower discount rate may be more costly now, but have higher future benefits, which weights more than the costs.

9 Conclusion

In order to overcome the problem of climate change, some climate policies must be made. To decide which climate policy imitative to choose, Integrated Assessment Model is used to predict economic damages from climate change. This paper uses a simple climate-Solow model to analyze the average global temperature, the level of carbon emission, and output per worker. The simulated results will be compared with the more complex DICE model to answer the problem of this paper: *'How will the global economy be affected by climate change?'* The values used in the simulated results are the same as in [Tsigaris and Wood, 2016]. To compare the simulated results, the analysis first looks at the Business-as-usual (BAU) scenario, secondly, the analysis will look at a climate policy - CO_2-neutrality in the year 2050, and then analyze if the climate policy is postponed. Then an optimal scenario with two different discount rates is analyzed, and lastly, the impact of damages on output per worker is analyzed.

The analysis shows that in order to reduce the average global temperature and the level of carbon emission, climate policies are needed. In the simple climate-Solow model, the policy is controlled by a control rate M_t that can be adjusted. The average global temperature in the CO_2-neutrality scenario increases until the year 2050, after which the temperature is stable. If the climate policy is postponed, the temperature after the year 2050 is a little bit higher and thus, it is suggested to not postpone the climate policy. The same is seen when analyzing the impact of a climate policy and a postponement of the climate policy on the level of carbon emission. The climate policy is more strict and there is a higher level of carbon emission the further the climate policy is postponed. Based on the simulated results on the average global temperature and the level of carbon emission, it is not recommended to postpone a climate policy. In order to meet the criticism of economists for not valuing damages enough, the analysis simulates how output per worker will be affected by different damage functions. Damages will slow down the growth of output per worker, and hence it is essential for critics to have the damages valued more for policymakers to accommodate climate policy. And lastly, it is discussed how sensitive the DICE model is to the discount rate. The higher the discount rate is, the fewer policy initiatives are profitable. And the lower the discount rate is, the higher the value society gives the climate policy. The analysis shows that the lower the discount rate is, the more costly is it, but the net benefits are higher. It is, therefore, more favorable to choose a climate policy with a lower discount rate, since the future benefits weights more than the costs.

In comparison to the DICE model, the simple climate-Solow model gives an okay prediction and understanding of how the global economy will be affected by climate change, and what impact climate policy initiatives have.

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10 Appendix

10.1 Values from [Tsigaris and Wood, 2016]

All parameters and values used in the analysis are the same as in [Tsigaris and Wood, 2016].

Parameters

		Column		
		A	B	C
Row	1	Description	Symbol	Value
	2	Capital's share of income	α	0.3
	3	Savings rate	s	0.25
	4	Depreciation rate	δ_0	0.1
	5	Impact of temperature on depreciation rate	δ_1	0.01
	6			
	7	Initial 2010 population (in billions)	L_0	6.838
	8	Initial 2010 population growth rate	$g_{L,0}$	0.023
	9	Parameter affecting population growth	δ_L	0.052
	10			
	11	Initial 2010 total factor productivity	A_0	3.955
	12	Initial productivity growth rate	$g_{A,0}$	0.015
	13	Parameter affecting productivity growth	δ_A	0.011
	14	Temperature impact on productivity growth		0.001
	15			
	16	Initial world GDP (trillions of 2005 US $)	Y_0	63.69
	17	Initial world capital (trillion of 2005 US $s)	K_0	135
	18			
	19	Initial emission intensity	σ_0	0.549
	20	Initial 2010 growth of emissions intensity	$g_{\sigma,0}$	−0.01
	21	Parameter affecting emissions intensity growth	δ_σ	−0.0002
	23	Damage parameter	θ_1	0.002384
	24	Damage parameter	θ_2	2
	25	Damage parameter	θ_3	0.00000507
	26	Damage parameter	θ_4	6.754
	27			
	28	CCR per trillion tonnes	β	0.0018
	29	Initial Carbon (billions of tonnes)		530

source: [Tsigaris and Wood, 2016]

Figure 37: Variables, symbols, and values used for the simulated results (BAU scenario)

