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Simulating sustainable futures

Investigating the implications of CO_2 emission caps on economic growth in the OECD

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Abstract

The matters of economic growth and climate change are both widely subjected to discussions and policymakers are under immense pressure to make decisions that enhance economic growth and stop climate change. Policies that ensure economic growth have traditionally had a negative impact on climate change and vice versa. It is therefore important to study how various policies can address the connection between the two. This paper analyses the potential effectiveness of implementing absolute caps on carbon emitting capital stock and investments in environmentally friendly technology as policy strategies to combat climate change and its implications on economic growth within the OECD. The analysis is based on a model for economic growth that considers technology to be endogenous. It is conducted through simulations in order to observe the trajectory of GDP per capita as well as accumulated pollution, which is then compared to set carbon budgets. The results show that technological advancements are crucial in order to sustain long-term economic growth. It also shows an initial period of degrowth is likely to happen. The study emphasises the welfare gains that are acquired through sustainability that could compensate for the initial losses in material well being. Further, the results show that a complete reduction in environmentally harmful capital stock is necessary. By investigating these policies, this paper contributes with useful insights in the duality that is economic growth and climate change.

Key words: Economic growth, Climate change, Absolute caps on emissions, Technological change, OECD

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Abbreviations

AR6	IPCC Sixth Assessment Report
BAU	Business as usual
CAPMF	Climate Actions and Policies Measurements Framework
CO_2	Carbon Dioxide
COP21	2015 United Nations Climate Change Conference
DICE	Dynamic Integrated Climate-Economy Model
GDP	Gross Domestic Product
GHG	Greenhouse Gas
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contributions
OECD	Organisation for Economic Co-operation and Development
R&D	Research and Development
RICE	Regional Integrated Climate-Economy Model
UN	United Nations
US	United States
USD	United States Dollars

1. Introduction

1.1. Background

Global warming is a prevalent threat to the environment, and therefore a substantial threat to humanity. Discussions regarding economic growth have for a long time ignored the presence of climate change and the devastating effects it brings. If economic actors continue operations as they are today, these actions run the risk of pushing 132 million people into poverty and, in addition, forcing 216 million people into migration due to the environmental changes in their home countries (OECD, 2022a).

Furthermore, the economic losses and damages caused by climate change are steadily increasing, and the costs countries face resulting from natural disasters are growing at a more rapid rate than the growth in gross domestic product (GDP). Since the year 1980, the United States (US) has faced direct costs of 2 278 trillion USD resulting from natural disasters. Similarly, Europe is estimated to have faced costs of between 450 and 520 billion euros. Additionally, natural disasters disproportionately affect those living in low- and middle-income countries, who are less equipped to meet the economic losses related to natural disasters (OECD, 2022a).

Even though climate change is a global problem, this study zeros in on the countries that are part of the Organisation for Economic Co-operation and Development (OECD). The OECD consists of roughly 19.5 percent of the world's countries. However, their greenhouse gas (GHG) emissions take up one third of the world's total GHG emissions. Furthermore, when looking at per capita carbon dioxide (CO_2) emissions, the relevance of studying the OECD countries becomes even more apparent. China emits the most aggregate GHGs in the world, roughly 26 percent, whilst the US emits about 12 percent. However, looking at *per capita* emissions, the OECD countries exhibit numbers that are almost double the amount (8.3 tonnes) compared to the rest of the world's average (4.4 tonnes) (OECD, 2022a). In addition to the relatively high intensity of GHG emissions per capita, the OECD consists of developed countries, which can be assumed to have reached a GDP per capita that is compatible with high living standards, as opposed to developing countries who have yet to reach that kind of economic stability. This makes them more relevant to study when exploring different policy adaptations, since it is more realistic for them to be able to implement those kinds of policies.

The members of the OECD have committed to implement climate action policies with the goal of reaching net-zero emissions by the year 2050. This ambition follows from the 2015 Paris Agreement which set up goals for global warming to be limited to 2°C above pre-industrial levels. The OECD developed a framework, called the Climate Actions and Policies Measurements Framework (CAPMF) under the International Program for Action on Climate. As of now, CAPMF consists of 128 policy variables which are distributed through 56 policy instruments. The policies are categorised as sectoral, cross-sectoral and international policies. CAPMF continuously tracks the progress of the countries, through the number of policies adopted as well as the stringency of those policies. There are continuously more policy instruments added to the framework (Nachtigall et al., 2022).

Currently, results in how effective the framework has been have varied. Whilst some countries make constant strides in terms of the number of policies implemented, some countries' progress has come to a halt, and some have even removed policies in the past few years. In addition, not a single OECD country has as of now implemented all policies, and the policies implemented have not been done so at a desirable stringency. Therefore, even though GHG emissions have decreased since 2007, the OECD is not on track to achieving their goals. Additionally, a share of the decrease in GHG emissions can be attributed to the reduction in production following the financial crisis of 2008, not the policies put in place (OECD, 2022a).

1.2. Purpose and research question

The purpose of this study is to analyse how viable caps on carbon dioxide and investments in environmentally sound technology are in order to combat the issue of climate change and what the consequences are for the OECD's economic growth of implementing such policies. The primary subject of the study will be the member countries of the OECD, which will be treated as a unit as opposed to separate countries.

The study focuses on carbon dioxide emissions since they constitute a majority of the GHG emissions that contribute to global warming. As of now, the goal set out by the OECD is net-zero emissions which in effect means that emissions can still exist, but that they have to be compensated for through various strategies. For this study the emission inducing part of the capital stock is reduced to reach zero, 25 and 50 percent of current levels in order to examine how drastic the changes have to be in order to reach a sustainable level of aggregate pollution up until the year 2050. This measure is combined with two different levels of and delays in investment in environmentally sound technology.

1.3. Method

The analysis is conducted by applying absolute caps on carbon dioxide inducing capital stock at three different intensities while simultaneously investing in environmentally sound technology at two different rates. Furthermore, two separate temporal delays in the investments will be applied. Doing so allows for analysing what economic growth is present when contracting part of the economy that traditionally has been considered to be more fruitful, in favour of another that is more in tune with long term social welfare.

The different combinations of policy adaptation available result in a total of 12 simulations. These are then compared to a 13th simulation, where no policies are implemented and the economic activities are assumed to continue as they are now. For the simulations a modified model is used to simulate the development of GDP per capita and aggregate pollution with starting values collected from the year 2019. The starting year of 2019 was chosen since this is the last year that all databases had observed data for. The simulations are conducted using Microsoft Office Excel and the time frame studied is the years 2019 to 2050.

1.4. Delimitations

For this study there are a number of delimitations that should be recognised. For simplicity, there is a disregard for the presence of trade with countries outside of the OECD as well as any possible transfer of production resulting from the caps. Furthermore, since the study examines how much is needed in order to reach sustainability, the funding of the green investments in technology is purely hypothetical with the addition of disregard for possible transition costs. Lastly, there is an assumption that there are existing preferences for sustainability, indicating that an increase in sustainability positively affects social welfare.

1.5. Disposition

The remainder of the thesis begins by introducing the theories that constitute the framework for the analysis. This is presented in section 2. Afterwards, section 3 explores previous research that has been conducted on climate change, economic growth, policies and the connection between the three. This is followed by section 4, which presents the modified model used to conduct the analysis. Section 5 includes a description of the methodology used, as well as what data, calculations and parameters were needed for the simulations. Moving forward, section 6 presents the simulations, which is then followed by their results in section 7. The following section, section 8, contains a discussion of the results, as well as proposed topics for future research. Lastly, section 9 consists of the conclusion.

2. Theoretical framework

2.1. Growth theories

The field of economic growth studies the percentage increase in countries' GDP over time (Hansson, 2023). Since the introduction of the field, three distinct branches of economic growth theories have developed. The earliest branch, the classical growth models, stated that a temporary and positive increase in economic growth leads to an increase in population size, due to increased welfare. Combined with the notion of limited resources this aspect causes an inevitable decrease in real GDP per capita since the resources are shared by more people. A crucial aspect that these theories disregarded was the notion of technology and its effect on long-term economic growth which the second branch, the neoclassical growth theorists, captured in their models. Lastly, endogenous growth theories, which make up the third branch within the field of study, state that economic growth is generated endogenously, e.g. through governmental policies aimed at promoting the acquisition of human capital. This contradicts the notion of the neoclassical models that accentuated exogenous factors, such as technological advances, as the driving force behind sustained GDP per capita growth (CFI Team, 2022). The rest of this section will lift some growth models that were judged to be relevant for this study.

2.2. The Solow growth model

One of the main contributors to the neoclassical branch within the study of economic growth is Robert Solow, who in 1956 introduced the so-called Solow growth model. Solow's growth model originates from the understanding that a country's GDP is a function of their level of labour (or population), *L*, capital, *K*, and technology, *A* (Solow, 1956). This relation is captured by Jones and Vollrath (2013), among others, in equation 2.2.1 below.

$$Y = K^{\alpha}(AL)^{1-\alpha} \tag{2.2.1}$$

In his studies of long-term economic growth, Solow makes central assumptions, some of which will be relevant to the economic model presented in the current paper in later sections. Firstly, Solow assumes that countries only produce one good captured by their GDP, which is the key economic measure that growth studies focus on. Trade between countries is disregarded in Solow's model which in turn implies that the product, i.e. a country's GDP, either can be consumed or saved. This aspect is visible in the expression for the changes in a country's capital stock (Jones & Vollrath, 2013):

$$\dot{K} = sY - \delta K \tag{2.2.2}$$

The change in capital stock, $\dot{K}$, depends on the country's savings rate, *s*, which is multiplied by their output, *Y*. The depreciation of the capital stock due to wear and tear, *δK*, presents the negative term in the equation, since it causes a decrease in capital stock. Solow further assumes that a country's savings equal their investments, *s* (Jones & Vollrath, 2013).

