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"EXTREMELY LONG INTEREST RATE ANALYSIS IN INTEGRATED ASSESSMENT MODELS"

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Abstract

“This thesis aims at disentangling the effect of choosing different rationales when determining discounting rates in the highly extended time horizons required by climate models, such as Integrated Assessment Models (IAMs), and verify whether distinct approaches can enable equilibria consistent with the latest climate objectives as outlined by the IPCC in its latest assessment cycle. As to effectively frame the issue, this review sets out to propose an economic framework widely used in the field which serves as theoretical ground both to formalize the damage stemming from a warming planet and to establish a discounting structure. The analysis relies on the latest version of the DICE model (Barrage and Nordhaus, 2023), which allows to integrate a climate module within the same framework. Multiple scenarios are considered as to incorporate distinct interest rate proposals from the literature, encompassing a range of discounting approaches that span from “empirical” methodologies to determine discounting parameters to more “normative” ones, explicitly influenced by ethical and moral considerations. Finally, this review concludes by assessing whether the outputs retrieved from these approaches align, within the framework, with the carbon budget estimated by the IPCC in its latest publications.

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Introduction

In the late 2000s, the release of the Stern Review on the Economics of Climate Change (Stern, 2007) sparked a profound and extensive debate. Commissioned by the English Government to the renowned economist Nicholas Stern, this review presented a comprehensive assessment of the economic implications of climate change and called for urgent action to invest in mitigating its potentially devastating future effects. The report shed light on the implications of a warming planet capturing attention at a global level and igniting a fundamental shift in how experts study the economics of climate change. The role that discounting plays in assessing future damages and therefore informing current policies was at the heart of the debate around the review. The most argued aspect, in fact, revolved around the criticism of the potential shortcomings of conventional discounting approaches in accurately capturing the true costs associated with long-term temperature changes. Drawing upon these discussions sparked by the Stern Review, this thesis aims to provide some insights into the complex relationship between the selection of a discounting rationale and climate change modelling.

In particular, by analyzing the long-term implications of discounting choices in Integrated Assessment Models (IAMs) and exploring the influence of different parameter selections within the Ramsey formula, which is the standard approach to discounting in the field, this study aims to provide some intuitions into how discounting practices impact the feasibility of achieving climate transition objectives outlined by influential bodies, namely the Intergovernmental Panel on Climate Change (IPCC). This study is developed though three main steps: first of all, the analysis starts by providing a qualitative overview of the potential impacts of climate change on the economy, highlighting in this way the challenges it poses for economic modelling. The discussion will progress by presenting a widely adopted framework that is commonly used to model the long-term economic damages caused by climate change and serves as the basis for the widely employed discounting approach in the field. In this first section, a description of the impact of climate change on this framework will be presented and, crucially, the main debate regarding the rationale of the selection of interest rate parameters and its variations across the field will be explored. Secondly, an overview of the type of tool used to conduct the analysis, Integrated Assessment Models, will be presented, providing the background for understanding IAMs and offering insights into the selection of the specific model employed for this analysis. Finally, the last section of this thesis focuses on assessing whether different approaches to extremely long interest rates, which reflect different rationales for selecting discounting parameters, have the potential to meet the carbon budget as presented by the IPCC in its latest assessment cycle, the AR6 (2022c). To achieve this, the examination will construct multiple scenarios using one of the most influential integrated models, the DICE model developed by Nobel laureate William Nordhaus in its latest iteration: these scenarios will shed light into whether different assumptions regarding discount rates are projected to generate emission pathways that align with the thresholds proposed by the IPCC.

By examining the broad consequences of discounting practices, this study aims to contribute to the understanding of the rationale behind different long-term interest rate approaches. It aims at emphasizing how a sometimes seemingly arbitrary aspect of climate modeling can actually have a profound influence on achieving pivotal targets that can determine the well-being of future generations and the stability of the environment. Through this exploration, the study tries to shed light on the importance of making informed choices in discounting practices to ensure that the policies implemented take into account how society really values both its planet and the prosperity of its descendants.

Chapter 1 – The economic cost of a changing climate

In the last few decades, the impacts of climate change have been the subject of growing attention and have emerged as a prevalent topic of debate in the field of economics. Although some concerns about the economic role of pollution can be traced as back as the late 1960ies, both the scope and the nature of research on global warming used to be quite different. In 1969, for instance, Ayres and Knees, writing in *The American Economic Review* underplayed the role that climate change has in shaping economic activity, stating that "discharge of carbon dioxide can be considered harmless in the short run", even if they already recognized that "continued combustion of fossil fuel at a high rate could produce externalities affecting the entire world". Over the last four decades, however, increasingly compelling data on climate events and damages (see, for instance, Figure 1) have raised awareness in several fields and among the general population. Discussions about the risks that stem from a warming planet were more broadly introduced to the economic literature in the early 1990s and have been gaining momentum ever since. As climate change was brought to the public attention, a growing portion of economic literature began focusing on the critical aspects of this crisis, namely the obstacles in implementing adequate policies in response to global warming (e.g., Nordhaus 1993), and how current models underestimate the costs and risks of carbon emissions (e.g., Stern, 2007; Richard, 1995; Revesz et al., 2014). As a result, methodological and empirical contributions have played a crucial role in assessing the damage of a changing climate and shaping policy prescriptions of the most influential organizations, such as the IPCC, as early as its first assessment cycle in 1990 (IPCC, 2010).

This chapter aims at providing the context and the essential macroeconomic framework necessary in order to introduce and understand the main features and the objectives of the current modelling techniques. The following paragraphs lay out an account of the most common risks and costs that a warming planet brings about, together with an illustration of how economists think about the climate issue and how they try to formalize it. As climate change impacts almost every aspect of economics, the scope of this review is reduced to formalizations that are generally used in order to model the damages resulting from a warming planet, and that are relevant to the model under consideration in the analysis in Chapter 3.

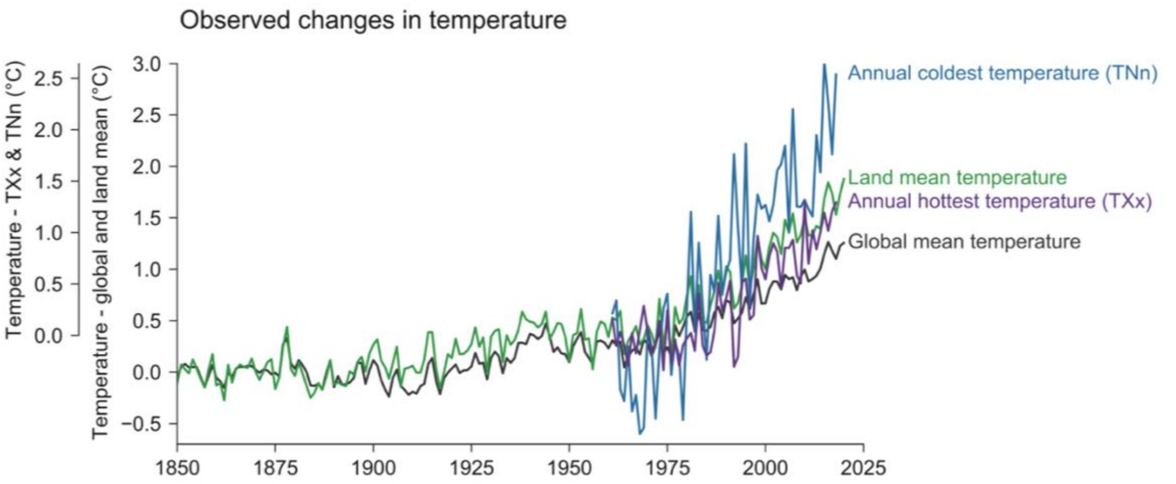

Figure 1. Observed temperature anomalies for global average annual mean temperature, land average mean temperature, land average annual hottest daily maximum temperature and land average annual coldest daily minimum temperature (IPCC, 2022c). The deviation from previous temperature levels accelerated considerably in the mid 1970ies.

1.1 Climate change risks and economic costs

Approaching the climate issue from an economic perspective requires to establish a framework that goes beyond the simple concept of damage and introduces the role of risks generated by global warming. In defining the concept of risk related to climate change, Jones and Boer (2005) describe it as the outcome of three main factors: hazard, probability, and vulnerability. Hazard is defined as “an event with the potential to cause harm” (pg. 94): climate hazards range from droughts and tropical cyclones to more subtle consequences of global warming, such as the development of favorable conditions for disease outbreaks. They may be generally defined as adverse consequences to natural or human systems, directly linked to climate change. Many modelling tools, for instance, operate through an estimation of the probability of a certain hazard. Vulnerability, on the other hand, relates to how the hazard interacts with a given context and can be measured as the effective outcome of the event based on costs or other estimates based on value. Risk is therefore a complex combination of the likelihood (i.e., probability of occurrence) and the disruptive consequences of global warming. A frequently used taxonomy groups these phenomena into physical and transition risks.