Values

Year	gL,t	Lt	g_σ,t	σt	yt-1	C02/Lt	Et	C02	Tt
	$g_{L,t} = g_{L,t-1}/(1+\delta_L)$	$L_t = L_{t-1} * (1 + G_{L,t})$	$g_{\sigma,t} = \frac{g_{\sigma,t-1}}{1+\delta_\sigma}$	$\sigma_t = \sigma_{t-1}(1+g_{\sigma,t})$	(y_{t-1})	$y_{t-1} * \sigma_t$	$E_t = \sigma_t Y_t$.	$C_0 + \sum_{t=1}^{t} E_i$	$T_t = \beta\left[C_0 + \sum_{i=1}^{t} E_i\right]$;
2010	0,0230	6,8380	-0,0100	0,5490	9,3141	5,1135	9,5275	530,0000	0,9540
2011	0,0219	6,9875	-0,0100	0,5435	9,6314	5,2347	9,9667	539,5275	0,9711
2012	0,0208	7,1327	-0,0100	0,5381	9,8742	5,3130	10,3260	549,4941	0,9891
2013	0,0198	7,2736	-0,0100	0,5327	10,1191	5,3903	10,6832	559,8201	1,0077
2014	0,0188	7,4102	-0,0100	0,5274	10,3661	5,4667	11,0379	570,5033	1,0269
2015	0,0179	7,5425	-0,0100	0,5221	10,6151	5,5419	11,3896	581,5412	1,0468
2016	0,0170	7,6705	-0,0100	0,5169	10,8660	5,6161	11,7379	592,9308	1,0673
2017	0,0161	7,7942	-0,0100	0,5117	11,1187	5,6892	12,0824	604,6687	1,0884
2018	0,0153	7,9137	-0,0100	0,5065	11,3733	5,7611	12,4228	616,7512	1,1102
2019	0,0146	8,0290	-0,0100	0,5015	11,6295	5,8319	12,7588	629,1740	1,1325
2020	0,0139	8,1403	-0,0100	0,4965	11,8875	5,9015	13,0899	641,9328	1,1555
2195	0,0000	10,6155	-0,0104	0,0826	48,7086	4,0216	11,6326	3809,8306	6,8577
2196	0,0000	10,6155	-0,0104	0,0817	48,8036	3,9877	11,5343	3821,4632	6,8786
2197	0,0000	10,6155	-0,0104	0,0809	48,8976	3,9539	11,4365	3832,9975	6,8994
2198	0,0000	10,6155	-0,0104	0,0800	48,9905	3,9202	11,3393	3844,4340	6,9200
2199	0,0000	10,6155	-0,0104	0,0792	49,0824	3,8868	11,2426	3855,7734	6,9404
2200	0,0000	10,6155	-0,0104	0,0784	49,1732	3,8535	11,1464	3867,0160	6,9606

source: [Tsigaris and Wood, 2016]

Figure 38: Formulas and values used for the simulated results (BAU scenario)