In the model, technology is assumed to be constant and exogenous. The latter aspect will be a key difference to the model developed for this study, which will be elaborated on in later sections. The labour force, *L*, in Solow's production function, grows at a constant rate and proportionally to the country's population. This equates the growth rate of the population, *n*, with the growth rate of the labour force.

$$\frac{\dot{L}}{L} = n \tag{2.2.3}$$

Solow proceeds in his study to develop expressions for both GDP per capita and the growth in GDP per capita. Both formulas with respective derivations can be found in Appendices 1 and 2. Solow's derivation of the growth rate in GDP per capita, *y*, as well as capital stock per capita, *k*, leads to an important insight that technological advances are the main determinant of economic growth in the long run. This relation is shown in equation 2.2.4 below and stems from the derivation shown in Appendix 2 (Jones & Vollrath, 2013).

$$g_y = g_A \tag{2.2.4}$$

2.3. The Romer model of economic growth

Paul Romer advanced the model Solow presented by examining how technological advances come about. Romer accepts the assumption about technological development being the determinant of long-term GDP per capita growth. However, in contrast to Solow, Romer does not take those advances as given (Romer, 1990). This idea leads Romer to a distinction between the part of the labour force that works with the production of output, i.e. GDP, L_Y, and the part that works with research and development (R&D), L_A. Dividing the labour force into two distinct parts generates a production function that differs from the one presented earlier by Solow, as shown in 2.3.1 (Jones & Vollrath, 2013).

$$Y = K^{\alpha}(AL_Y)^{1-\alpha} \tag{2.3.1}$$

The workers that are employed in R&D are instead part of the function that describes how new technology is gained, which is what equation 2.3.2 represents.

$$\dot{A} = \theta L_A^{\lambda} A^{\phi} \tag{2.3.2}$$

The change in technology depends on θ which captures how fast new ideas are developed within the field of research. The variable θ is multiplied by the current level of technology, A, and the number of workers employed in R&D, L_A. The parameter λ shows how much an additional researcher contributes to the level of technology, which is likely to be less than one, indicating a diminishing rate of return. Lastly, ϕ captures how well new research can utilise the current level of technology. Dividing equation 2.3.2 by A generates the general growth rate of technology according to the Romer model (Jones & Vollrath, 2013).

$$g_A = \frac{\dot{A}}{A} = \theta \frac{L_A^{\lambda}}{A^{1-\phi}} \tag{2.3.3}$$

As previously mentioned, the labour force is divided into two distinct groups, one that is employed in the production of goods and services, L_Y, and one employed in R&D, L_A. Equation 2.3.4 captures this aspect.

$$L = L_A + L_Y \tag{2.3.4}$$

A general expression for the GDP per capita growth is given by dividing the production function in 2.3.1 by the labour force, L, taking the expression's logarithm and deriving it with respect to time, shown in equation 2.3.5.

$$g_y = \alpha \cdot g_k + (1-\alpha) \cdot g_A + (1-\alpha) \cdot g_{L_Y/L} \tag{2.3.5}$$

From the Solow model, the calculation that is presented in Appendix 3 indicates that the variables Y and K exhibit the same growth rate, which is also found to be true in Romer's model. Romer further notes that the ratio $\frac{L_Y}{L}$ has to be constant, which following the same argument as Solow, leads to L_Y and L having to grow at the same rate. The growth rate for the ratio $\frac{L_Y}{L}$ will therefore be equal to zero in the economy's steady state. Using the insights presented in the previous paragraph, i.e. equating the growth rates in GDP and capital stock per capita, y and k, and setting the growth rate in the ratio $\frac{L_Y}{L}$ to zero, enables equation 2.3.5 to be simplified as:

$$g_y = g_A \tag{2.3.6}$$

The last important aspect to include from Romer's model of economic growth is the expression for g_A, the technological growth rate. The expression is derived from 2.3.3 by using the understanding that the change in the technological growth rate equals zero in the steady state. This derivation, which is found in Appendix 4 in its entirety, generates the following expression:

$$g_A = \frac{\lambda n}{1-\phi} \tag{2.3.7}$$

The technological growth rate in steady state therefore depends on how much researchers contribute to the development of new technology, λ, the country's population growth rate, n, as well as the ability of current researchers to build their ideas on the existing level of technology and knowledge, ϕ (Jones & Vollrath, 2013).

2.4. Nordhaus' DICE model

The link between the environment and economic growth is often seen as problematic and was, until the later decades of the 20th century, mainly an unexplored field of study. In the ambition to study how governmental policies can influence, and what variables generate sustained economic growth, the phenomenon's environmental impact was often neglected (Brock & Taylor, 2005). This gap within economic growth theories was, however, remedied through a growing number of economists who modified existing growth models by introducing variables that captured the environmental externalities that follow from positive economic growth. One prominent economist that is worth mentioning in this context is William Nordhaus who created the Regional Integrated Climate-Economy (RICE) and the Dynamic Integrated Climate-Economy (DICE) models which explore the interaction between economics and climate change (Nordhaus, 1992).

In his research, Nordhaus uses the RICE model and later the revised version, the DICE model, to explain how economic growth causes an increase in CO_2 emissions. The increase in emissions leads to changes in temperature affecting the ecosystems, which the production of goods and services depends on. Economic growth therefore changes the external conditions for production through the process of environmental change. Nordhaus further lifts the temporal delay that exists in aspects connected to the environment. Here, he both mentions the delay regarding how the production level, GDP, affects the environment, as well as the existing delay in the implementation of (governmental) policies and their effect on climate change (Nordhaus, 1992).

The DICE model is rather complex and will only be briefly summarised here to capture the main idea behind its formation. Nordhaus utilises an established neoclassical growth model, the Ramsey model, and introduces a damage function which relates the CO_2 emissions to GDP growth (Nordhaus, 2019). By doing so, Nordhaus captures the previously overlooked market externalities that the production of goods and services, GDP, causes and that have long-term negative effects on the possibilities for future production. Employing Nordhaus' assumptions, Hansson (2023) created a simplified model which illustrates the core ideas in Nordhaus' model as well as their implication for the economy. Equation 2.4.1 illustrates the production function including a variable, P, that captures the aforementioned pollution externality that Nordhaus lifts.

$$Y = K^{\alpha}(AL)^{1-\alpha}P^{-\gamma} \tag{2.4.1}$$

Changes in the pollution variabel, P, are captured by equation 2.4.2 below.

$$\dot{P} = \frac{\theta}{B}Y - \delta_P P \tag{2.4.2}$$

Equation 2.4.2 consists of one positive term, showing that an increase in the share of an economy's production that is environmentally hazardous, θ, also leads to an increase in P. B captures how big the impact is of the environmentally damaging production, where a higher value for B implies a smaller negative impact. The negative term of the equation, $\delta_P P$, captures the depreciation of P, which is assumed to exhibit a very small number (Hansson, 2023).

The production function in equation 2.4.1 leads to the following expression for GDP per capita growth in steady state:

$$g_y = \frac{1-\alpha}{1-\alpha+\gamma}g_A + \frac{\gamma}{1-\alpha+\gamma}(g_B - n) \tag{2.4.3}$$

Equation 2.4.3 shows that a country's GDP per capita growth in steady state is affected positively by technological advances, g_A, whilst an accumulation in pollution, g_B, and a state's population growth, n, exert a negative impact (Hansson, 2023). The related derivation for equation 2.4.3 can be found in Appendix 5.

3. Previous research

The departure point of this study is the understanding that climate change following economic activities poses a serious threat to the OECD. Therefore, this section presents research on the matter. This is followed by a review of research on absolute caps, since this is the policy strategy investigated in this paper. Absolute caps lead to a contraction of certain economic activities, which is why the concept of degrowth is presented. Lastly, the challenges of implementing economic policies in response to climate change are reviewed.

3.1. Climate change

Human activities in terms of production and consumption have greatly affected the global warming that is observed today (IPCC, 2023a). During the past 200 years, there has been an observed 50 percent increase in carbon dioxide, which constitutes the majority of GHGs (NASA, 2023). Those who are most affected by climate change are vulnerable countries, which coincidentally are the ones who have contributed the least to the climate change observed during the previous decades. The amount of people residing in these communities are estimated to be 3.3–3.6 billion. This means that developed countries, such as the member countries of the OECD, contribute to climate change in a significantly harmful way, whilst not suffering consequences proportional to their contributions (IPCC, 2023a).

The United Nations Framework Convention on Climate Change is the branch within the United Nations (UN) responsible for coordinating the response to climate change on a global level (United Nations, 2023a). In 2015, the UN Climate Change Conference (COP21) took place. During COP21, 194 parties, including the member countries of the OECD, agreed to long-term goals with regards to the climate change the world faces, commonly known as the Paris Agreement. The goal of the Paris Agreement is to limit global warming to 2°C, by pursuing policies that will keep it at 1.5°C. This is the most extensive, legally binding agreement regarding climate change to date (United Nations, 2023b).

A panel that is prevalent in the field of climate change is the IPCC which was formed in 1988 by the World Meteorological Organisation and the United Nations Environment Programme, with the purpose of providing policy recommendations regarding climate change and the difficulties surrounding it (IPCC, 2023b). These recommendations are based on scientific knowledge on climate change. They are presented mainly through their Assessment Reports, of which there are six, the latest one being the IPCC Sixth Assessment Report (AR6). In addition to their Assessment Reports, they also give out Special Reports. They continuously publish information on the current state of climate change in between the Assessment- and Special reports (IPCC, 2023b).

The IPCC has in AR6 set out a so-called climate budget, which states the allowed amount of CO_2 emissions in order to stay within the limits set out by the Paris Agreement (IPCC, 2021). From 2021, the IPCC estimates that in order to have a 50% chance of staying within the 1.5°C goal as set out by the Paris Agreement the world can emit 500 $GtCO_2$ up until the year 2050. The percentiles and carbon budgets are summarised in Table 1.

	1.5°C	1.7°C	2.0°C
50% likelihood	500 $GtCO_2$	850 $GtCO_2$	1350 $GtCO_2$
67% likelihood	400 $GtCO_2$	700 $GtCO_2$	1150 $GtCO_2$

Table 1. World carbon budget, 2020-2050 (IPCC, 2021)

The adaptation of policies so far is rather ineffective according to the IPCC (2023a). Firstly, significant gaps in adaptation exist, and secondly, these gaps seem to grow over time. In addition, there is an observed uneven policy coverage. The emission level indicated in nationally determined contributions (NDC) does not match the trends that the GHG emissions actually follow, so there is an implementation gap (IPCC, 2023a). With the current trend, it is likely that global warming will exceed the goal of 2°C that was implemented under the Paris Agreement.

Furthermore, the risks that come with climate change are higher than previously estimated by the IPCC (2018). Economic losses attributed to GHG emissions will continue to rise and the more it escalates the more difficult it will be to solve. The world faces risks with the current rate of global warming that are unavoidable and irreversible, but they can be significantly reduced if there is an extensive reduction in GHG emissions, to a point of net-negative CO_2 emissions. There also needs to be an immediate reduction in the GHG emissions according to the IPCC (2023a).

To achieve the most optimal outcome, the implementation of policies needs to be accelerated. This would imply a more aggressive approach in the upcoming decades, followed by a less drastic trend towards net-zero emissions. If actions are not immediate, the economic losses will become greater and adaptation limits will be reached when it comes to both human and natural systems (IPCC, 2023a).

3.2. Caps

Caps on GHG emissions have mainly been applied in two ways. Either there is an absolute cap on quantity, or a certain level of intensity of the emission in relation to a certain level of output that is allowed (Ellerman & Wing, 2003). Under the Paris Agreement, there are NDCs including commitments to both intensity based and absolute caps on emissions. There are, however, more parties that have committed to absolute caps in comparison to intensity based caps (United Nations, 2021).

One of the most common designs for caps on emissions is cap-and-trade. This is a system where there is a set amount of emissions allowed for each party, and if one party goes beyond this limit they are allowed to buy the right to more emissions. Cap-and-trade policies have developed over the years, resulting in a few new branches, which include cap-and-share, cap-and-offset and strict carbon caps. Cap-and-share entails that there is a set amount of allowed emissions which are equally distributed between the parties. A strict carbon tax is similar to cap-and-share, where there is an allowed amount distributed between parties, but not necessarily equally. There is also an addition in strict carbon caps where there is a mechanism used as a deterrent, if one party goes beyond its allowed emission level they are penalised. Cap-and-offset is a system in which a party has an allowed amount of emissions, and they are granted investments in projects that are considered to be carbon-reducing. This kind of system is used sparingly because it does not effectively incentivise parties to reduce their emissions (Gurtu et al., 2022).

Cap-and-trade is the most widely adopted policy strategy used when it comes to carbon reduction strategies involving caps. The price of buying emission rights is set on the market. This means that the market for carbon emissions in some sense becomes self regulating in that it creates incentives for varying parties to lower their emissions when the rights to them become too expensive (Gurtu et al., 2022).