1.1.1 Physical risk

According to Batten et al. 2016, physical risk emerges from the interaction between climate change hazard and the exposure of both artificial and natural systems, taking into account their vulnerability. Such risks were already labelled as *moderate* in the fifth IPCC's assessment cycle (IPCC, 2014). In a macroeconomic framework, they are likely to manifest as shocks, i.e., events that cause a departure from the previous equilibrium on account of a significant and non-predicted effect on the economy. There is a large potential for these phenomena to affect different components of the aggregate demand, namely private and public consumption, investment, and international trade. Yet the supply-side of the economy has also significant exposure, as a consequence of possible shocks on, among others, labor, physical capital, and technology.

Extreme weather events come very close to the definition of macroeconomic shock, as a consequence of their exogenous nature. An extreme weather event is normally considered within the lowest 10th or highest 90th percentile of a probability density function estimated from observations (IPCC, 2022c). The increase in risk generated by climate change comes from a steady increase in their frequency and disruptive capacity, as the planet warms (Figure 2). Considering just the United States, the cost of such events skyrocketed in the last decades, resulting in a sevenfold increase in real terms from the 1980s' average (NOAA, 2023). Although it's difficult to determine the extent to which human activity contributes to each single event, anthropogenic pollution has clearly increased the level of both aggregate damage and probability, as highlighted by the recent developments in the *event attribution field* (see, e.g., NASEM, 2016).

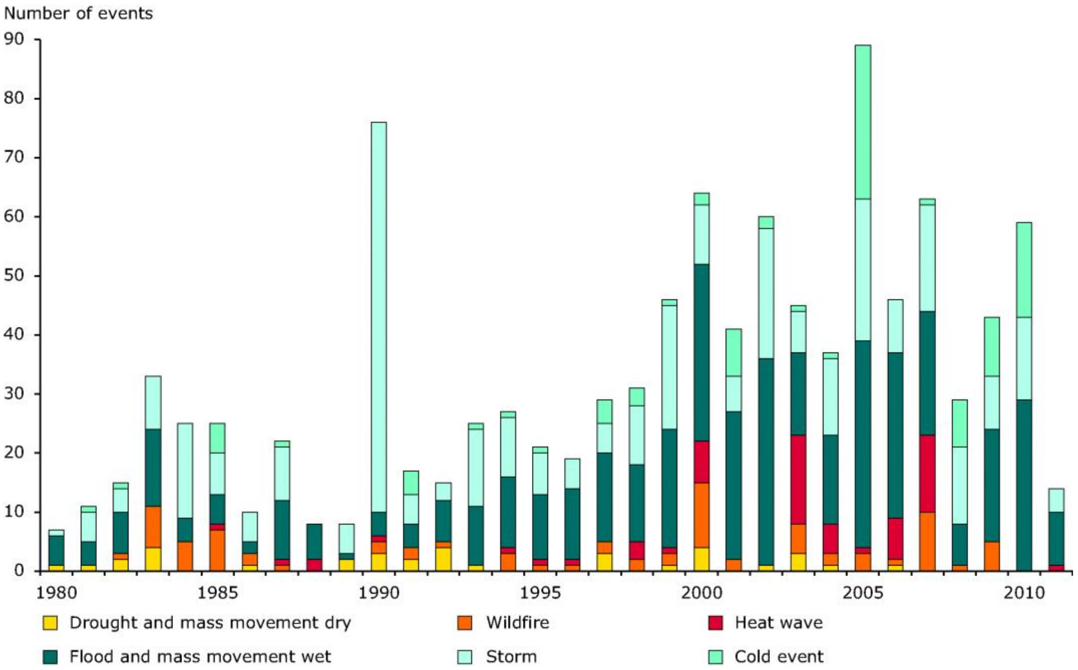

Figure 2. Number of extreme weather events per years in EEA members and collaborating countries in the period 1980-2011. (EEA, 2012)

The demand-side of the economy is likely to be damaged, at least in the short run. Locally, exceptional storms and floods have the potential to impact household wealth and, thus, consumption. These phenomena may also have long-lasting effects on investment in the most harmed regions, due not only to the damage provoked by the disasters, but also to the high uncertainty surrounding both the incidence of the weather events and the impact on local firms and, consequently, on the economy as a whole. These events have been shown to affect prices in financial markets, hampering investment levels and resulting in an increase in uncertainty even months after an extreme weather event takes place (Kruttli et al., 2021). Moreover, disasters can affect bilateral trade, and the overall effect is likely to be worse in smaller countries with weaker political systems (Gassebner et al., 2010). On the other hand, one of the main risks that relates to the supply-side of the economy concerns shortages on inputs. Commodities such as energy and food have the highest exposure, as they risk both shortages and high volatility in import prices (Batten, 2018). Additionally, extreme weather events may damage the capital stock and redirect resources from research and innovation to reconstruction and replacement, hindering the drivers of long-term growth.

Gradual global warming is also likely to impose significant costs, albeit slowly increasing. A warmer climate will hamper workers' productivity, a phenomenon, in the first place, notoriously noticed by Montesquieu in 1750. Such feature can be observed nowadays in a cross-country comparison as a significant decline of GDP per capita as temperatures increase. At first glance, this approach yields merely correlational results, yet many studies suggest that, depending on temperature ranges, the relationship is causal: in Deryugina and Hsiang (2014), e.g., productivity was observed to decline by 1.7% for each 1°C increase in daily average temperature over 15°C, using variations across counties within the United States and a 40-year dataset, resulting in a sharp loss of income as temperatures increase (Figure 3).

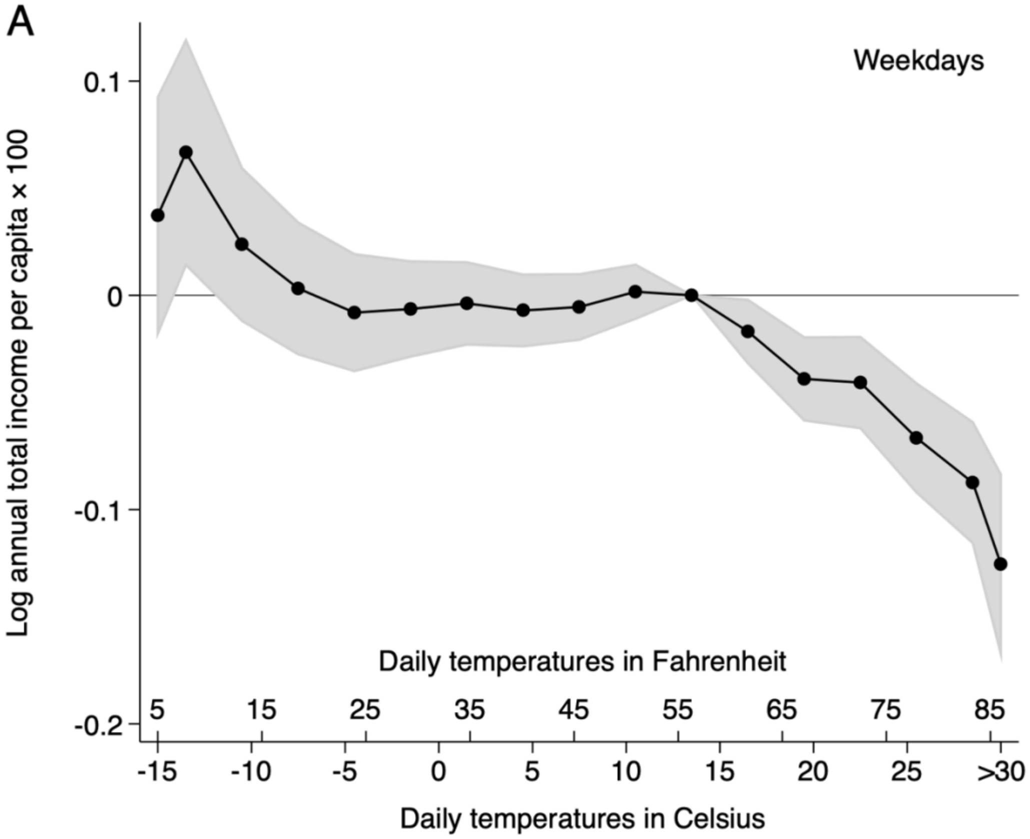

Figure 3. Log personal income per capita in response to daily temperature on weekdays (Deryugina and Hsiang, 2014).

An increase in geographical areas being exposed to extreme heat could, in fact, cause a loss of total hours worked. There is also substantial evidence that generally warmer temperatures affect agricultural crops, industrial output, energy demand, health, conflict, political stability, and economic growth more broadly. Furthermore, some empirical studies suggest a large heterogeneity in how these temperature changes damage different countries, with developing and poor economies more likely to suffer higher costs than rich ones (Dell et al., 2014).