Year	gA,t	At	δK	Dt	k,t	y,t	kss,t (no dmg)	yss,t (no dmg)
	$y_{t-1} * \sigma_t \frac{(1+G_{L,t})}{1+\delta_A} \sigma, t)$ $C_0 + \sum_{t=1} E_i$	$A_{t-1} * (1 + G_{A,t})$	$\delta_K = \delta_0 + \delta_1 T_t$.	$D_t = 1/\left(1 + \theta_1 T_t^{\theta_2}\right)$	$k_{ss,t} = \left[\frac{sA_tD_t}{\delta_K + g_{n,t}}\right]^{1/(1-\alpha)}$	$y_t = D_t A_t k_t^\alpha$.	$k_{ss,t} = \left[\frac{sA_tD_t}{\delta_K + g_{n,t}}\right]^{1/(1-\alpha)}$	$y_{ss,t} = D_t A_t k_{ss,t}^\alpha$.
2010	0,0150	3,9550	0,1000	0,9978	19,5760	9,6314	19,6389	9,6530
2011	0,0148	4,0137	0,1000	0,9977	20,2567	9,8742	20,3243	9,8972
2012	0,0147	4,0726	0,1000	0,9976	20,9450	10,1191	21,0175	10,1436
2013	0,0145	4,1317	0,1000	0,9975	21,6403	10,3661	21,7180	10,3922
2014	0,0144	4,1910	0,1000	0,9974	22,3422	10,6151	22,4256	10,6428
2015	0,0142	4,2505	0,1000	0,9973	23,0504	10,8660	23,1399	10,8955
2016	0,0140	4,3102	0,1000	0,9972	23,7645	11,1187	23,8604	11,1501
2017	0,0139	4,3701	0,1000	0,9971	24,4841	11,3733	24,5869	11,4067
2018	0,0137	4,4302	0,1000	0,9970	25,2088	11,6295	25,3190	11,6651
2019	0,0136	4,4904	0,1000	0,9968	25,9383	11,8875	26,0563	11,9253
2020	0,0134	4,5508	0,1000	0,9967	26,6723	12,1470	26,7987	12,1872
2195	0,0020	12,8515	0,1000	0,8986	122,0067	48,8036	142,1328	54,3087
2196	0,0020	12,8767	0,1000	0,8981	122,2417	48,8976	142,5312	54,4466
2197	0,0019	12,9017	0,1000	0,8975	122,4741	48,9905	142,9264	54,5833
2198	0,0019	12,9264	0,1000	0,8970	122,7039	49,0824	143,3184	54,7187
2199	0,0019	12,9510	0,1000	0,8965	122,9310	49,1732	143,7072	54,8530
2200	0,0019	12,9753	0,1000	0,8965	123,2609	49,3051	144,0927	55,0001

source: [Tsigaris and Wood, 2016]

Figure 39: Formulas and values used for the simulated results

Other values used to recreate models from [Tsigaris and Wood, 2016]

Year	AC,t	M0 = 0.09	m = 0.04267	Omega	E_t (M)	cyt	PV_1,4	PV_5
	$AC_t = \Omega_t M_t^2$	$M_t = M_{t-1}(1+m)$		$\Omega_t = \Omega_{t-1}(1+g_{\Omega,t})$	$E_t = (1-M_t)\sigma_t Y_t$	$cy_t = (1-AC)D_t A_t k_t$	$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t}$	$NPV = \sum_{t=0}^{n} \frac{B_t - C_t}{(1+r)^t}$
2010	0,000	0,090	0,043	0,060	4,81	9,63	0,00	0,00
2011	0,001	0,094	0,043	0,059	4,86	9,87	-0,01	0,00
2012	0,001	0,098	0,043	0,058	4,91	10,11	-0,01	-0,01
2013	0,001	0,102	0,043	0,057	4,96	10,36	-0,01	-0,01
2014	0,001	0,106	0,043	0,057	5,00	10,61	-0,01	-0,01
2015	0,001	0,111	0,043	0,056	5,04	10,86	-0,01	-0,01
2016	0,001	0,116	0,043	0,055	5,08	11,11	-0,01	-0,01
2017	0,001	0,121	0,043	0,054	5,12	11,36	-0,01	-0,01
2018	0,001	0,126	0,043	0,053	5,15	11,62	-0,01	-0,01
2019	0,001	0,131	0,043	0,053	5,18	11,88	-0,01	-0,01
2020	0,001	0,137	0,043	0,052	5,21	12,14	-0,01	-0,01
2195	0,018	1,000	0,043	0,018	0,00	47,91	-0,07	0,00
2196	0,018	1,000	0,043	0,018	0,00	48,01	-0,07	0,00
2197	0,018	1,000	0,043	0,018	0,00	48,10	-0,07	0,00
2198	0,018	1,000	0,043	0,018	0,00	48,19	-0,07	0,00
2199	0,018	1,000	0,043	0,018	0,00	48,28	-0,06	0,00
2200	0,018	1,000	0,043	0,018	0,00	48,41	-0,06	0,00

source: [Tsigaris and Wood, 2016]

Figure 40: Other formulas and values used for the simulated results (BAU scenario)