Strict carbon caps are considered to be one of the more stringent policies that are used within carbon abatement. The reason for this is that strict carbon caps affect certain parts of the economy in such a way that is potentially harmful, since it lowers production (Gurtu et al., 2022).

3.3. Degrowth

Degrowth as a concept was first discussed by the Austrian-French social philosopher André Gorz and has since been a prevalent subject of study for various economists. Generally, degrowth is defined as a reduction followed by a stabilisation of societies' throughput, which Kallis et al. define as "the energy and resource flows in and out of an economy" (2018:292). It comes from an insight that current actions towards a more sustainable society are not sufficient. Additionally, degrowth aims to redistribute wealth and social security as well as natural resources. This is believed to be achievable through a number of policies. These include work-sharing, increased taxes on high-income workers, shifts in taxation from the labour force to resource use and caps on resources (Kallis et al., 2012). Daly (1992) proposes three objectives when considering policies that should be implemented: sustainable scale of resource use, fair distribution of income and wealth and efficient allocation of resources.

Degrowth opposes the belief that welfare is attributed purely to economic growth, but that an increase in welfare can also be attained by more sustainable activities. Degrowth does not entail a contraction in all economic activities. It does, however, involve a certain decrease in GDP following reductions in economic activities that are considered to be of a large-scale and resource intensive nature. Kallis et al. (2012) argue that degrowth is not only a necessity for solving climate change, but also desirable from an economic standpoint, partly due to the economic losses that come from natural disasters. This is further supported by the fact that CO_2 emissions have been shown to be tightly correlated with economic growth (Nordhaus, 2019).

3.4. Economic policies

Nordhaus (2019) points out that climate change, mainly global warming, presents a great threat to ecosystems and humans. Up until today, the policies and agreements that aim to diminish global warming have been rather ineffective. One major contributor according to Nordhaus are free-riding problems, where he identifies two different types. Firstly, nations tend to act in a way that benefits their national interests the most, which gives rise to non-cooperative policies. A single nation is therefore unlikely to tackle the global problem with climate change alone. The difficulties here are twofold since both climate change and knowledge are public goods. Public goods are goods characterised by nonrivalry and nonexcludability (Samuelson, 1954). Global warming is a global negative externality and knowledge is a positive externality, which tends to have a positive spillover effect. Due to the free-riding problems, the incentives for one single nation to take on the responsibility of investing in environmentally friendly technologies become low. The second free-riding problem that arises is the temptation to push the problem onto the next generation, due to the delay that climate change exhibits (Nordhaus, 2019).

There are several policies that have been introduced as possible solutions for the threat that global warming poses. Nordhaus (2019) argues that the most realistic, and most effective, approach is reductions in emissions, also known as abatement. This is, however, argued by Nordhaus to be expensive and not possible with the current level of technology. Nordhaus proposes that the necessary policies should be introduced as quickly as possible, they should have a high participation rate and the policies should accelerate over time. One vital characteristic that the policies must have is that they need to raise the market price of emissions, which could be achieved by limiting emissions that are allowed. Doing this would correct one market failure, which is the under-pricing of the negative externality that emissions constitute. This would not only signal to consumers and producers what is “good” and “bad”, but also create incentives for investing in environmentally friendly technologies (Nordhaus, 2019).

Since climate change is a global issue, Nordhaus (2019) stresses that governance is of utmost importance when fighting it, and that cooperative multinational policies have to exist in order for the efforts to be efficient. In response to the free-riding problem, Nordhaus proposes climate clubs as a solution. These would constitute agreements that are binding, rather than voluntary, with a system that penalises those who do not adhere to them. This would in turn induce a situation in which each nation takes on the same actions and policies simultaneously, which, in theory, should eliminate the free-riding problems. Nordhaus reaches the conclusion that what is necessary for effectively fighting climate change is new technology, cooperative action, correct pricing and knowledge.

Popp (2006) is another researcher that examines the aspect of market failures in conjunction with environmentally sound research. In his article, Popp highlights the two market failures, i.e. “environmental externalities and the public goods nature of new knowledge” (Popp, 2006:313). Financial incentives are argued by Popp to be necessary in order to, at least partially, remedy the mentioned market failures. Policies that Popp (2006) suggests to provide economic incentives include, but are not limited to, subsidising environmentally sound research and introducing stronger patent rights. Different countries’ governments can therefore either directly increase the amount of environmental research, through direct investments and/or subsidies, or indirectly by providing an economic environment for companies that ensures the profitability of investing in research that benefits the environment.

4. Modified model

The modified model is largely based on the previously presented Romer model. In addition to this, elements from Solow's and Nordhaus' insights are incorporated in order to make the necessary adjustments needed to conduct the analysis. Nordhaus uses a production function, as shown in 2.4.1, that incorporates the environmental impact of the production that is harmful to the environment. The model used in this paper does take the environmental impact into account, but it is independent of the production function. Instead of prescribing it a monetary value, it is seen as something that affects social welfare. Because of this, the environmental impact is analysed separately. There are slight deviations from Romer's original model as well, making the model unique and adapted for the specific needs of this paper.

4.1. Production function

The analysis is based on a production function that shows how GDP is affected by a series of variables and follows Romer's assumption of endogenous technology. There are clear distinctions made in the analysis of the capital stock and technology. Both are divided into one part that is considered to be harmful for the environment and a second part that is considered to be environmentally sound. In this case, the harmful components are those resulting in emissions of carbon dioxide, and the environmentally sound are those that do not. These components will be accounted for in later sections. The production function is shown in its entirety in 4.1.1. The components are as follows: $\overline{K}$ is the capital stock, $\overline{A}$ is technology and L_Y is the part of the labour force that is employed in the production sector.

$$Y = \bar{K}^{\alpha}(\bar{A}L_Y)^{1-\alpha} \tag{4.1.1}$$

As shown in equation 4.1.2 below, technology is divided into two parts. B shows the part of technology that is considered to be harmful for the environment, and C is the part of the technology that is environmentally sound. The parameter ϑ, which is a number between zero and one, shows how well the environmentally sound technology can substitute the technology that is harmful.

$$\bar{A} = B + \vartheta C \tag{4.1.2}$$

Similarly, the capital stock, $\overline{K}$, is divided into two components: environmentally sound capital, N, and environmentally harmful capital, D, as shown in 4.1.3. The parameter ρ reveals to what extent one unit of non-damaging capital can substitute damaging capital. Similarly to ϑ, the parameter ρ also lies between zero and one.

$$\overline{K} = D + \rho N \tag{4.1.3}$$

The respective shares of the environmentally sound and environmentally damaging capital stocks are presented in equations 4.1.4 and 4.1.5. Since β captures a share, it takes on a value between zero and one.

$$D = \beta \overline{K} \tag{4.1.4}$$

$$N = (1 - \beta)\overline{K} \tag{4.1.5}$$

4.2. Environment

The value of and changes in P will be examined independently from the production function. For this, equation 4.2.1 is utilised which shows the different variables and parameters that the changes in P depend on.

$$\dot{P} = s_{BD}(B + D) \tag{4.2.1}$$

Equation 4.2.1 shows the change in the pollution variable, P, which captures CO_2 emissions expressed in $GtCO_2$. As seen in the equation, the changes are a function of the total amount of environmentally damaging technology and capital, B and D. The expression also includes the parameter s_{BD} which captures the impact that the combination of B and D has on the environment.

4.3. Labour force

The labour force in Romer's model consists of people employed in production and people employed in research. For this paper the people employed in R&D are divided into two groups, those employed in the research sector that is seen as environmentally sound, L_C, and those within the environmentally damaging research sector, L_B. The labour force therefore consists of three distinct parts, which equation 4.3.1 shows.

$$L = L_Y + L_B + L_C \tag{4.3.1}$$

L_B and L_C combined present the total number of people employed within the research sector and for the analysis it is assumed that 20 percent of researchers belong to the environmentally sound research sector, L_C. The remaining 80 percent is employed within the environmentally damaging sector, L_B.

Moreover, the growth rate of the labour force is assumed to be the same as in Solow's growth model, see equation 2.2.3.

4.4. Technology

The model makes a distinction between two different types of technology. The first type includes technology that is seen as harmful for the environment and is denoted by the letter B. Changes in B occur according to equation 4.4.1 below, and depend on the general productivity of the research sector, θ_B, the total amount of researchers employed within the sector, L_B, each researcher's ability to contribute, λ, and how well new research can utilise the current level of technology, B^{ϕ}. The parameters θ_B, λ and ϕ are all assumed to take on a value between zero and one.

$$\dot{B} = \theta_B L_B^{\lambda} B^{\phi} \tag{4.4.1}$$

The second part that constitutes a country's total level of technology is the type that is judged to be environmentally sound, C. Changes in C are a function of the same variables as in equation 4.4.1 with the exception of θ_C, i.e. the general productivity of the research sector, which is assumed to differ from θ_B. Equation 4.4.2 captures the changes in C.

$$\dot{C} = \theta_C L_C^{\lambda} C^{\phi} \tag{4.4.2}$$

4.5. Technological growth rate in steady state

Dividing equations 4.4.1 and 4.4.2 by the level of B and C respectively, taking the logarithm of the expressions and deriving them with regards to time generates a general expression for their growth rate in steady state. This is captured in the expression below, where X denotes either B or C. An extensive derivation of this formula can be found in Appendix 6.

$$g_X = \frac{\lambda n}{1-\phi} \tag{4.5.1}$$

4.6. GDP per capita growth in steady state

Similar to the Romer model the growth rate in GDP per capita, g_y, equals the growth rate in a country's technology, $g_{\bar{A}}$. This is shown in the following equation:

$$g_y = g_{\bar{A}} \tag{4.6.1}$$

The derivation follows the same derivation that is used in the Romer model. The expression for the growth rate in $\bar{A}$ in steady state is identical to the expression derived in Romer's model and shown by equation 2.3.7. The only difference is the denotation for the technology level, i.e. using $\bar{A}$ instead of the letter A.

4.7. GDP per capita in steady state

The level of a country's GDP per capita in steady state is shown in the following expression:

$$y^*(t) = \left(\frac{s}{\delta+g+n}\right)^{\alpha/(1-\alpha)} \cdot \left(\frac{L_Y}{L}\right) \cdot \bar{A}(t) \tag{4.7.1}$$

Equation 4.7.1 shows that the level of GDP per capita in steady state positively depends on a country's savings rate, s, the number of workers employed in the production sector, L_Y, as well as their level of technology, $\bar{A}$. Variables that negatively impact GDP per capita are the depreciation rate of capital, δ, the growth rate of technology, g, the country's population growth rate, n, and their population size, L. A derivation for equation 4.7.1 can be found in Appendix 7.

5. Methodology

The study is conducted through 13 simulations using the modified model in order to investigate how the levels of GDP per capita and CO_2 emissions are affected by the introduction of absolute caps on emission inducing capital stock and investments in environmentally sound technology. There are three different extents the caps take on, and the investments take on one of two levels. The simulations are conducted by using the existing data collected from the year 2019 and different combinations of policy measures. The program used is Microsoft Office Excel. The upcoming sections introduce the data that has been collected, the calculations that were made as well as assumptions regarding the parameters.

5.1. Data

Two general remarks about the data used for the simulations should be mentioned. First, the numbers that were chosen for this study were all adjusted for purchasing power to avoid the effects of inflation and different price levels across the observed countries. Second, while some databases provide numbers for the OECD as an entity, other databases, like the Penn World Table (PWT), only included numbers for the member states. In cases like the latter the numbers for the 38 member states were put together in an aggregate number for the OECD as a whole.