1.1.2 Transition risk

The goal of keeping global temperature rise below 2° Celsius was formalized at the 21st UN Conference of the Parties (COP) in Paris. Member States also pledged to attempt to keep the temperature increase below 1.5° Celsius above the pre-industrial average (United Nations, 2015). As of 2023, this objective still represents the main reference for most public actors and policies around the globe. It was reaffirmed in the last COP meetings, including COP 26 in Glasgow and the latest COP 27 in Sharm El-Sheikh (United Nations, 2022; United Nations, 2023).

Curbing future temperature increases requires at least a swift stabilization of GHGs concentration in the air, leading to a zero-emission pathway. Since carbon removal technology (CDR) is not affordable enough to make it competitive on a large scale, the most credible solutions currently involve restraining and disincentivizing carbon emitting activities. This is particularly problematic as climate change it’s not a simple externality, as reported by Stern in 2007, but it has distinct features that distinguish it from others, namely because of:

- Global causes and consequences
- Long-term and persistent damages
- Pervasive uncertainties
- Major risk of irreversible damage

The vast inefficiency generated by this market failure needs to be addressed with global and decisive climate policies, aimed specifically at including in the effort to curb emissions countries with either current or predicted high levels of pollution.

Mitigation policies are aimed at reducing the speed of global warming and ultimately stabilizing it. Limiting significantly GHGs emissions will require demand-side interventions, such as reductions in consumption of highly polluting products and services, as well as supply-side innovations, e.g., encouraging investment in technologies that reduce *energy intensity* (i.e., ratio of energy used and unit of output) and *carbon intensity* (i.e., ratio between carbon emission and energy produced). Nowadays, different policies are already implemented, mainly focusing on pricing, subsidies, research policies and regulation. A mixture of these instruments is likely to be the most effective option to curb emissions (Stern, 2007). Yet, such interventions are prone to weigh down growth and economic activity in general, particularly in the short and medium term: compliance with environmental regulation and higher costs in firm’s input may affect profitability and productivity, as resources are increasingly allocated towards emission abatement. Moreover, existing industries may face profound declines resulting in sizeable job destruction, with unemployment levels risking a structural increase, if workers are not reskilled and redirected toward new occupations. The contraction may be largely different depending on the sector: some branches of the energy industry are clearly the most likely to suffer higher losses and that includes coal mining, oil and gas extraction and refining. Other industries are still expected to incur significant costs, such as agriculture high technology manufacturing and trading, while sectors like finance, services, and food may experience small declines if not output increases as a consequence of such policies (Goettle and Fawcett, 2009).

In general terms, there is significant uncertainty about the net outcome on the job market. There is, in fact, growth potential for renewable energy firms and, thus, renewable employment creation in several markets across the globe. In the long run, labor losses in fossil fuel and nuclear energy production can be outweighed by job creation in green energy generation and storage (Manish et al., 2020). However, this positive outcome is conditional on markets being reassured by stable and carefully designed policies that allow for an effective transition while minimizing the risk of large losses on job markets. Governments should act swiftly, and probably innovative schemes and policies should be considered as well: Château et al. (2011), for instance, propose that sector-specific rigidities, namely due to the critical reallocation of skilled-specific jobs, may be addressed by human capital investment that could be financed by Emission Trading Systems (ETSs) revenues.

The risk of transitioning will also come from adjustments aimed at moderating damage in natural and human systems responding to predicted extreme and gradual events and their effects. Such interventions are defined by the IPCC (2022a) as *adaptation*, a collection of processes implemented in order to minimize adverse impacts from existing climate conditions and variability. The benefits provided by adaptation practices are more local when compared to the ones generated by mitigation, yet they are realized in a much shorter time lag. Adapting to a changing climate is not simple nor inexpensive. There will be limits to the extent to which these processes have the capacity to minimize physical risks. Although to some extent adaptation may occur autonomously, as individual economic agents respond to the growing risk of higher damages, much of the process will require public actors to engage in specific planning, including major infrastructure decisions. Interventions will concern short-term risks, namely improving emergency responses to extreme climate events, but more importantly they will require a long-run perspective, e.g., increasing drainage capacity or building higher see-walls. Market incentives are unlikely to deliver optimal outcomes, mainly because of limited information about how the average temperature increase will affect individual firms, and uncertainty about how much investment in adaptation will cost and how such interventions could benefit business activities. Moreover, the necessity to allocate upfront a significant amount of resources may also hinder investment. As usual, developing countries are likely to suffer the most from such inefficiencies, both because of lack of information, for instance lack of developed insurance markets that could effectively provide clear price signals via premia variations, but also because of limited access to financial markets that restricts investment possibilities.

Therefore, targeted measures from public actors are necessary. Yet even assuming that there is decisive political will to adopt the appropriate policies, the effectiveness of such interventions could still be obstructed by uncertainty about damage prediction and technical limits. Thus, it's crucial for adaptation policies to be robust to a range of climate outcomes and to be flexible, easily modifiable along the way (Stern, 2007, pg. 404-413). Properly managed economic development remains still the most effective and resilient approach to adaptation for developing countries (World Bank, 2010): it generates resources and opportunities to minimize the cost of climate change also by ensuring that the creation of new assets, such as infrastructure and buildings, consider the effect of global warming on performance. The main factors exposing poor countries to physical effects of climate change, together with their geographical features, are indeed rigid economic structures, particularly reliant on agriculture, which are prone to damages from climate events and low income and wealth constrain their ability to adapt. On top of these dynamics, there is another factor that complicates credible and effective modelling: the poorest fringes of the population tend to have lower representation when looking at aggregate macroeconomic variables. In South Africa, a racially divided and water-stressed country in which droughts occur regularly, 10% of the population accounts for 80% of the total wealth. The World Bank estimates that in Colombia, which scores more than 50% in the Gini index, more than one million people will be directly affected by the rising sea levels of as much as 60 cm by 2050: these individuals are likely to belong to that 20% of the population that contributes just 4% to the national income (World Bank, 2023). Much of the current modelling and, therefore, policy planning still focuses mainly on the aggregate impact of damage and risk of climate events, ignoring other measurements that could better represents the unequal cost of a changing climate, such as the effect on each household's savings and assets. In general, adaptation and development practices are too often built upon a *one-size fits all* approach, that risks damaging the extremely poor even more. There are many cases like Salt Lake in Kolkata, India, that has been developing steadily over the last 50 years, and is now a relatively rich, wellplanned, and flood-resistant district, yet it still has massive flood-prone informal settlements on the outskirts where the poorest portion of the population lives (Rumbach, 2014). Fortunately, there are many successful cases of *equitable adaptation* too that can be a blueprint for future interventions, including simple solutions such as the incentives offered to Costa Rican coffee farmers to grow more citrus, an income source more resistant to climate events, and more structured and policy-driven ones, namely the flood evacuation routes in the urban slums of Santo Domingo that allow for safer access to schools and build social cohesion (Pelling and Garschagen, 2019).

1.2 How to formalize the climate issue

On account of all of these dynamics, climate change affects economies at different levels and through different mechanisms. Policy is bound to play a pivotal role: effectively implemented measures have the potential to curb emissions while providing the opportunity and the means to successfully adapt, whereas poor decision-making can easily result in unnecessary economic costs and exacerbate already existing societal inequalities. Every model that aims at informing public actors on decisions concerning, for instance, carbon pricing or climate-related investment projects has to walk a fine line: an overoptimistic estimate of the impact of climate change can easily result in large economic costs and unnecessarily increase the likelihood to scar the environment in a permanent way. On the other hand, to overstate the risks or to fail to properly identity the cause of the damage implies choosing a suboptimal solution, thus imposing an ineffective, if not purposeless, burden on society. The basic economic framework, therefore, needs to be able to interact with different elements and entanglements that define the relationship between the climate issue and economic activity. Global warming is a matter of unprecedented complexity that stretches the limits of economic analysis and forces economists to refine their techniques. The climate can be thought of as an economic resource that shapes societies in ways that were largely overlooked at least until the 1990ies: the peculiar nature of this phenomenon played into the difficulties in, first of all, recognizing the problem and then studying it. Climate change has been defined as the "mother of all externalities: larger, more complex, and more uncertain than any other environmental problem" (Tol, 2009). The sources of GHGs are distributed all around the globe and more diffuse than any other environmental issue, as they are emitted by virtually any economic agent. Crucially, the field of economics was also caught unprepared in dealing with the astonishingly long timeframe required to analyze thoroughly climate change and its consequences. Traditional modelling relies on horizons ranging from a few months up to a few decades in the case of development economics. On the other hand, when studying global warming, the crux of the matter lies in the extremely long atmospheric lifetime of some GHGs: while methane, for instance, takes barely more than one decade to be decomposed in the atmosphere, carbon dioxide, the most emitted GHG, has a half-life of about 120 years. For other particles, such as fluorinated gases, the figure is many times that. Considering that about half of the anthropogenic emissions of GHGs can be attributed to the last 40 years and they have not peaked yet, it can be safely stated that the polluting effect and, consequently, the economic damage will last for quite some time.