10.2 Simulated results based on values from [Tsigaris and Wood, 2016]

Year	BAU	CO2-neutrality 2050	Postponed climate policy	Opt_3.5	Opt_1.4
2010	0,95	0,95	0,95	0,95	0,95
2020	1,16	1,13	1,16	1,12	1,07
2030	1,42	1,33	1,40	1,34	1,21
2040	1,73	1,52	1,64	1,58	1,39
2050	2,07	1,61	1,77	1,85	1,58
2060	2,44	1,61	1,77	2,14	1,79
2070	2,83	1,61	1,77	2,42	2,01
2080	3,23	1,61	1,77	2,70	2,23
2090	3,62	1,61	1,77	2,97	2,45
2100	4,00	1,61	1,77	3,23	2,66
2110	4,38	1,61	1,77	3,47	2,87
2120	4,74	1,61	1,77	3,68	3,08
2130	5,09	1,61	1,77	3,87	3,27
2140	5,41	1,61	1,77	4,04	3,45
2150	5,72	1,61	1,77	4,18	3,62
2160	6,01	1,61	1,77	4,30	3,78
2170	6,27	1,61	1,77	4,40	3,93
2180	6,52	1,61	1,77	4,47	4,07
2190	6,75	1,61	1,77	4,52	4,20
2200	6,96	1,61	1,77	4,56	4,32

source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 41: Simulated results of average global temperature

Year	BAU	CO2-neutrality 2050	Postponed climate policy	Opt_3.5	Opt_1.4
2010	9,53	8,67	9,53	8,00	5,34
2020	13,09	10,94	13,09	10,80	7,33
2030	16,09	11,26	13,75	13,01	9,01
2040	18,44	8,32	11,40	14,58	10,33
2050	20,13	0,00	0,00	15,52	11,27
2060	21,21	0,00	0,00	15,90	11,88
2070	21,78	0,00	0,00	15,81	12,20
2080	21,91	0,00	0,00	15,35	12,27
2090	21,69	0,00	0,00	14,58	12,15
2100	21,19	0,00	0,00	13,59	11,86
2110	20,47	0,00	0,00	12,45	11,46
2120	19,59	0,00	0,00	11,19	10,97
2130	18,60	0,00	0,00	9,88	10,42
2140	17,54	0,00	0,00	8,55	9,82
2150	16,44	0,00	0,00	7,22	9,21
2160	15,33	0,00	0,00	5,93	8,59
2170	14,24	0,00	0,00	4,68	7,97
2180	13,16	0,00	0,00	3,50	7,37
2190	12,13	0,00	0,00	2,39	6,79
2200	11,15	0,00	0,00	1,36	6,24

source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 42: Simulated results of the level of carbon emissions

Year	BAU	CO2-neutrality 2050	Postponed		Dt_1	Dt_0,9	Dt_0,7	Dt_0,5
2010	9,63	9,63	9,63		9,65	8,69	6,76	4,83
2020	12,15	12,13	12,15		12,19	10,97	8,53	6,09
2030	14,82	14,76	14,80		14,89	13,40	10,42	7,45
2040	17,58	17,37	17,48		17,71	15,94	12,40	8,86
2050	20,40	19,64	19,64		20,61	18,55	14,43	10,31
2060	23,20	22,42	22,42		23,54	21,19	16,48	11,77
2070	25,97	25,16	25,16		26,48	23,83	18,53	13,24
2080	28,64	27,82	27,82		29,37	26,43	20,56	14,69
2090	31,21	30,36	30,36		32,20	28,98	22,54	16,10
2100	33,63	32,77	32,77		34,94	31,45	24,46	17,47
2110	35,90	35,03	35,03		37,57	33,81	26,30	18,78
2120	38,00	37,13	37,13		40,07	36,06	28,05	20,03
2130	39,94	39,06	39,06		42,43	38,19	29,70	21,22
2140	41,71	40,82	40,82		44,66	40,19	31,26	22,33
2150	43,32	42,43	42,43		46,73	42,06	32,71	23,36
2160	44,77	43,88	43,88		48,66	43,79	34,06	24,33
2170	46,08	45,19	45,19		50,44	45,40	35,31	25,22
2180	47,26	46,37	46,37		52,09	46,88	36,46	26,04
2190	48,32	47,43	47,43		53,60	48,24	37,52	26,80
2200	49,31	48,41	48,41		55,00	49,50	38,50	27,50

source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 43: Simulated results of output per worker and damages