5.1.1. Gross domestic product

The value for GDP in the starting year of 2019 was found in OECD dataset 1 (2023). It is the indicator "Gross domestic product (expenditure approach)" and is measured per head, current prices, current PPPs.

5.1.2. Capital stock

The starting value for the total amount of capital, $\overline{K}$, was gathered from PWT 10.01 (University of Groningen, 2023). This variable is "Capital stock at current PPPs (in mil. 2017USD)" (cn). In order to derive the amount of capital that is damaging, D, and non-damaging, N, the indicator "Renewable energy consumption (% of total final energy consumption)" from the World Bank (2023) was used.

5.1.3. Labour force

For the labour force, three different values were used. The values for population and number of people employed, L, were collected from PWT 10.01 (University of Groningen, 2023). These indicators are called "Population (in millions)", (pop), and "Number of persons engaged (in millions)", (emp), respectively. The value for the number of researchers, used to derive L_B and L_C, was gathered from OECD (2022b). In the database this indicator is called "Total researchers in full-time equivalent" (FTE).

5.1.4. Pollution

The starting value for pollution was gathered from the World Bank (2023). In the dataset, the indicator is called “CO2 emissions (kt)” (EN.ATM.CO2.KT).

5.1.5 Overview of starting values

Table 2 below presents an overview of the starting values that were collected.

Variable	Value
GDP per capita (in USD)	46 667
Capital stock	258 073 092
% renewable energy	13.4
Population	1 365 325 143
Labour force	642 755 668
Researchers	5 521 922
Pollution (in $GtCO_2$)	11.61

Table 2. Overview of starting values for variables used, collected from the year 2019

5.2. Calculations

This section presents the calculations that were made in order to obtain the values for the variables that had no existing data.

5.2.1. Capital stock

The starting value for the OECD’s capital stock in 2019 was found in PWT 10.01 (University of Groningen, 2023). As previously mentioned, the simulations conducted in this paper assume a difference between environmentally sound, N, and environmentally damaging capital, D. The weight of the respective categories of capital was captured by the parameter β in equations 4.1.4 and 4.1.5. For the starting values of N and D the parameter β was set to equal 0.866, indicating that 86.6 percent of the OECD’s total capital stock in the year 2019 was assumed to be damaging to the environment. Correspondingly, the environmentally sound capital stock, N, was assumed to constitute 13.4 percent of the total capital stock in 2019.

Since there is a lack of a definite categorisation of the capital stock into environmentally damaging and non-damaging types, the estimate used for this study was based on the share of renewable energy consumption in the OECD. This share was assumed to be proportional to the share of environmentally sound capital stock. The value of N was further divided by 0.75 which follows from solving for N in equation 4.1.3 and setting ρ to 0.75.

5.2.2. Labour force

As captured in equation 4.3.1, the OECD's labour force was divided into three distinct groups. L_Y was calculated by subtracting the number of total researchers (L_B and L_C combined) from the total number of people engaged. The number for total researchers was found in OECD Main Science and Technology Indicators (OECD, 2022b) and in order to find values for L_B and L_C it was assumed that 20 percent of researchers conduct environmentally sound research, while the remaining 80 percent are engaged within the environmentally damaging research sector.

5.2.3. Technology

The technological level for 2019, $\bar{A}_{2019}$, was retrieved by using equation 4.1.1, dividing it by L and solving for $\bar{A}$. This led to the following expression for $\bar{A}$:

$$\bar{A} = \left(\frac{y}{k^{\alpha}}\right)^{1/(1-\alpha)} \cdot \frac{L}{L_Y} \qquad (5.2.1)$$

Similarly to the calculations for the capital stock, the OECD's technology was divided into environmentally damaging technology, B, which constituted 80 percent of the total technology, and environmentally sound technology, C, which amounted to 20 percent. Since the parameter ϑ was set to 0.75, it was assumed that one unit of C only substitutes for 0.75 units of B.

5.2.4. Remaining calculations

Some variables were assumed to exhibit a steady growth and were not subject to any specific modifications. In these cases, the average growth rate of the variable between the years 1990–2019 was calculated and used to make predictions about the variables' continued growth between 2019 and 2050. The average growth rate was calculated according to the following equation:

$$g_x = \left(\frac{x_{1990}}{x_{2019}}\right)^{\frac{1}{19}} - 1 \tag{5.2.2}$$

Variables such as pollution, *P*, and the two types of technology, *B* and *C,* were analysed within the model and equations 4.2.1, 4.4.1 and 4.4.2 capture how the mentioned variables change over time. The changed levels of *P*, *B* and *C* were calculated according to equation 5.2.3 where the changes were added to the previous year's level.

$$x_{t+1} = x_t + \Delta x_t \tag{5.2.3}$$

x denotes the variable in question while *t* denotes the previous year. Δx_t represents the change in the given variable from year *t* to year *t+1*.

5.3. Parameters

In order to perform the calculations, some assumptions had to be made regarding the different parameters used in the relevant equations, which are summarised in Table 3. Firstly, α was set to equal ⅓ in accordance with empirics and Solow's model presented by Jones & Vollrath (2013). The parameters ϑ and ρ were set to 0.75, indicating that the environmentally sound technology and capital cannot fully substitute the harmful ones. This assumption was judged to be realistic since harmful technologies and capital would not exist if there were no economic benefits attributed to them and if the assumption made earlier in the paper about countries' existing preference for environmental sustainability is considered. β shows the share of capital that is seen as environmentally damaging and was set to 0.866 indicating that 86.6 percent of capital was categorised as *D*. The remaining 13.4 percent of the capital stock are represented by *N*.

s_{BD} captures the impact that the combined amount of environmentally damaging capital and technology has on the environment. Since the used databases provided numbers for the change in pollution, $\dot{P}$, as well as numbers for the amount of *B* and *D* for the starting year of 2019, equation 4.2.1 was used to estimate a value for the parameter s_{BD}. Using equation 4.2.1 provided a value of 44.12 which was then used to estimate the accumulated changes in pollution from 2020–2050.

The parameters showing the general productivity of workers in the two different research sectors, θ_B and θ_C, were set to 0,00014 and 0,00857 respectively. These measures were derived by dividing equations 4.4.1 and 4.4.2 by B and C respectively and solving for θ. The growth rates were assumed to equal g_B=0,001 and g_C=0,04. A higher growth rate within the environmentally sound research sector follows from the idea that this sector is developing at a faster rate because of the increased demand for environmentally sound technology seen within the OECD today. The mentioned calculations for θ_B and θ_C can be found in Appendix 8.

Lastly, the parameters λ and ϕ usually lie between 0 and 1 (Jones & Vollrath, 2013). For the simulations conducted in this study they were set to 0,7 and 0,5 respectively.

Parameters	α	ϑ	ρ	β	s_{BD}	θ_B	θ_C	λ	ϕ
Value	⅓	0.75	0.75	0.866	44.12	0.00014	0.00857	0.7	0.5

Table 3. Overview of values for parameters

6. Simulations

There are a total of 13 simulations conducted in this study in order to examine the projection of GDP per capita and accumulated CO_2 emissions between the years 2019-2050. 12 of the simulations show the projection with added policies, and they are compared to a 13th simulation which shows the projection without policies. The two policies used are carbon caps on the capital stock that is considered to be damaging for the environment, D, and investments in environmentally sustainable technology, C. Additionally, there are different assumptions for the delay in implementation of the new technology resulting from the investments.

The first policy, absolute caps, was set out in accordance with the recommendation of the IPCC, which states the need for immediate and drastic policies. The caps on carbon emission indcuing capital stock were therefore introduced drastically, but at a diminishing rate, starting with caps which eliminate 50 percent of the desired amount by 2030, 80 percent by 2040 and 100 percent by 2050. Furthermore, the level of caps varies in that they either result in a reduction to 0, 25 or 50 percent of damaging capital stock left by the year 2050. The second policy, investments in environmentally sound technology, varies in two ways. Firstly, the investments are either “high” or “low”. Secondly, there are two different temporal delays the investments can take on, either a 5-year delay or a 10-year delay.

The simulations are divided into four groups in accordance with the level of caps. The first group consists of only one simulation which shows the projection when no policies are applied. The second group consists of the simulations that result in a complete reduction of the environmentally damaging capital stock. Group 3 are the simulations where the damaging capital stock is reduced to 25 percent by the year 2050. Lastly, group 4 consists of the simulations that leave 50 percent of the damaging capital stock by the year 2050. An overview of the 13 simulations is presented in Table 4 in Section 6.5.

6.1. Group 1

The first simulation conducted shows the projection without any policies or measures.

6.2. Group 2

Group 2 consists of simulations 2-5, where the introduced carbon caps lead to a complete reduction of the environmentally damaging capital stock by the year 2050.

The second simulation shows the predicted change in GDP per capita and accumulated emissions when the investments are high with a 5-year delay, and caps resulting in 0 damaging capital stock by year 2050.

The third simulation shows the predicted change in GDP per capita and accumulated emissions when investments are low with a 5-year delay, and caps resulting in 0 damaging capital stock by the year 2050.

The fourth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are high with a 10-year delay, and caps resulting in 0 damaging capital stock by 2050.

The fifth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are low with a 10-year delay, and caps resulting in 0 damaging capital stock by the year 2050.

6.3. Group 3

Group 3 includes simulations 6-9 which are all characterised by caps resulting in a reduction of the carbon inducing capital stock to 25 percent of its value in the starting year of 2019.

The sixth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are high with a 5-year delay, and carbon caps resulting in 25% of damaging capital stock left by the year 2050.

The seventh simulation shows the predicted change in GDP per capita and accumulated emissions when investments are low with a 5-year delay, and caps resulting in 25% of damaging capital stock left by the year 2050.

The eight simulation shows the predicted change in GDP per capita and accumulated emissions when investments are high with a 10-year delay, and caps resulting in 25% of damaging capital stock left by the year 2050.

The ninth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are low with a 10-year delay, and caps resulting in 25% of damaging capital stock left by the year 2050.

6.4. Group 4

The last group consists of simulations 10-13 where the common trait is that the carbon inducing capital stock is reduced to 50 percent by the year 2050 through the implementation of carbon caps.

The tenth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are high with a 5-year delay, and caps resulting in 50% of damaging capital stock left by the year 2050.

The eleventh simulation shows the predicted change in GDP per capita and accumulated emissions when investments are low with a 5-year delay, and caps resulting in 50% of damaging capital stock left by the year 2050.

The twelfth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are high with a 10-year delay, and caps resulting in 50% of damaging capital stock left by the year 2050.

The thirteenth simulation shows the predicted change in GDP per capita and accumulated emissions when investments are low with a 10-year delay, and carbon caps resulting in 50% of damaging capital stock left by the year 2050.

6.5. Overview of simulations

Table 4 below shows an overview of the simulations and the respective measures.