1.2.1 Interest rate and discounting

The clearest implication of such extended timeframes is that discount rates are central to the problem. The challenge with accounting for climate damage and mitigation stems from rewards of current policies being uncertain and far off in the future. They may not even appear to be profitable when compared to essential investments that yield more certain returns, such as education in developing countries, which is generally thought to generate returns of roughly 10% annually (e.g., Patrinos and Psacharopoulos, 2010). The way in which interest rates may be a misleading tool in the extremely long run is central to the issue. Although discounting is widely used to study investment opportunities and accounting for the monetary value of time, when applied to long timeframes, short term rates can lead to conclusions that are hardly reasonable, let alone theoretically valid: a single penny paid by Charlemagne to one of his subjects on the day of his coronation, for instance, invested at a moderate 2.5% rate, would be equivalent to 18 trillion in today's dollars, a figure higher than the GDP level of the whole European Union.

When approaching climate change in an economic perspective, *discounted utilitarianism* is the most common framework to analyze the outcomes generated by different policy decisions. The origin of this economic thinking can be traced back to “A mathematical theory of savings”, written by Ramsey in 1928 from which it can be retrieved what would become widely known in economics as the *Ramsey equation*, where the marginal productivity of capital, *r*, can be decomposed as following:

$$r = \delta + \eta g \tag{1}$$

Such result stems from a social planner trying to maximize the discounted sum of utilities under the assumption of isoelastic utility of consumption, $u(c_t)$, meaning that the elasticity of marginal utility with respect to consumption is constant. Thus, it must be highlighted how this theoretical framework aims at comparing the welfare of present and future generations, rather than individual preferences of consumption over time.
Analytically, Ramsey's rule results from a simple problem:

$$\text{Max} \int_0^\infty u(c_t)e^{-\delta t}dt \tag{2}$$

Optimizing the social welfare function given constant population and rate of growth of consumption for each generation, yields an equation that defines the real return on capital:

$$r = \delta + \eta \frac{\dot{c}}{c} = \delta + \eta g \tag{3}$$

Where:

- δ is defined as the *pure rate of time preferences.*
- η as the elasticity of marginal utility.
- g as the rate of growth of consumption.

This rule is central to the choice of parameters in multiple models that shaped the discussion about climate change modelling, namely Nordhaus's various DICE and RICE models, Stern (2007) and Weitzman (2007).

1.2.1.1 Choice of parameters: ethical and empirical approaches

The choice of δ, and η as well, can be broadly approached in two different ways, either:

- **Normatively**, also defined *prescriptive* approach.
- **Empirically**, also known as *descriptive* approach.

The former considers that both parameters have to represent how a society values consumption by individuals located in different points in time. Much of the debate around the subject has been focusing on determining a credible measure for δ, that can be, in other terms, thought as the rate at which society discounts the utility of future generations. Therefore, to assume a $\delta =$

0 is equivalent to assuming that the utility of future generations has the same impact on social welfare as the utility of the current ones, and, therefore, costs and benefits have the same symmetrical weight across time. Nordhaus (2007), for instance, makes use of a straightforward approach, assuming r as the average return on capital, approximating an acceptable value for the elasticity of marginal utility, η, and therefore determining a value for δ as g may be observed as output growth.

The original view of Ramsey (1928) was that "[to] discount later enjoyments in comparison with earlier ones [is] a practice which is ethically indefensible and arises merely from the weakness of the imagination" (pg.1), or, in other words, that is not morally justifiable to consider a value for δ different from 0; such approach has been agreed upon by many economists working in the field. Contemplating this ethical dilemma, it's still possible to allow for a positive utility discounting rate, for instance if one includes in the model a strictly positive *hazard rate of extinction*, i.e., the probability that future generations will not be alive at all: Stern (2007) formalized such possibility via the application of a 0.1% per year discounting. Every other normative assessment on δ is based strictly on personal beliefs, rather than economic principles. Indeed, it seems that economists are not able to produce an estimate of δ that's not a mere representation of their ethical view: Pindyck (2013) proposes that the lack of consistent estimates calls for such parameter to be *a policy parameter*, as it can just reflect the choice of policy makers and should therefore be representative of the choice of the majority of citizens. Nevertheless, a value for time preference has to be chosen, otherwise modelling tools such as IAMs are bound to provide a wide range of values for parameters such as the Social Cost of Carbon (SCC), which would defeat their actual purpose.

The choice of η may be even more complex as it's tasked with three roles in the model: Arrow et al. (2014) notice that it stands for:

- The inverse relationship with the intertemporal elasticity of substitution between current and future consumption
- The coefficient of relative risk aversion
- The aversion in intergenerational inequality

The estimation, or choice, of η will therefore vary, depending on how much emphasis is placed on each role. A common *normative* narrative (e.g., Gollier, 2012, Arrow et al., 2014; Dasgupta, 2008) suggests that η has to reflect the maximum sacrifice one generation should make to transfer income to another generation. The obvious shortfall of this reasoning is that there is no credible and universally accepted way to determine it.

Descriptive approaches are not straightforward either. The aforementioned DICE "empirical" estimations fall in this category as they are effectively based on observed values of macroeconomic aggregates. Nordhaus (2007) retrieves respectively $\delta = 1.5$ and $\eta = 2$, from an interest rate, r, that starts from 6.5% in 2015 and declines down to 4.5% in 2095, as opposed to Stern's (2007) that considers a far lower r (1.4%) which, consequently, is bound to result in a much higher SCC.

Therefore, although descriptive approaches are anchored in some real-world data, they still rely heavily on the personal assumptions of the modeler. Even not considering the issues previously discusses, such approach requires society to be in an optimal consumption path in order for market interest rates to approximate the consumption rate of discount, as noticed by Arrow et al. (2014).

Income redistribution may be considered as a proxy for estimating η: decisions on taxation need to be, albeit indirectly, approved by an electorate which may be a good proxy for society as a whole. Nevertheless, if one were to consider such approach in a climate-related framework, a couple of restricting assumptions would be required: the decision that the government has made in redistributing income is correct, in both an ethical and economic sense, and reallocation of resources in a specific country and in a given time frame is the same as redistribution between countries and over time. That's not consistent, for instance, with the results from Groom and Madison (2013) who used this approach to infer η based on UK income tax data, but found a significant time heterogeneity, as η averages 1.6 but exhibited peaks as high as 2.2 in the time frame considered, from 1945 to 2005 (Figure 4).

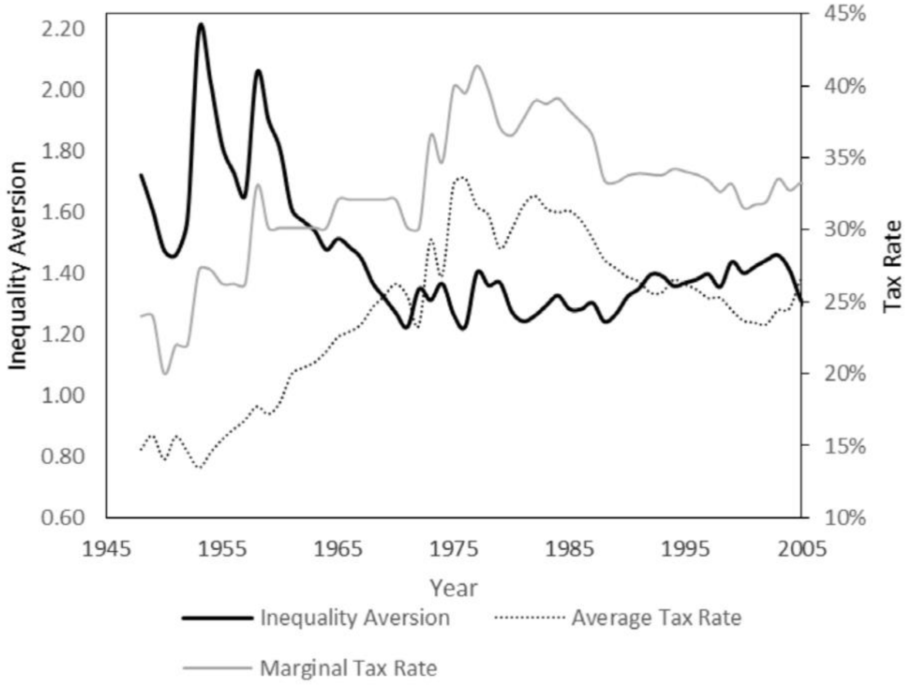

Figure 4. Inequality aversion, a suitable proxy for the value of η, as the implicit result of tax data in the UK, from 1945 to 2005 (Groom and Madison, 2013)

The determination of g may be more straightforward. It's common in many contexts to use simple output growth rates, i.e., projections of GDP growth, to approximate consumption growth rates. Yet, it's also worth noticing how such approach may be harder to justify as climate change could imply a growing and increasingly uncertain gap between output and consumption growth (Kelleher and Wagner, 2018).