Year	CO2-neutrality 2050 PV 3.5	CO2-neutrality 2050 PV 1.4	Postponed PV 3.5	Postponed PV 1.4
2010	-3,201	-3,201	0,000	0,000
2020	-9,859	-12,102	0,000	0,000
2030	-27,825	-41,926	-6,548	-9,866
2040	-74,256	-137,343	-35,943	-66,479
2050	-190,359	-432,184	-190,281	-432,008
2060	-143,362	-399,534	-143,362	-399,534
2070	-106,233	-363,416	-106,233	-363,416
2080	-77,835	-326,844	-77,835	-326,844
2090	-56,565	-291,567	-56,565	-291,567
2100	-40,860	-258,531	-40,860	-258,531
2110	-29,380	-228,187	-29,380	-228,187
2120	-21,051	-200,691	-21,051	-200,691
2130	-15,041	-176,019	-15,041	-176,019
2140	-10,723	-154,042	-10,723	-154,042
2150	-7,632	-134,578	-7,632	-134,578
2160	-5,425	-117,414	-5,425	-117,414
2170	-3,851	-102,332	-3,851	-102,332
2180	-2,732	-89,114	-2,732	-89,114
2190	-1,937	-77,556	-1,937	-77,556
2200	-1,374	-67,524	-1,374	-67,524

source: E. Rønnow calculations inspired by [Tsigaris and Wood, 2016]

Figure 44: Simulated results of the cost-benefit analysis

10.3 Equations in the simple climate-Solow model

All equations are based on the values from [Tsigaris and Wood, 2016]. Equations used in the CO_2-neutrality scenario are almost the same as in the BAU scenario. The difference is marked with the color red.

Output per worker in the year t, y_t:

$$y_t = D_t A_t k_t^{\alpha} \tag{29}$$

Damage function in the year t, D_t:

$$D_t = \frac{1}{1 + \theta_1 T_t^{\theta 2}} \leq 1 \tag{30}$$

Labor share in the year t, L_t:

$$L_t = L_{t-1} * (1 + g_{L,t}) \tag{31}$$

Technology in the year t, A_t:

$$A_t = A_{t-1} * (1 + g_{A,t}) \tag{32}$$

Capital in the year t, $k_{ss,t}$:

$$k_{ss,t} = [\frac{sA_tD_t}{\delta_K + g_{n,t}}]^{1/(1-\alpha)} \tag{33}$$

Change in annual average global temperature in the year t, T_t:

$$T_t = \beta[C_0 + \sum_{i=1}^{t} E_t] \tag{34}$$

emission intensity in year t, σ_t:

$$\sigma_t = \sigma_{t-1}(1 + g_{\sigma,t}) \tag{35}$$

The emissions control rate in the year t, M_t:

$$M_t = M_{t-1}(1 + m) \tag{36}$$

Carbon emission when calculating temperature in the year t, E_t:

$$E_t = (1 - M_t)\frac{(y_{t-1} * \sigma_t) * L_t}{3.67} \tag{37}$$

And Carbon emission when calculating carbon emission in the year t, E_t:

$$E_t = (1 - M_t)\sigma_t Y_t \tag{38}$$

The abatement cost function in the year t, AC_t:

$$AC_t = \Omega_t M_t^2 \tag{39}$$

The abatement cost coefficient in the year t, Ω_t:

$$\Omega_t = \Omega_{t-1}(1 + g_{A,t}) \tag{40}$$

Total income per capita net of abatement cost in year t, ct_t:

$$cy_t = (1 - AC)D_tA_tk_t \tag{41}$$

The net present value, NPV:

$$NPV = \sum_{t=0}^{n} \frac{NB_t}{(1+r)^t} \tag{42}$$