Group	Simulation	% of D left in 2050	Delay in implementation of C	Type of measure	Code
1	1	BAU	BAU	BAU	BAU
2	2	0	5 years	High	0/5/H
	3	0	5 years	Low	0/5/L
	4	0	10 years	High	0/10/H
	5	0	10 years	Low	0/10/L
3	6	25	5 years	High	25/5/H
	7	25	5 years	Low	25/5/L
	8	25	10 years	High	25/10/H
	9	25	10 years	Low	25/10/L
4	10	50	5 years	High	50/5/H
	11	50	5 years	Low	50/5/L
	12	50	10 years	High	50/10/H
	13	50	10 years	Low	50/10/L

Table 4. Overview of the policies included in each simulation

7. Results & analysis

The following section presents the results that were derived from the 13 simulations. The results will be presented for each simulation as well as an overall result for each group. Additionally, the levels of aggregate pollution derived from the simulations are related to the carbon budgets set out by the IPCC based on two different shares of global emissions that the OECD can be assumed to take on.

7.1. Results from simulations

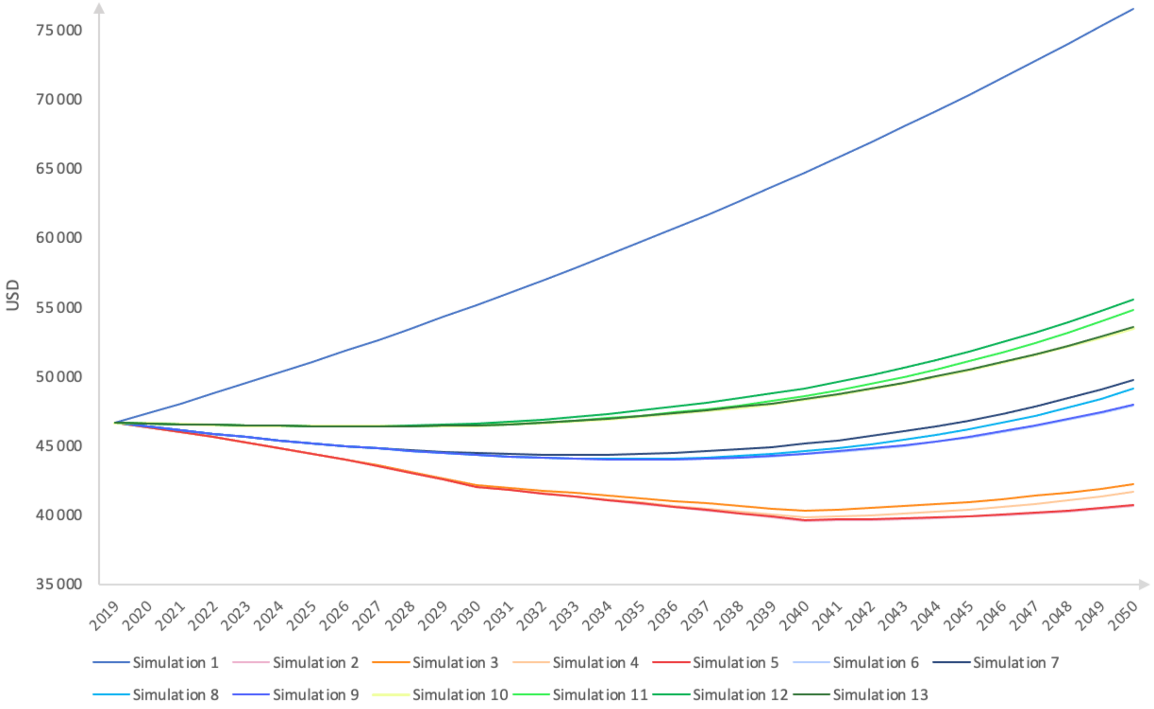

Figure 1. Simulations of the OECD's GDP per capita in USD, 2019–2050. Values for each year can be found in Appendix 9

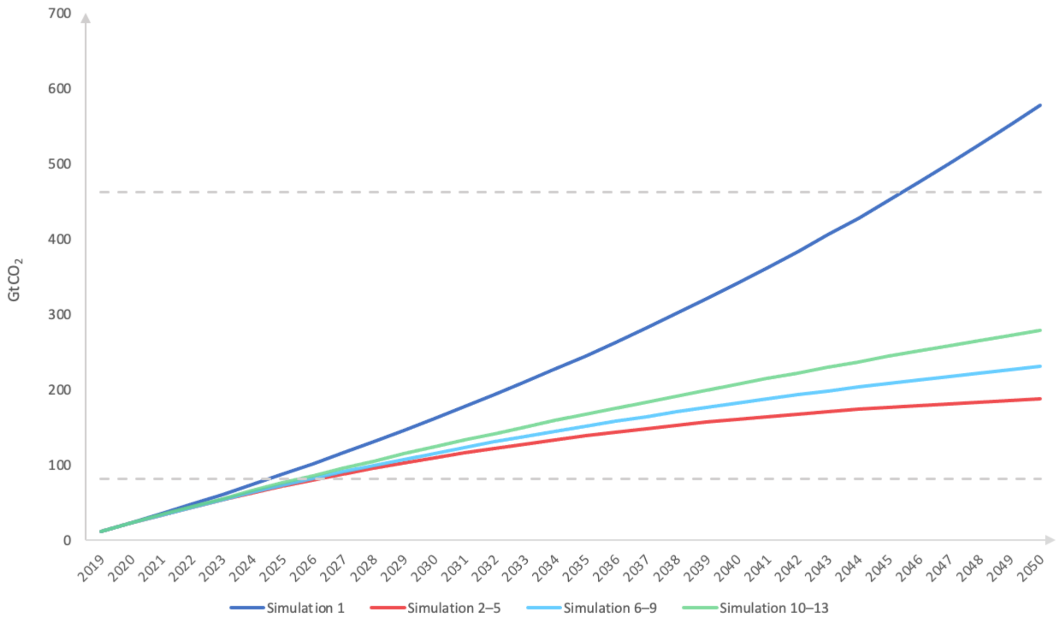

Figure 2. Simulations of accumulated pollution ($GtCO_2$) of the OECD, 2019–2050. There is no visible difference regarding the values of pollution within the groups, they are therefore seen as one when it comes to pollution. Values for each year can be found in Appendix 10

7.1.1. Group 1

Simulation 1, Business as usual (BAU), shows the most growth in GDP per capita and CO_2 emissions out of all the simulations. In the year 2050, GDP per capita reaches 76 555 USD, compared to the starting value of 46 667 USD. Furthermore, pollution increases by roughly 98% between the starting and end year. Both GDP per capita and pollution grow at an increasing rate.

7.1.2. Group 2

This section presents the results from group 2 where the simulations were subject to carbon caps resulting in a complete reduction of the carbon inducing capital stock.

In simulation 2, 0/5/H, the GDP per capita level exhibits an initial decrease until the year 2041. After that turning point, the growth in GDP per capita becomes positive, leading to a level of 40 627 USD per capita in the year 2050. In comparison with the initial level in 2019, the level of GDP per capita in scenario 2 has decreased by roughly 6 000 USD. The aggregate pollution in this scenario grows with a diminishing rate and has by the year 2047 almost stagnated entirely. Much like simulation 2, the third simulation, 0/5/L, shows an initial decrease in GDP per capita, with the same turning point in the year 2041. In this scenario, GDP per capita ends at a level of 42 202 USD, which is a bit higher than in the previous simulation. The growth rate of the aggregate pollution also shows a diminishing tendency but decreases at a slower rate than in the previous scenario.

Simulation 4, 0/10/H, shows an initial decrease in GDP per capita. From the year 2041, GDP per capita exhibits a positive growth, and reaches 41 646 USD by the year 2050. Pollution increases at a diminishing rate, similarly to simulation 3.

Simulation 5, 0/10/L, shows an initial decrease in GDP per capita up until the year 2041, after which it grows at a positive rate. By 2050, GDP per capita reaches 40 964 USD. Pollution follows roughly the same trend as seen in simulation 3 and 4.

Overall, the simulations belonging to group 2 render the lowest GDP per capita. They also entail the longest period of degrowth, before the investments in technology are able to substitute for the losses in capital stock. A switch from degrowth to positive growth in GDP per capita happens after about 22 years. Additionally, GDP per capita is not able to recover completely from the degrowth during the time frame observed. However, aggregate pollution is projected to be the lowest within this group.

7.1.3. Group 3

In simulations 6-9, i.e. group 3, the introduced carbon caps led to a reduction of the carbon inducing capital stock to 25 percent by the year 2050.

Simulation 6, 25/5/H, exhibits an initial decrease in GDP per capita up until the year 2036, after which it grows at a positive rate. By the year 2050, GDP per capita amounts to 47 909 USD. Pollution increases more than in simulation 2–5 but also at a diminishing rate.

Simulation 7, 25/5/L, shows an initial decrease in GDP per capita, which shifts to positive growth after the year 2035. By 2050, the level of GDP per capita reaches 49 766 USD. Pollution increases at a diminishing rate, but ends up at a higher level than in simulation 6.

Simulation 8, 25/10/H, exhibits an initial decrease in GDP per capita, shifting to positive growth the year 2035. By 2050, GDP per capita amounts to 49 110 USD. Pollution follows roughly the same trend as in simulation 7.

Simulation 9, 25/10/L, shows an initial decrease in GDP per capita up until 2035, after which there is positive growth. By the year 2050, GDP per capita reaches 47 988 USD. Pollution increases at a diminishing rate, following about the same trend as simulations 7 and 8.

In general, group 3 exhibits smaller loss in GDP per capita than group 2, with a shorter period of degrowth. A switch from degrowth to positive growth in GDP per capita happens after 16-17 years. Additionally, GDP per capita is able to recover during the observed time frame. Aggregate pollution is higher than in group 2, but significantly lower than in group 1.

7.1.4. Group 4

Results from group 4, where all simulations were characterised by the introduction of carbon caps leading to a 50 percent reduction of the environmentally damaging capital stock, are presented below.

Simulation 10, 50/5/H, exhibits an initial decrease in GDP per capita, shifting to positive growth by the year 2028. GDP per capita reaches 53 469 USD by the year 2050. Pollution increases at a higher rate than in simulations 2-9, although still at a diminishing rate.

Simulation 11, 50/5/L, shows an initial decrease in GDP per capita, which shifts to positive growth by the year 2027. By 2050, GDP per capita amounts to 54 810 USD. Pollution is overall higher than for simulations 2-10, with only a slight diminishing characteristic to the curve.

Simulation 12, 50/10/H, shows an initial GDP per capita decrease up until year 2026. There is positive growth starting in 2027, and by 2050 GDP per capita amounts to 55 543 USD. For pollution, the curve shows roughly the same characteristics and values as in simulation 11.

Simulation 13, 50/10/L, exhibits a decrease in GDP per capita up until 2026, shifting to positive growth in the year 2027. By 2050, GDP per capita amounts to 53 558 USD. Accumulated pollution follows approximately the same curve as simulations 11 and 12.

Overall, group 4 rendered the highest GDP per capita amongst the groups where policies were adopted. It is, however, still significantly lower than for the simulation with no policies. Group 4 also exhibited the shortest time period with degrowth, where the switch to positive growth happens after 8-9 years. Aggregate pollution was higher within group 4 compared to both group 2 and 3, but significantly lower than group 1.

7.2. Results related to the carbon budget

As previously mentioned the IPCC has set out global carbon budgets that state how much the world can emit until the year 2050 in order to reach the goals and/or ambitions set out by the Paris Agreement. The exact numbers for the OECD's carbon budget are presented in Table 5 below. There are two scenarios that were chosen to calculate the budgets that the OECD faces until the year 2050. The third column shows the budget when the OECD's share of the global budget is set to one third, in accordance with their current share of total emission. Column 4 shows their budget when their share of global emissions is assumed to be proportional to their size.