Moreover, a more theoretically precise way to formalize discounting may be to apply declining consumption rates of discount, r, an approach already followed in cost-benefit evaluations of public projects both in France and in the UK. Decreasing discounting over time can be, in fact, the natural result of consumption uncertainty within the Ramsey's framework. Assuming that future shocks to consumption are IID and normally distributed, Ramsey's formula has to include another term as a consequence of uncertainty, such that:

$$r_{\mathrm{t}} = \delta + \eta\mu_g - 0.5\eta^2\sigma_g^2 \tag{4}$$

Where μ_g and σ_g^2 are respectively mean and variance of the growth rate of consumption. The last term, that captures the impact of uncertainty, can be defined as *precautionary effect* and it weighs down the overall discounting rate, implying that future consumption is more relevant when consumption is uncertain. Yet such relationship doesn't imply that uncertainty in consumption per se justifies a declining interest rate over time and, moreover, precautionary effect estimations suggest a rather limited decrease in r_t too: for instance, in Kocherlakota's computations from 1996, it was found to be almost negligible, a mere 0.26% over an estimated $r_t = 3.6\%$ in the standard Ramsey's equation. If shocks to consumption are positively correlated, however, there is theoretical ground for a declining r_t. A detailed demonstration is provided in Gollier (2012), chapter 8. Generally speaking, the underlying reasoning is that expected future shocks result in increased volatility and, thus, risk in future consumption. Consequently, the impact of the precautionary effect for distant time horizons should be larger.

It has been discussed how, over the years, various parameters for the Ramsey formula and different figures and term structures for the discount rate have been proposed. Yet, it's evident that the most notable distinction doesn't relate to the temporal evolution of interest rates, or the specific estimates used in the Ramsey formula. As it will be further explored in Chapter 3, the most consequential differentiation lies in the underlying rationale guiding the choice of a particular discount rate. In fact, there exists a fundamental disparity between normative and descriptive approaches, which leads to significantly divergent ranges of values for the discount rate and its determining parameters. Consequently, this disparity gives rise to significantly contrasting long-term equilibria projected by the model in question, yielding in turn distinct recommendations for climate policies. In other words, the rationale behind the discounting choice in a climate model has the potential to be the decisive factor in recommending policies that align or diverge from current climate objectives.

1.2.2 Transmission channels

To gain a deeper understanding of climate modeling, it's essential to comprehend how climate damages may impact the economy and whether their inclusion or exclusion in a model's specification has the potential to yield substantial variations in its results. With this aim, the following two sections delve into the representation of how damages associated with a warming planet spread and into how different specifications can significantly influence the models' projections.

In order to capture both direct and indirect effects, given this framework, the most logical way to proceed with the study the impact of climate events on long-term growth is to use the extension to the Ramsey model provided by Cass and Koopmans (Cass, 1965; Koopmans, 1963). Specifically, such approach still entails that a central decisionmaker aims at maximizing a social welfare function represented by the discounted value of utility of consumption over an indefinite period of time. Yet, given the problem provided at the beginning of Section 1.2.1, the Ramsey-Cass-Koopmans model establishes some additional constraints, maximizing long-term utility, but supplementing it with the following conditions:

$$\begin{aligned} \dot{K} &= F(K,L,T) - cL - \delta(T)K \\ \dot{L} &= n(T)L, \qquad L_0 = 1 \end{aligned} \tag{5}$$

Where F is a function returning the output, K is capital that depreciates at a δ(T) rate, and L is labor supply, growing at a *n* rate and normalized at a level of 1 at period 0, that, therefore, reflects changes in both the population and the labor productivity. Finally, *T* is a time-dependent measure of climate effects. Direct consequences of the latter can be easily seen in the previous equations, as climate impacts output, the depreciation rate of capital, and labor supply. Yet, a more detailed analysis has also to take into account the indirect effects of climate variables in the long-term equilibrium. As proposed by Fankhauser and Tol (2005) climate change may also have an indirect effect on both savings and capital accumulation and these dynamics can have subtle and less intuitive consequences. The steady-state solution of the Ramsey-Cass-Koopmans framework is found by setting $\dot{c}$ and $\dot{k}$ equal to 0, such that an equilibrium for both consumption and output can be retrieved:

$$\begin{aligned} f_k &= \delta + \rho \\ c &= f - k(\delta - n) \end{aligned} \tag{6}$$

Although the Ramsey-Cass-Koopmans features endogeneity of savings, keeping this parameter at a constant fraction of output allows for the isolation of the effect on capital accumulation. Defining $\bar{s} = 1 - \frac{c}{f}$ implies that the overall level of savings is given by:

$$\bar{s}f = (\delta + n)k \tag{7}$$

In order to get a measure of the impact on *k*, capital-to-labor ratio can be differentiated according to equation (7) with respect to climate damage:

$$\frac{\partial k}{\partial T} = \frac{k(\delta_T + n_T) - \bar{s}f_T}{\bar{s}f_k - \delta - n} \tag{8}$$

In which δ_T, n_T and f_T are respectively the derivatives with respect to climate damage of depreciation, labor supply and output. Such relationship suggests that the impact of climate change on the capital to labor ratio may actually be ambiguous once indirect effects are considered. The convexity of the saving function implies a negative denominator. The effect of climate change on depreciation is undoubtedly positive, leading to a lower level of capital accumulation. The same principle applies to output, that is directly affected: as climate events result in a smaller economy, the absolute negative effect on production weighs down the overall level of capital. Yet Fankhauser and Tol (2005) propose that a lower supply of labor would result from the negative relationship between the severity of climate change and population growth, due to both the easier spread of diseases and the higher incidence of relevant climate events. Formally, it implies that $\frac{\partial n}{\partial T} = n_T < 0$. Therefore, the impact of T on n would affect $\frac{\partial k}{\partial T}$ in the opposite direction, at least in part offsetting the negative effect on k of output and depreciation: theoretically, assuming that $n_T > \delta_T - \frac{\bar{s} f_T}{k}$, a more severe effect of climate change results in a positive effect on capital to labor ratio. The insight here is that a sufficiently large impact on the population could result in higher per capita levels of capital stock, merely due to the decline in the labor force. However, it's really implausible that such assumption holds. Moreover, in the unlikely case it did, this framework still maintains with certainty that the effect on overall capital stock, *K*, is negative, as it clearly results if effects on *n* are not considered. This analysis still provides an interesting insight: in countries where the population exhibits a larger susceptibility to climate events, one could expect, *ceteris paribus*, that the reduction of capital per worker is more significantly offset by the effect on population. In broader terms, this finding emphasizes how including indirect effects in the analysis may be significant and underscores how accounting for such dynamics in a model that aims to predict the relationships between the economy and the climate issue has, at least, the potential to yield substantially different results.

The Ramsey–Cass–Koopmans specification allows for the endogenous determination of savings, as opposed to others, such as the Solow-Swan's, where it's determined exogenously as a given fraction of income. Therefore, the definition of the level of gross savings per capita as $s^{\mathrm{G}} = f - c$ implies that, considering equation (6), the level can be alternatively defined as:

$$s^{\mathrm{G}} = (\delta + n)k = f - c \tag{9}$$

Thus, differentiating this function and combining it with (6) allows to illustrate the factors determining the effect on the levels of savings per capita:

$$\frac{\partial s^{\mathrm{G}}}{\partial T} = \delta_T\left(k + \frac{\delta + n}{f_{kk}}\right) + n_T k - \frac{(\delta + n) f_{kT}}{f_{kk}} \tag{10}$$

First of all, one may notice that climate variables affect savings directly via output reduction. Yet such dynamic is only a partial representation of a more extensive impact: as f_{kT} is negative, a reduction in the marginal product of capital comes about. In other words, an inferior return on capital is bound to reduce the level of investment, which in turn will burden the size of the capital stock in equilibrium. The negative relationship between extreme climate events and population growth, $n_T < 0$, allows for the representation of another direct impact: larger health impacts result in fewer savers, which, in turns, leads to a lower s^{G}. On the other hand, an attentive observation of the impact of depreciation reveals an ambiguous effect in this case as well: the lower yield of capital provides agents with a disincentive to save, yet faster deterioration also incentives consumers to compensate increasing the supply of savings. Overall, under the reasonable assumption that the partial effect of climate variables on depreciation is positive, i.e., $\delta_T > 0$, the sign of the impact defined in equation (10) cannot be determined a priori. Moreover, starting from the definition of gross savings previously provided (9), and differentiating it with respect to T, the relationship can be rearranged as:

$$\frac{\partial s^{\mathrm{G}}}{\partial T} = (\delta_T + n_T)k + (\delta + n)\frac{\partial k}{\partial T} \tag{11}$$

And therefore, combining it with the first equation in (6):

$$\frac{\partial s^{G}}{\partial T} = (\delta_T + n_T)k + (f_k - \rho + n)\frac{\partial k}{\partial T} \tag{12}$$

Such relationship allows for an assessment of the impact of the discount rate on savings in this specific framework. Previously it has been discussed how a higher interest rate, ρ, would lead to a lesser consideration of future consumption, therefore implying that savings should be lower as a result. In this case, as $\frac{\partial k}{\partial T} < 0$, the model suggests that there is also an opposite tendency.

Discount rates have an effect on savings through the impact of climate change on capital: lower rates incentivize agents to react more strongly to the future loss in productivity and therefore have a negative effect on savings. This dynamic can be easily detected in equation (12): choosing a value of ρ closer to 0 results in a more sizeable impact of climate events on savings.

The Ramsey-Cass-Koopman specification has been the building block of the influential DICE model, since 1992. However, it's interesting to notice how DICE channels all climate impacts through the production function, and it doesn't specify the aforementioned mechanisms that may significantly shape the long-term equilibrium. In general, this section has found many dynamics that may be worth including in a model aimed at projecting long-term economic variables in a climate change related framework. It's reasonable to believe that failing to reproduce these relationships is bound to distort estimates and potentially produce biased insights. Yet that is hardly the only way in which a framework aiming to model global warming can produce unreliable outcomes. Many of these discrepancies stem from variations in other more or less subtle dynamics that are either included or omitted in the analysis, as explored in the next section.

1.2.3 Specifications: direct and indirect impacts

This is obviously one of the many approaches that one could take to address the issue of formalizing climate effects. Yet, the previous demonstration proves a universally fundamental point: how modelers think about climate events and their impacts, and the specification they choose for their models plays a pivotal role in the results that quantitative analyses bring about.

The formalization previously discussed allows for the endogeneity of savings and, therefore, it takes into account the effect of climate change on how much agents decide so save, rather than treating them simply as a predetermined fraction of income, as it's the case in the Solow-Swan model (Solow, 1957). We may generalize the output from the latter model in a Cobb-Douglas form as:

$$Y(t) = \frac{A(t)K^{\alpha}L^{1-\alpha}}{1+\beta T(t)^2} \tag{13}$$

In which α and β are calibration parameters and T is temperature as a proxy for climate damage, dependent on time t. Output is dependent on capital, K, and productivity, $A(t)$.

The advantages of the assessment proposed by Fankhauser and Tol (Figure 5) arise from the effects of different specifications being computed via the same model, DICE, using its parameters and functional forms. Such approach allows for a direct comparison of the output resulting from different frameworks, thus isolating the impact of including specific dynamics from the variability that may be caused, e.g., by different calibrations. Given the similarities, the comparison between Ramsey and Solow, for instance, provides an insight into what is the effect of the endogeneity of savings, which, on climate damage, is marginal at best, according to Figure 5.

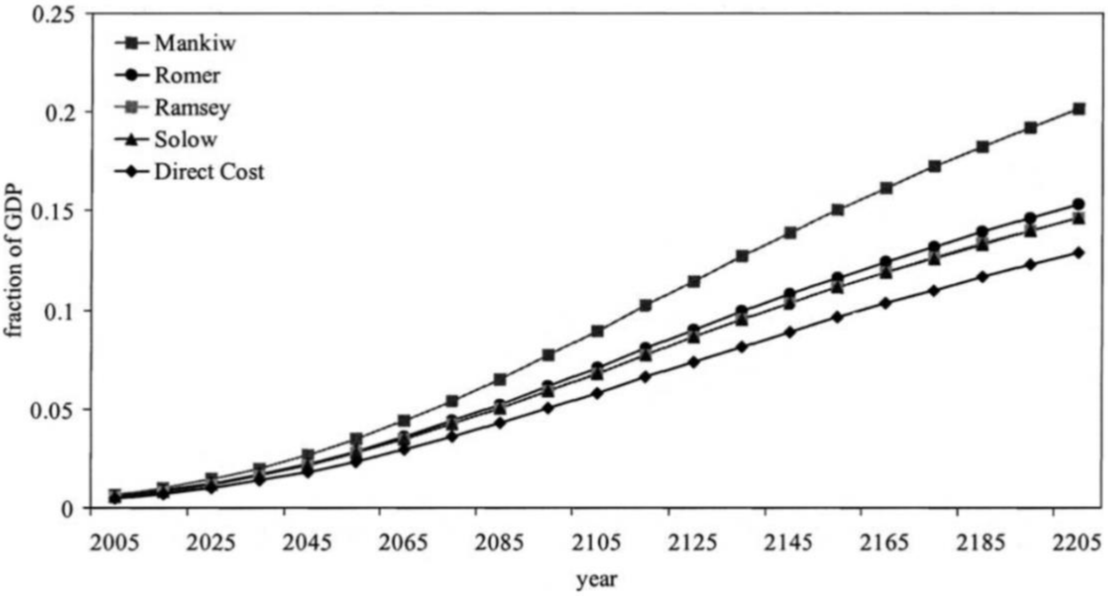

Figure 5. Economic impact of climate change as a fraction of GDP under different specifications (Fankhauser and Tol, 2005). The impact is computed as loss of output in the case of a 3° warming scenario, compared with the absence of warming.
This analysis shows that different specifications within the same framework can lead to significantly different long-term results.
Given the age of the study, the estimates provided are significantly lower when compared to current estimations. For up-to-date estimates from the DICE model consult Chapter 3.

On the other hand, the extension of the Solow model proposed by Mankiw, Romer and Weil in 1992 includes *human capital* in the long-term modeling. In a climate relevant framework, output may be formalized as:

$$Y(t) = \frac{H(t)^{\vartheta} K(t)^{\alpha} (A(t)L(t))^{1-\alpha-\vartheta}}{1 + \beta T(t)^2} \tag{14}$$

Where $H(t)$ represents the human capital and ϑ is the elasticity between human capital and effective labor. It's necessary to incorporate the assumptions that both human and physical capital exhibit the same depreciation rate (i.e., $\delta_H = \delta_K$) and that savings can be allocated toward human or physical capital (i.e., $s = s_H + s_K$). Comparing Mankiw's modelling to the Solow-Swan specification allows therefore to establish a measure of how climate change affects output also via human capital cumulation, as both models consider savings and technological progress as exogenous variables. According to the analysis by Fankhauser and Tol (2005), this specification yields the highest effects of climate change on GDP (Figure 5).

The previously discussed models didn't provide any explanations of the factors that determine productivity, which is effectively one of the key drivers of long-term growth. Since the purpose of this analysis is to provide a model that also takes into account endogenous technology and climate change effects, one may consider a simple framework, in which there is no human capital stock but R&D, that enhances productivity, is financed via part of the capital and the labor stock. Therefore, output can be generalized as:

$$Y(t) = \frac{A(t)((1-\gamma_k)K)^{\alpha}\big((1-\gamma_L)L\big)^{1-\alpha}}{1+\beta T(t)^2} \tag{15}$$

And productivity evolves according to the following equation:

$$\dot{A} = B(t)(\gamma_K K)^{\lambda}(\gamma_L L)^{\lambda} A(t)^{\lambda} \tag{16}$$

As B(t) is the time-dependent productivity of research and development, $\gamma_{K,L}$ represent the impact of capital and labor on productivity, and λ describes the extent to which diminishing marginal productivity sets in more resources are allocated toward research and development. In this framework, changes in climate don't affect productivity, as the impact is only felt *ex post*, in the production function. Clearly, in the computations displayed in Figure 5, this specification provides a measure to assess what happens when productivity is included in the model.

The most obvious result is that indirect effects play a major role in determining the equilibrium of the economy in the long run. A model considering only direct costs has the potential to underestimate the impact of global warming on the economy. This analysis also emphasizes how human capital (Mankiw's model), and the accumulation of knowledge (Romer's model) are key components of modelling, as both produce more sensitivity to global warming. A failure in reproducing these dynamics may result in a less precise model, that could, for instance, underestimate the climate effect on the economies of richer countries. The direct effect is, in fact, still likely to be larger in areas where income levels are lower, and probably the overall effect is far more sizeable as well. Yet, assuming that physical capital is the largest driver of growth in less developed economies (see, for instance, Rossi, 2020), while knowledge cumulation and R&D have a larger impact in richer countries, modelling based on a simple form of the Solow-Swan or the Ramsey-Cass-Koopmans specifications, as previously formalized, underestimate the impact on wealthier economies.