		Global carbon budget (2020-2050)	Estimated OECD carbon budget (2019-2050), (⅓)	Estimated OECD carbon budget (2019-2050), proportional
50% likelihood	1.5°C	500	178.28	99.53
	1.7°C	850	294.94	161.07
	2.0°C	1350	461.61	248.98
67% likelihood	1.5°C	400	144.94	81.94
	1.7°C	700	244.94	134.69
	2.0°C	1150	394.94	213.82

Table 5. Global carbon budget & estimated carbon budget for the OECD, based on two scenarios (IPCC, 2021)

The numbers found in Table 5 which show the amount of aggregate pollution that the OECD is allowed to emit until the year 2050 were then compared to the values of aggregate pollution found in the different simulations in the year 2050.

Table 6 shows whether or not the OECD stays within their budget when the share of the global carbon budget that they are permitted was set to one third. Table 7 states whether or not they are able to stay within the budget if their share of global emissions is proportional to their size.

		Group 1	Group 2	Group 3	Group 4
50% likelihood	1.5°C	No	No	No	No
	1.7°C	No	Yes	Yes	Yes
	2.0°C	No	Yes	Yes	Yes
67% likelihood	1.5°C	No	No	No	No
	1.7°C	No	Yes	Yes	No
	2.0°C	No	Yes	Yes	Yes

Table 6. Overview of the OECD’s ability to stay within the carbon budget if their share of carbon emissions equals ⅓ of the global budget.

		Group 1	Group 2	Group 3	Group 4
50% likelihood	1.5°C	No	No	No	No
	1.7°C	No	No	No	No
	2.0°C	No	Yes	Yes	No
67% likelihood	1.5°C	No	No	No	No
	1.7°C	No	No	No	No
	2.0°C	No	Yes	No	No

Table 7. Overview of the OECD’s ability to stay within the carbon budget if their share of global CO_2 emissions is proportional to their size.

7.3. Analysis of results

The results, both for GDP per capita and pollution, show clear cluster formations among the simulations with the same level of caps, which can be seen in Figure 1 and Figure 2. The simulations with caps leading to a 100 percent reduction of emission inducing capital stock render the overall lowest GDP per capita and lowest level of accumulated pollution, whilst the simulations with policies that lead to a 50 percent reduction of the damaging capital stock lead to the highest levels of GDP per capita and highest levels of accumulated pollution among the simulations with policies. Policies leading to a 75 percent reduction in emission inducing capital stock form a cluster in between the aforementioned.

When comparing the simulations that have policies to BAU, there are significant losses in GDP per capita. The simulation in group 2 that renders the highest GDP per capita in the year 2050 amounts to about 55 percent of the level for BAU. This number is roughly 65 percent and 73 percent for groups 3 and 4 respectively. In contrast, there are clear upsides when comparing the same simulations in terms of aggregate pollution. Group 2 renders aggregate pollution that amounts to roughly 32 percent of the aggregate pollution for BAU. For group 3 and group 4, these numbers are roughly 40 percent and 48 percent respectively.

The cluster formation shows that the factor that has the largest effect on both GDP per capita and pollution accumulation is the extent of the implemented caps. The differences within the clusters were especially small regarding the aggregate pollution, making it apparent that differences in when and to what extent the investments in environmentally sound technology, *C*, are implemented only have a marginal effect.

Looking closer at each cluster, there is another solidified trend. On the one hand, a 5-year delay in combination with the measure “high” and a 10-year delay with the measure “low” render the lower GDP per capita in each cluster. On the other hand, a 5-year delay in combination with the measure “low” and a 10-year delay with the measure “high”, lead to the highest GDP per capita within the clusters.

All simulations exhibit an initial decrease in GDP due to the loss of damaging capital stock, which is turned around due to the assumed technological advancements that come with the investments in the labour force engaged with environmentally sound research. A closer look at GDP per capita for each group can be found in Appendix 11.

8. Discussion and future research

8.1. Discussion

As per the Paris Agreement, the goal is to keep global warming below 2°C above pre-industrialisation levels, but with an ambition to pursue policies that contain global warming to under 1.5°C. Looking at the results in Tables 6 and 7 it becomes apparent that caps are not sufficient to keep global warming under 1.5°C. The results do, however, look more promising when the goal is set to keep global warming under 2°C. If the OECD keeps their current share of total emissions they will be able to stay within their carbon budget for 2°C with a likelihood of 67% with caps that prohibit only 50% of environmentally damaging capital stock. However, the OECD is disproportionately responsible for the global CO_2 emissions. If they, instead, were to operate at a level which is proportional to their population size, they would need to have a complete reduction of environmentally damaging capital stock in order to reach the same likelihood for 2°C, which is shown in Table 7. Furthermore, there is still the agreed upon ambition to pursue policies for 1.5°C, making it even less tangible for them to have less harsh caps on emissions.

Since the member countries of the OECD are disproportionately large emitters relative to their size, it raises the question of which carbon budget actually applies to them. In the assessment of the carbon budgets presented in previous sections, two alternatives were used to estimate the size of the budgets that the OECD faces during the observed time frame. In Table 6, it was assumed that the OECD meets a carbon budget that makes out one third of the global budget. This number was based on the share of total emissions that the OECD is currently responsible for. In addition to this, a scenario was played out where the OECD’s carbon budget was set to be proportional to their population size in relation to the rest of the world's population, which is what Table 7 captures. The scenarios were chosen to estimate an interval for the carbon budgets that the OECD faces until the year 2050 but were, however, both judged to be unlikely. On the one hand, continuing at the current share of global carbon emissions is unlikely since there are measures in place for the OECD to reduce their emissions. On the other hand, the ambition for the OECD to reach a share that is proportional to their population size calls for measures that are rather unrealistic. It is therefore likely that their share of the global carbon budget will fall somewhere in between the two aforementioned scenarios.

That being said the promised ambition as set out during COP21 was to pursue policies that are predicted to contain global warming to under 1.5°C. Regardless of what proportion is considered, for the OECD to come even close to fulfilling this promise, if using absolute caps as their choice of policy strategy, they would have to choose caps that lead to a complete reduction of carbon inducing capital stock.

The trend that emerges with the initial degrowth coincides with Nordhaus' claim that the current level of technology does not allow the world to effectively fight climate change. Therefore, in order to compensate for the degrowth that the caps on capital stock induce, investments in technology are crucial for sustained growth in the long run.

As previously mentioned, Nordhaus (2019) stresses the need for incentives to invest in environmentally sound technology in order for a transition to a sustainable society to work. Legally binding caps on emissions raise the market price of CO_2 emissions, which makes the previously lucrative market less attractive in favour of the environmentally sound technology that has traditionally been seen as inferior. Additionally, extending the caps to several nations that are large contributors to climate change, like the OECD, negates one of the free-riding problems that Nordhaus identifies, by creating a so-called climate club. Although there are no subsidies on research in sustainable technology, caps turn environmentally damaging activities into a declining market, which reduces incentives to invest in them and instead pushes investments into environmentally sound activities.

Using absolute caps in this manner leads to an initial degrowth in GDP per capita in all simulations. This has in traditional growth models been equivalent to a decrease in welfare. However, assuming that individuals show a preference for sustainability, the loss of welfare that comes with the initial degrowth following the policies could potentially be levelled out by the fact that there is an increase in sustainability.

Essential to this discussion is who will be affected by the decrease in production. Those in favour of degrowth have emphasised the importance of not only reducing societies' throughput, but also redistributing wealth and social security. This could be of importance to consider when introducing caps of this nature. Not only do the policies have to lead to a sustainable use of resources, but the allocation has to be efficient and done in such a way that income- and wealth distribution is fair, as suggested by Daly (1992). Absolute caps on emissions constitute a solution for sustainable use. In order for the well-being that is gained from more sustainable economic activities to not be cancelled out, they have to be constructed in such a way that they are fair, or have complementary policies that prohibit income distribution from becoming even more uneven.

One thing that may appear to be counterintuitive is the result of which measure gives what projection of GDP per capita when there is a 5-year delay. The measure “high” rendered lower GDP per capita than the measure “low”. This happens because with the measure “low”, more people stay in research that is considered to be harmful for the environment, whilst the measure “high” pushes more people from the harmful sector to the sound sector. The part of the research that focuses on environmentally harmful technology is superior in that it amounts to larger profits. Because of this, when more people stay in the harmful sector, it will show more economic growth.

Looking at what happens with GDP per capita with a 10-year delay of the investments in environmentally sound technology, the results are the opposite from what happens with a 5-year delay. When there is a 10-year delay with the measure “high”, workers stay in the damaging sector longer and then move to the non-damaging sector at a faster rate, making room for more economic growth. This could also be attributed to the fact that if researchers have a longer time period to adapt, it is possible to gain better substitutes. It is reasonable to think that allowing room for a longer transition, renders a substitute to the previously superior technology that is more comparable in terms of efficiency. This would lessen the gap in efficiency between the two types of technology.

8.2. Future research

In order to construct a simplified model this paper made a series of assumptions that could be explored in future research. This section presents a few topics that could be further examined in order to gain a more comprehensive understanding of the implications of absolute caps on emissions and investment in more sustainable technology on GDP per capita and pollution.

One central parameter that was found to have a large effect on the results regarding the aggregate pollution was s_{BD}, which showed the environmental impact of B and D combined. By only using one parameter, it was assumed that B and D exhibit the same impact on the environment. This assumption could be modified, e.g. by assigning B a larger share of the impact than D or vice versa. Identifying the true value of ϕ, λ, θ_B and θ_C exceeded the scope of this paper but could give rise to potential future research within the field of economic growth and the environment. Furthermore, it could be of interest to examine how much the delay in technological investments affect the substitutability of the loss in GDP per capita caused by the carbon caps.

Another aspect that could be considered in future papers is the monetary impact that an increase in pollution has on the economic wealth of people. Nordhaus implements this idea in his research by including a variable in the GDP production function, which is something that could be interesting to examine in this context as well.

There were assumptions made that omitted both trade and the potential transfer of harmful activities following caps. In order to gain further understanding of the scope of the OECD's CO_2 emissions, it could be useful to look at their closest trading partners. Furthermore, it could be useful to look at how countries that are subject to policies transfer their harmful activities to other countries, in order to gain understanding as to how to prevent it from happening.

Lastly, it could be of interest to study how to go about redistributing income and wealth in order to prevent an overall loss in welfare. This also goes hand in hand with trade, since there is not only inequality within the OECD, but also between the OECD and the countries that are not part of the organisation.

9. Conclusion

The purpose of this study is to examine how absolute caps on carbon dioxide inducing capital stock and investments in environmentally sound technology affect the level of GDP per capita and accumulated pollution in the OECD. This matter is investigated through a series of simulations using a modified model constructed to accommodate the assumptions made in the paper. The results of the simulations are related to the commitments taken on by the OECD in order to contain global warming.

The results show that the strongest determining factor for the trajectory of both GDP per capita and pollution is the extent of the caps. The level of investments does have an effect on the general outcome of GDP per capita, but only a marginal one on pollution.

As to whether or not absolute caps on carbon emissions are a viable solution in order to meet the goals set out by the Paris Agreement, it is found that caps are not sufficient in order for the OECD to meet the 1.5°C ambition, but are able to accommodate the goal of 2°C. Therefore, if using absolute caps as a policy strategy, the OECD should aim at a complete reduction of carbon emission inducing capital stock in order to try and fulfil their promises.

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Appendices

Appendix 1. Solow's model – GDP per capita

$$Y = K^{\alpha}(AL)^{1-\alpha}$$

Divide production function by population, L, to receive general expression for GDP per capita:

$$\frac{Y}{L} = \frac{K^{\alpha}(AL)^{1-\alpha}}{L^{\alpha}L^{1-\alpha}} \Rightarrow y = k^{\alpha}A^{1-\alpha}$$

Appendix 2. Solow's model – Growth in GDP per capita

$$y = k^{\alpha}A^{1-\alpha}$$

Take the logarithm of the expression for GDP per capita:

$$ln(y) = \alpha \cdot ln(k) + (1-\alpha) \cdot ln\,(A)$$

Derive with regards to time:

$$\frac{dln(y)}{dt} = \alpha \cdot \frac{dln(k)}{dt} + (1-\alpha) \cdot \frac{dln(A)}{dt}$$

General expression for the growth rate in GDP per capita:

$$g_y = \alpha \cdot \underbrace{g_k}_{= g_y \text{ in steady state}} + (1-\alpha) \cdot g_A$$

Solve for g_y:

$$g_y - \alpha \cdot g_y = (1-\alpha) \cdot g_A$$

Growth rate in GDP per capita in steady state:

$$g_y = g_A$$

Appendix 3. Solow's model – Growth rate in capital stock

Divide the change in K by the level of K:

$$g_k = \frac{\dot{K}}{K} = \frac{sY - \delta K}{K} = s\underbrace{\frac{Y}{K}}_{\substack{\text{Y and K must} \\ \text{grow at the} \\ \text{same rate for} \\ g_k \text{ to be} \\ \text{constant in} \\ \text{steady state}}} - \delta$$

Appendix 4. Romer's model – Growth rate of A in steady state

Divide the change in A by the level of A:

$$g_A = \frac{\dot{A}}{A} = \frac{\theta A^{\phi} L_A^{\lambda}}{A} = \theta A^{\phi - 1} L_A^{\lambda}$$

Take the logarithm:

$$ln(g_A) = ln(\theta) + (\phi - 1) \cdot ln(A) + \lambda \cdot ln\,(L_A)$$

Derive with regards to time:

$$\frac{dln(g_A)}{dt} = \frac{dln(\theta)}{dt} + (\phi - 1) \cdot \frac{dln(A)}{dt} + \lambda \cdot \frac{dln(L_A)}{dt}$$

$$\underbrace{\frac{\dot{g}_A}{g_A}}_{\substack{= 0 \text{ in} \\ \text{steady} \\ \text{state}}} = \underbrace{g_\theta}_{= 0} + (\phi - 1) \cdot g_A + \lambda \cdot \underbrace{g_{L_A}}_{\substack{= g_L \\ = n}}$$

Solve for g_A:

$$0 = (\phi - 1) \cdot g_A + \lambda \cdot n$$

$$\Leftrightarrow$$

$$g_A = \frac{\lambda n}{1 - \phi}$$

Appendix 5. Nordhaus' model – GDP per capita growth rate in steady state

Divide production function by population, L, to receive general expression for GDP per capita:

$$y = \frac{Y}{L} = \frac{K^{\alpha} (AL)^{1-\alpha} P^{-\gamma}}{L^{\alpha} L^{1-\alpha}} = k^{\alpha} A^{1-\alpha} P^{-\gamma}$$

Take the logarithm:

$$ln(y) = \alpha \cdot ln(k) + (1 - \alpha) \cdot ln(A) - \gamma \cdot ln\,(P)$$

Derive with regards to time:

$$\frac{dln(y)}{dt} = \alpha \cdot \frac{dln(k)}{dt} + (1 - \alpha) \cdot \frac{dln(A)}{dt} - \gamma \cdot \frac{dln(P)}{dt}$$

$$g_y = \alpha \cdot \underbrace{g_k}_{\substack{= g_y \text{ in} \\ \text{steady} \\ \text{state}}} + (1 - \alpha) \cdot g_A - \gamma \cdot g_P$$

Solve for g_y:

$$g_y = g_A - \frac{\gamma}{1 - \alpha} \cdot g_P$$

Find an expression for g_P in steady state:

$$g_P = \frac{\dot{P}}{P} = \frac{\frac{\theta}{B} Y - \delta_P P}{P} = \frac{\theta Y}{BP} - \delta_P$$

Since g_P is constant in steady state, the ratio $\frac{Y}{BP}$ must be constant too, which in turn leads to the following expression:

$$g_Y = g_B + g_P$$

Solve for g_P:

$$g_P = g_Y - g_B$$

$$\Leftrightarrow$$

$$g_P = g_y + n - g_B$$

In steady state:

$$g_y = g_A - \frac{\gamma}{1-\alpha}\left[g_y + n - g_B\right]$$

Solve for g_y:

$$g_y = \frac{1-\alpha}{1-\alpha+\gamma} g_A + \frac{\gamma}{1-\alpha+\gamma}(g_B - n)$$

Appendix 6. Modified model – Derivation of technological growth rate in steady state

X denotes either B or C:

$$\dot{X} = \theta_X L_X^{\lambda} X^{\phi}$$

Divide the change in X by the level of X:

$$g_X = \frac{\dot{X}}{X} = \frac{\theta_X L_X^{\lambda} X^{\phi}}{X} = \theta_X X^{\phi-1} L_X^{\lambda}$$

Take the logarithm:

$$\ln(g_X) = \ln(\theta) + (\phi - 1)\cdot \ln(X) + \lambda \cdot \ln\,(L_X)$$

Derive with regards to time:

$$\frac{d\ln(g_X)}{dt} = \frac{d\ln(\theta)}{dt} + (\phi - 1)\cdot \frac{d\ln(X)}{dt} + \lambda \cdot \frac{d\ln(L_X)}{dt}$$

Solve for g_X:

$$\underbrace{\frac{\dot{g}_X}{g_X}}_{=0 \text{ in steady state}} = \underbrace{g_\theta}_{=0 \text{ in steady state}} + (\phi - 1)\cdot g_X + \lambda \cdot \underbrace{g_{L_X}}_{= g_L = n \text{ in steady state}}$$

$$\Leftrightarrow$$

$$g_X = \frac{\lambda n}{1-\phi}$$

Appendix 7. Modified model – GDP per capita in steady state

GDP production function:

$$Y = \bar{K}^{\alpha}(\bar{A}L_Y)^{1-\alpha}$$

Two auxiliary variables, $\tilde{y}$ and $\tilde{k}$, are created and defined as follows:

$$\tilde{y} = \frac{Y}{\bar{A}L}$$

$$\tilde{k} = \frac{K}{\bar{A}L}$$

Express $\tilde{y}$ in terms of $\tilde{k}$:

$$\tilde{y} = \frac{Y}{\bar{A}L} = \frac{\bar{K}^{\alpha}(\bar{A}L)^{1-\alpha}}{(\bar{A}L)^{\alpha}(\bar{A}L)^{1-\alpha}} = \left(\frac{K}{\bar{A}L}\right)^{\alpha} \cdot \left(\frac{L_Y}{L}\right)^{1-\alpha} = \tilde{k}^{\alpha}\left(\frac{L_Y}{L}\right)^{1-\alpha}$$

Set $\dot{\tilde{k}}$ equal to zero in steady state:

$$\dot{\tilde{k}} = s\tilde{y} - (\delta + n + g)\tilde{k} = s\tilde{k}^{\alpha}\left(\frac{L_Y}{L}\right)^{1-\alpha} - (\delta + n + g)\tilde{k} = 0$$

Solve for $\tilde{k}$:

$$s\tilde{k}^{\alpha}\left(\frac{L_Y}{L}\right)^{1-\alpha} = (\delta + g + n)\tilde{k}$$

$$\frac{s}{(\delta+g+n)} \cdot \left(\frac{L_Y}{L}\right)^{1-\alpha} = \tilde{k}^{1-\alpha}$$

$$\tilde{k}^{*} = \left(\frac{s}{\delta+n+g}\right)^{\alpha/(1-\alpha)} \cdot \left(\frac{L_Y}{L}\right)$$

Insert expression for $\tilde{k}^{*}$ in equation $\tilde{y} = \tilde{k}^{\alpha}\left(\frac{L_Y}{L}\right)^{1-\alpha}$:

$$\tilde{y}^{*} = \left(\frac{s}{\delta+g+n}\right)^{\alpha/(1-\alpha)} \cdot \left(\frac{L_Y}{L}\right)^{\alpha} \cdot \left(\frac{L_Y}{L}\right)^{\frac{1}{1-\alpha}}$$

$$\Leftrightarrow$$

$$\tilde{y}^{*} = \left(\frac{s}{\delta+g+n}\right)^{\alpha/(1-\alpha)} \cdot \left(\frac{L_Y}{L}\right)$$

Utilising the fact that $y = \tilde{y} \cdot \bar{A}$ generates an expression for GDP per capita in steady state:

$$y^{*}(t) = \left(\frac{s}{\delta+g+n}\right)^{\alpha/(1-\alpha)} \cdot \left(\frac{L_Y}{L}\right) \cdot \bar{A}(t)$$

Appendix 8. Derivation of θ

X denotes either B or C:
$\dot{X} = \theta_X L_X^{\lambda} X^{\phi}$

Divide change in X by level of X:
$g_X = \frac{\dot{X}}{X} = \theta_X X^{\phi - 1} L_X^{\lambda}$

Solve for θ_X:
$\theta_X = \frac{g_X}{X^{\phi - 1} L_X^{\lambda}}$

Appendix 9. Values for GDP per capita, simulations 1-13

Year	Sim1	Sim2	Sim3	Sim4	Sim5	Sim6	Sim7	Sim8	Sim9	Sim10	Sim11	Sim12	Sim13
2019	46667	46667	46667	46667	46667	46667	46667	46667	46667	46667	46667	46667	46667
2020	47359	46331	46331	46331	46331	46382	46382	46382	46382	46602	46602	46602	46602
2021	48066	45982	45982	45982	45982	46111	46111	46111	46111	46546	46546	46546	46546
2022	48787	45619	45619	45619	45619	45854	45854	45854	45854	46499	46499	46499	46499
2023	49524	45240	45240	45240	45240	45613	45613	45613	45613	46461	46461	46461	46461
2024	50277	44845	44845	44845	44845	45387	45387	45387	45387	46432	46432	46432	46432
2025	51045	44432	44432	44432	44432	45176	45176	45176	45176	46412	46412	46412	46412
2026	51830	43998	44007	43999	43999	44979	44988	44980	44980	46401	46402	46410	46402
2027	52631	43543	43569	43546	43546	44798	44824	44801	44801	46399	46402	46426	46402
2028	53450	43064	43116	43070	43070	44632	44686	44638	44638	46405	46411	46461	46411
2029	54285	42560	42647	42569	42569	44482	44573	44491	44491	46421	46431	46516	46431
2030	55139	42029	42160	42041	42041	44348	44487	44361	44361	46447	46461	46592	46461
2031	56010	41790	41968	41808	41806	44219	44408	44239	44236	46537	46558	46736	46556
2032	56900	41550	41777	41577	41570	44116	44358	44146	44138	46646	46677	46902	46669
2033	57809	41309	41588	41348	41333	44042	44339	44084	44068	46775	46819	47090	46802
2034	58737	41068	41399	41121	41095	43996	44351	44053	44026	46924	46985	47302	46956
2035	59684	40826	41211	40897	40857	43980	44395	44057	44013	47095	47177	47540	47131
2036	60652	40582	41024	40674	40616	43995	44474	44094	44032	47289	47396	47804	47328
2037	61640	40338	40838	40454	40375	44041	44587	44168	44081	47506	47643	48095	47550
2038	62649	40091	40652	40237	40131	44120	44737	44280	44164	47748	47921	48416	47795
2039	63680	39843	40467	40022	39886	44232	44924	44431	44280	48015	48231	48767	48067
2040	64732	39593	40281	39809	39638	44379	45151	44622	44430	48310	48575	49150	48365
2041	65806	39617	40377	39879	39665	44543	45397	44837	44597	48677	48999	49611	48736
2042	66903	39656	40491	39969	39707	44745	45687	45098	44802	49073	49460	50106	49136
2043	68024	39711	40624	40081	39764	44987	46021	45406	45047	49499	49961	50638	49566
2044	69167	39782	40778	40218	39838	45269	46402	45765	45332	49957	50504	51207	50027
2045	70335	39871	40953	40380	39929	45594	46831	46176	45660	50449	51092	51817	50522
2046	71528	39979	41151	40569	40039	45963	47310	46641	46032	50975	51728	52469	51052
2047	72746	40107	41373	40788	40169	46377	47841	47165	46449	51539	52414	53165	51618
2048	73989	40257	41621	41039	40321	46838	48426	47749	46913	52141	53154	53908	52224
2049	75259	40430	41897	41324	40495	47348	49067	48396	47425	52784	53952	54699	52869
2050	76555	40627	42202	41646	40694	47909	49766	49110	47988	53469	54810	55543	53558