A conclusion that remains unambiguous is that the nature of climate effects retrieved analyzing the impact via these standard growth models is almost consistently and unconditionally negative. Absolute capital stock is certain to be damaged and the only specification that allows for agents to adjust their savings based on climate events yields a negative impact on the capital to labor ratio as well. Such dynamics consequently imply that the effect on net savings (i.e., $s^{\mathrm{N}} = nk$) is bound to be a definite reduction, in spite of some ambiguity concerning the comprehensive impact on gross savings. There is a necessity to address the shortfalls of these approaches: capital and savings are undoubtedly key drivers of growth in the long term, yet they are not the only way in which climate change can shape economies and affect growth. As already discussed in Section 1.1.2, global warming may have a sizeable impact on how economies are structured. Some industries are likely to experience sharp declines, while other are bound to grow as a result of adaptation to climate change, and the impact of such change in GDP composition is not modelled in the previous equations. Moreover, these approaches fail to provide any representation of international trade and capital flows that should be reasonably expected to produce significant effects on how climate events impact long term equilibria.

1.2.4 Abatement costs and transitioning

This simple framework allows to establish that the specification of physical risks in the economy is a pivotal element of formalizing the effects of climate change on output. Yet, it doesn't provide any insight into how transitioning dynamics contribute to shaping the long-term equilibrium. As an example, one may reorganize the specification of the climate impact on the economy of the latest DICE output function:

$$Y(t) = A(t)K(t)^{\gamma}L(t)^{1-\gamma} \cdot D(t) \tag{17}$$

The first three terms are equivalent to the ones used in previous specifications and have the same meaning, whereas damages here are represented in a single term, encompassing both physical damages and abatement costs:

$$\mathrm{D}(t) = [1 - \Lambda(t)][1 - \Omega(t)] \tag{18}$$

Which suggests that the impact spread in the economy via physical damages $\Omega(t)$, and via abatement costs as well, $\Lambda(t)$. The specification of the former has already been discussed as it can be intuitively represented as a direct output reduction. However, the formalization of abatement costs also provides some interesting insights. In DICE (Barrage and Nordhaus, 2023), for instance, these costs are determined as:

$$\Lambda(\mathrm{t}) = \theta_1(t)\mu(t)^{\theta_2} \tag{19}$$

A polynomial function of the *emission control rate*, $\mu(t)$, a variable further explored in Chapter 3. Some features of the abatement cost function can be explained intuitively: one may expect the emission control rate to be proportional to output, and the function as a whole to be distinctly convex. This is due to the marginal cost of reducing climate impacts being likely to increase more than linearly, since resources allocated toward abatement grow ineffective as the most efficacious steps in fighting climate effects are increasingly taken. Such straightforward representation allows, therefore, to capture a pivotal dynamic in the evolution of economies affected by climate change: one may costly reduce climate damage, but the effort has to be weighed against the increasing inefficiency of these actions. Yet, there are far more complex representations of the defining drivers of abatement costs. Nordhaus, for instance, chooses to include in its modelling a *backstop technology*, i.e., a zero-carbon source of energy that has the potential to replace fossil fuel consumption, at a relatively high cost. Nevertheless, in order to do so, it has to rely on highly uncertain and controversial estimates that result from extremely detailed process models[1]. Other approaches are available: for instance, FUND, another influential IAM, doesn't include backstop technology but it relies on a more detailed

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[1] More information on detailed process models and on the relevant equation in Nordhaus' DICE are provided in Chapter 2 and Chapter 3 respectively.

representation of emission reduction costs. FUND, in fact, specifies the regional and global cumulation of knowledge in abating technologies and its spillovers, a dynamic likely to have a significant impact in the long term and that offsets the increase in cost per unit of abatement with a decrease in costs over time.

1.3 Concluding remarks on the economics of climate change

This chapter has examined some of the most critical challenges that are expected to arise from a warming planet and has presented a widely used macroeconomic framework to formalize the costs associated with climate change. There are many issues pertaining the underlying theoretical framework that may hamper both the credibility and the efficacy of climate modelling.

The most crucial, and central to this analysis, is that each prediction of future consumption or utility needs to be discounted in some way to account for the cost of utilizing resources now rather than in the future, and, maybe more importantly, in this generation rather than in the next ones. Yet, there is a clear lack of consensus on the magnitude of the rates and that is exacerbated by the sensitivity of such parameters to ethical considerations, which hinder unanimous agreement for their very nature. Much of this prominent quantitative disparity in the choice of the discount rate and the parameters of the Ramsey formula reflects the different rationales employed in determining the discount rate: a descriptive approach to discounting implies that the interest rate should be the result of quantifiable comparisons with figures extracted from real world variables, such as the return of capital in financial markets, or GDP growth. On the other hand, the normative, or prescriptive, approach suggests that eliciting discounting measurements should be at least partially anchored to ethical considerations, recognizing the difficulty in retrieving universally acceptable variables obtained, for instance, via measurements from other macroeconomic indicators. Part of the disparity should be attributed to the different roles that variables, namely the pure rate of time preferences and the elasticity of consumption, are expected to fulfill within the Ramsey framework. Another aspect of the disparity should be attributed to the role that the Ramsey equation itself is intended to fulfill, as it will be further explored in the analysis presented in Chapter 3.

As to provide a more complete overview of the framework used, and its limitations, this chapter delved into the mechanisms through which climate change has the potential to affect the economy and what can be the impact of specifying different dynamics within the same model. First of all, it should be considered that there is an evidently large uncertainty in predicting economic growth and stability in extended timeframes under normal circumstances and, additionally, the precariousness of the current estimates is likely to be aggravated by the climate issue in the following decades. It's clear that climate change is bound to result in a negative aggregate effect on the main macroeconomic variables, but global warming has also the potential to affect economies through mechanisms that may be subtle and difficult to formalize. How the modeler specifies the dynamics of climate change in shaping economic activity is, therefore, a fundamental part of the process. Failing to comprehensively represent some pivotal dynamics could effectively imply a distortion of long-term estimates and, thus, it could hinder the credibility of the model. However, it's important to consider these factors within the appropriate context. As elaborated in Chapter 2, the selection of the framework should be also closely aligned with the intended purpose of the model under consideration.

Chapter 2 – Integrated Assessment Models

The purpose of this chapter is to present an overview of the features of the tool employed in the analysis. The broad scope of IAMs and their extensive use in the literature and in policy making decisions has resulted in a large number of models being developed and utilized, and, consequently, generated various critiques and considerations on the matter, raised by supporters and critics as well. This section doesn't aim at providing an extensive depiction of all the models in the literature nor does it intend to delve into all the objections and perspectives that have been debated in recent decades. It rather serves two main objectives: to introduce the reader to these modelling techniques and to provide an overview of their distinctive features, that in turn is fundamental to understand the selection of the tool specifically used for the analysis. In order to do so, the initial section presents an introduction to the use of these modeling technique in climate science and highlights its significant historical milestones. Secondly, the following section serves to describe what are the objectives of these tools and provides some pivotal distinctions based on crucial features. Finally, an overview of the primary challenges and criticisms encountered by these models will be presented. While the overview will not cover every single issue raised nor provide a comprehensive analysis, it will provide a glimpse into the most prominent limitations of these tools.

Integrated assessment models are a fundamental part of the evaluation of the impact of policies implemented in the short term and their projected effects on long-term equilibria. At their fundamental level, they are simplified quantifiable representations of reality that have the potential to combine information from multiple disciplinary domains, ranging from climate sciences to economics, into a unified framework. Initially, they were mainly employed to evaluate and develop individual components within several fields such as physical sciences, biological sciences, economics, and social sciences. Yet, in recent decades, there has been a growing emphasis on a more detailed understanding of climate change, sparked by the efforts of actors and agencies such as the IPCC, and, as a result, researchers have made significant progress in developing increasingly inclusive frameworks capable of integrating multiple modules. The distinctive value of these models, in fact, stems from their ability to deliver an assessment of interdisciplinary interactions, a pivotal aspect when studying the effects and the potential policy response to a warming climate.