Table 8. Values for projected GDP per capita in USD, simulations 1-13

Appendix 10. Accumulated pollution, simulations 1-13

Year	Sim1	Sim2	Sim3	Sim4	Sim5	Sim6	Sim7	Sim8	Sim9	Sim10	Sim11	Sim12	Sim13
2019	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6	11.6
2020	23.5	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8	23.0	23.0	23.0	23.0
2021	35.7	33.5	33.5	33.5	33.5	33.6	33.6	33.6	33.6	34.1	34.1	34.1	34.1
2022	48.3	43.8	43.8	43.8	43.8	44.0	44.0	44.0	44.0	45.0	45.0	45.0	45.0
2023	61.2	53.6	53.6	53.6	53.6	54.1	54.1	54.1	54.1	55.6	55.6	55.6	55.6
2024	74.4	63.0	63.0	63.0	63.0	63.8	63.8	63.8	63.8	66.0	66.0	66.0	66.0
2025	87.9	71.9	71.9	71.9	71.9	73.2	73.2	73.2	73.2	76.2	76.2	76.2	76.2
2026	101.8	80.4	80.4	80.4	80.4	82.3	82.3	82.3	82.3	86.2	86.2	86.2	86.2
2027	116.1	88.4	88.4	88.4	88.4	91.1	91.1	91.1	91.1	95.9	95.9	95.9	95.9
2028	130.8	96.0	96.0	96.0	96.0	99.6	99.6	99.6	99.6	105.5	105.5	105.5	105.5
2029	145.9	103.2	103.2	103.2	103.2	107.8	107.8	107.8	107.8	114.8	114.8	114.8	114.8
2030	161.3	109.9	109.9	109.9	109.9	115.7	115.7	115.7	115.7	124.0	124.0	124.0	124.0
2031	177.2	116.3	116.3	116.3	116.3	123.4	123.4	123.4	123.4	133.0	133.0	133.0	133.0
2032	193.5	122.4	122.4	122.4	122.4	130.8	130.8	130.8	130.8	141.9	141.9	141.9	141.9
2033	210.3	128.2	128.2	128.2	128.2	137.9	137.9	137.9	137.9	150.5	150.5	150.6	150.6
2034	227.5	133.7	133.7	133.7	133.7	144.9	144.9	144.9	144.9	159.1	159.1	159.1	159.1
2035	245.2	139.0	139.0	139.0	139.0	151.6	151.6	151.6	151.6	167.5	167.5	167.5	167.5
2036	263.3	143.9	143.9	143.9	143.9	158.1	158.1	158.1	158.1	175.7	175.7	175.7	175.7
2037	282.0	148.5	148.5	148.5	148.5	164.3	164.3	164.4	164.4	183.8	183.8	183.8	183.8
2038	301.2	152.9	152.9	152.9	152.9	170.4	170.4	170.5	170.5	191.8	191.8	191.8	191.8
2039	320.9	156.9	156.9	156.9	156.9	176.3	176.3	176.4	176.4	199.6	199.6	199.6	199.6
2040	341.1	160.7	160.7	160.7	160.7	182.1	182.1	182.1	182.1	207.3	207.3	207.3	207.3
2041	362.0	164.2	164.2	164.3	164.3	187.6	187.6	187.6	187.6	214.9	214.9	214.9	214.9
2042	383.4	167.6	167.6	167.6	167.6	193.0	193.0	193.0	193.0	222.4	222.4	222.4	222.4
2043	405.4	170.7	170.8	170.8	170.8	198.2	198.2	198.2	198.2	229.8	229.8	229.8	229.8
2044	428.0	173.7	173.7	173.8	173.8	203.2	203.3	203.3	203.3	237.1	237.1	237.1	237.1
2045	451.2	176.5	176.5	176.5	176.5	208.1	208.2	208.2	208.2	244.2	244.3	244.3	244.3
2046	475.1	179.1	179.1	179.1	179.1	212.9	212.9	213.0	213.0	251.3	251.4	251.4	251.4
2047	499.7	181.4	181.5	181.5	181.5	217.5	217.6	217.6	217.6	258.3	258.3	258.4	258.4
2048	524.9	183.6	183.7	183.7	183.7	222.0	222.0	222.1	222.1	265.2	265.3	265.3	265.3
2049	550.9	185.6	185.6	185.7	185.7	226.4	226.4	226.5	226.5	272.0	272.1	272.1	272.1
2050	577.6	187.4	187.4	187.5	187.5	230.6	230.7	230.7	230.7	278.7	278.8	278.8	278.8

Table 9. Values for projected aggregate pollution in $GtCO_2$, simulations 1-13

Appendix 11. GDP per capita simulations, sorted by clusters

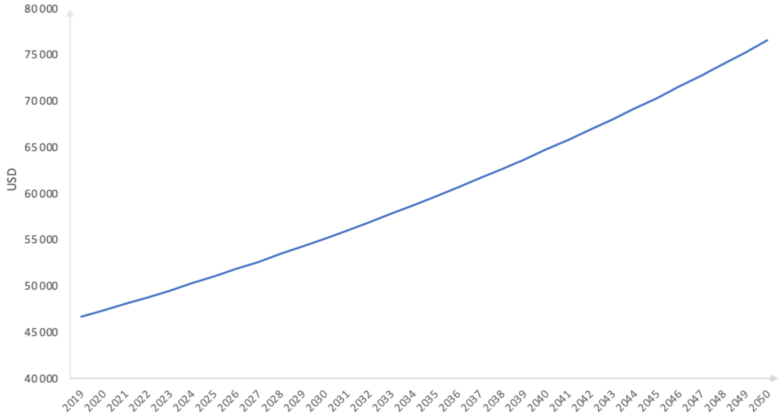

Figure 3. GDP per capita in USD, group 1

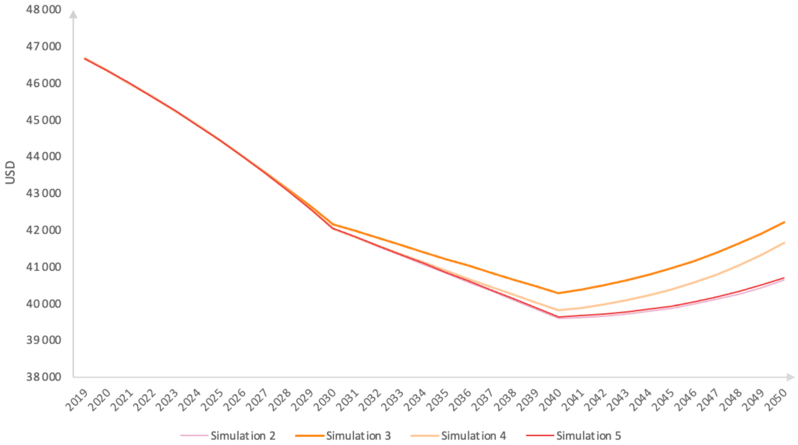

Figure 4. GDP per capita in USD, group 2

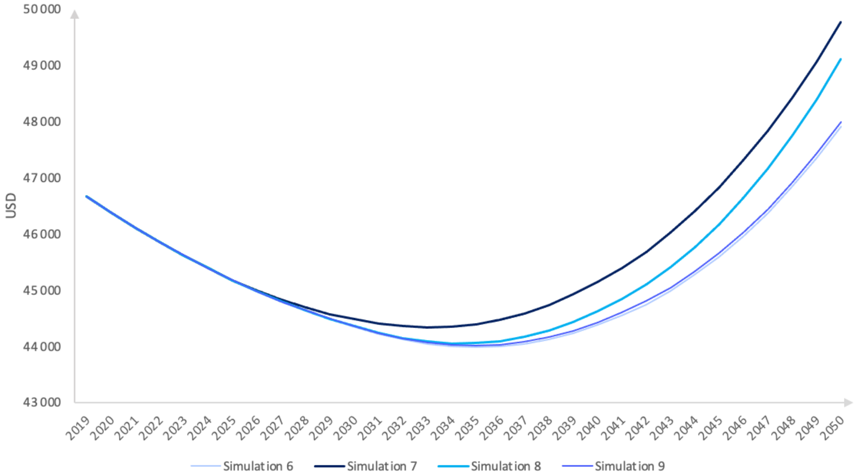

Figure 5. GDP per capita in USD, group 3

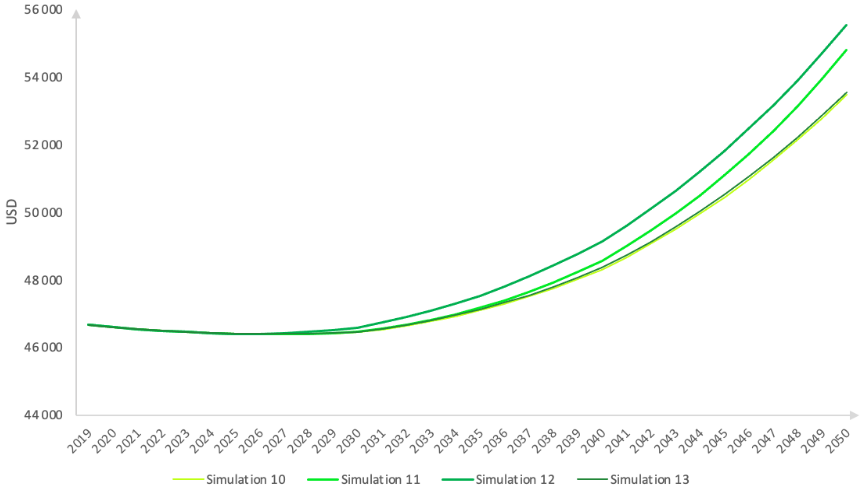

Figure 6. GDP per capita in USD, group 4