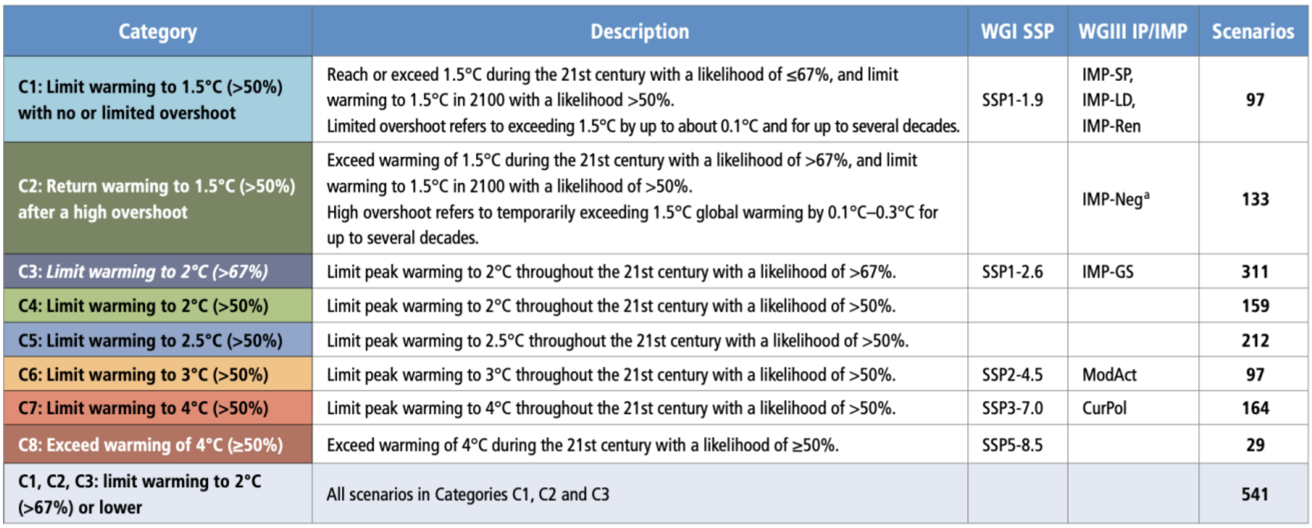
2.1 A brief history of IAMs and climate change

The CIAP (Climatic Impact Assessment Program) is generally deemed to be the first large integrated assessment of climate issues, even though the project was centered around assessing the potential atmospheric effect of the American supersonic transport aircraft, rather than global warming (Barrington, 1972). Even though it lasted just 3 years, and it was capable of producing estimates for a relatively short 20-year timeframe, this research project effectively funded much of the basic research on the stratosphere and on the damages that anthropogenic emission can cause to it.

The first insight that climate issues would have repercussions in other fields of study and the initial concerns regarding the necessity to assess the resulting interdisciplinary dynamics dates back to the late 1970ies. As early as 1979, researchers working in the study of the effects of carbon dioxide on climate expressed concerns about the growing certainty of global warming and the lack of tools available to effectively project its socioeconomic impact (Charney et al., 1979). As the impact of climate change became increasingly evident, expert started to focus on developing more complex models to predict the physical and natural impact of anthropogenic emissions but at the same time they also began emphasizing the importance of exploring the socioeconomic implications associated with this issue. In the following decade it emerged how mitigation but also adaptation to climate change were bound to play a crucial role in formulating optimal policies. In this same period there were the first examples of research including IAMs that were aimed at integrating an economic component in their modelling, balancing the cost of emission mitigation with the benefit of avoided future climate damage. This effort that would eventually result in the creation of an entire family of models generally called the *cost-benefit* IAMs.

However, if we were to pinpoint a single crucial moment in the development of IAMs, it would undoubtedly be the establishment of the Intergovernmental Panel on Climate Change (IPCC) in 1988, the United Nation’s intergovernmental body tasked with the role of advancing scientific knowledge about climate change caused by human activities. Specifically, the IPCC is mandated to produce comprehensive periodic assessment reports, the so-called AR, that provide a comprehensive overview of the current scientific, technical, and socioeconomic knowledge related to climate change. The agency, in fact, played a crucial role in the development of another family of models, the *detailed-process* IAMs, which are substantially more elaborated and are generally more influenced by disciplines such as physics and earth science. For instance, its first assessment, the AR1 in 1990, heavily relied on the IMAGE (Integrated Model for the Assessment of the Greenhouse Effect) model, a detailed-process IAM which served as the primary reference for estimating the trajectory of carbon emissions and is still employed in the latest AR6 in its most recent iteration (Figure 3).

Another significant moment was the release of the IPCC's Special Report on Emission Scenarios (2000), which marked the first publication where the agency utilized a series of integrated models and relied upon multiple multidisciplinary teams to generate several pathway scenarios. In this report different models that would subsequently gain significant influence, including MESSAGE, AIM, and MiniCam, were utilized by the agency for the first time. However, the most significant feature of this publication lied in the opportunity for multiple IAM teams to collaborate and investigate the practical integration of their models, aiming at effectively operating together in a cohesive manner. This *modus operandi* would characterize all of the agency's following publications, which generally encompass a range of scenarios and rely on a wide selection of integrated models. For instance, the third Working Group (WGIII) of the current AR6, which assesses climate change mitigation, relies on 1686 scenarios, selected from an initial set of 2266 proposed scenarios with global scope and generated by more than 50 different models (Figure 6). That's also the case for less comprehensive publications: the 2018 special report of on global warming of 1.5 °C (IPCC, 2018) relied upon 411 scenarios drawn from 10 different global IAMs. In other words, over time the alternative pathways built by the agency grew more sophisticated and the latest publications rely not only on the development of several emission scenarios, but also on the generation of five shared socio-economic pathways, known as SSPs. This approach to modelling, which takes into account several methodologies to build a likely forecast of future trends, also represents the foundation of organizations such as the IAMC (IAM Consortium), founded in 2007. This evolution has been fundamental as to provide greater transparency in this field: the consortium provides accessible knowledge and information on the numerous integrated models currently used both in the academic literature across several fields and that serve as the fundamental basis for informing policy decisions.



Category	Description	WGI SSP	WGIII IP/IMP	Scenarios
C1: Limit warming to 1.5°C (>50%) with no or limited overshoot	Reach or exceed 1.5°C during the 21st century with a likelihood of ≤67%, and limit warming to 1.5°C in 2100 with a likelihood >50%. Limited overshoot refers to exceeding 1.5°C by up to about 0.1°C and for up to several decades.	SSP1-1.9	IMP-SP, IMP-LD, IMP-Ren	**97**
C2: Return warming to 1.5°C (>50%) after a high overshoot	Exceed warming of 1.5°C during the 21st century with a likelihood of >67%, and limit warming to 1.5°C in 2100 with a likelihood of >50%. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1°C–0.3°C for up to several decades.		IMP-Neg[a]	**133**
C3: *Limit warming to 2°C (>67%)*	Limit peak warming to 2°C throughout the 21st century with a likelihood of >67%.	SSP1-2.6	IMP-GS	**311**
C4: Limit warming to 2°C (>50%)	Limit peak warming to 2°C throughout the 21st century with a likelihood of >50%.			**159**
C5: Limit warming to 2.5°C (>50%)	Limit peak warming to 2.5°C throughout the 21st century with a likelihood of >50%.			**212**
C6: Limit warming to 3°C (>50%)	Limit peak warming to 3°C throughout the 21st century with a likelihood of >50%.	SSP2-4.5	ModAct	**97**
C7: Limit warming to 4°C (>50%)	Limit peak warming to 4°C throughout the 21st century with a likelihood of >50%.	SSP3-7.0	CurPol	**164**
C8: Exceed warming of 4°C (≥50%)	Exceed warming of 4°C during the 21st century with a likelihood of ≥50%.	SSP5-8.5		**29**
C1, C2, C3: limit warming to 2°C (>67%) or lower	All scenarios in Categories C1, C2 and C3			**541**

Figure 6. Classification of emission pathway scenarios studied by the WGIII in the latest AR6 divided into temperature level targets, using the MAGICC model. This table includes all the scenarios that passed the vetting process and that generated sufficient data to be classified according to temperature, that is 1202 over 1686. IPCC (2022b)

2.2 Objectives and taxonomy

Due to the variation in objectives, the heterogeneity in academic fields from which they originate, and the distinct strategies employed to project future emission pathways, the overall framework of existing models is inevitably complex. Yet, in spite of the complexity, there are certain common features and similarities among the models that can yield valuable distinctions. First of all, integrated models employed in the study of climate change inquire about one, or more, of the following (Bosetti, 2021):

1. What are likely to be the **long-term consequences** of the **current policies** or fossil fuel usage? This is generally referred to as a *BAU* (Business-As-Usual) or *baseline* scenario. In this case the focus may revolve around a scientific aspect such as the current level of emissions, or around the present state of policy measures as well as other types of socioeconomic indicators.
2. What is the **likely result of policies** undertaken to curb GHG emissions? This approach is commonly applied, for example, with the implementation of NDCs (Nationally Determined Contributions) outlined in the Paris Agreement.

3. What is the **optimal temperature change**? This goal generally aims to strike a balance between the macroeconomic cost of mitigation and the expected future damages stemming from climate change.
4. What **strategies**, **investments** and **technologies** can yield the most effective results given a climate target? In other words, the integrated models in this case aim at assessing the effect of a single, or a mix, of strategies and technologies that may align with a given target.

In broader terms, the objective of this type of modelling concerns the exploration of the *solution space*, as a range of economic or climate pathways that aims at informing the long-term implications of both currently implemented and prospective policies. If we were to pinpoint a shared feature among all IAMs, it would likely relate to the inclusion of a representation of economic trends as well as some levels of climate aspects. The specification of these dynamics it's not necessarily computed endogenously within the model, yet it may be derived from external sources and subsequently integrated with other components of the framework. In fact, models that have evolved from particular fields are inherently more focused on analyzing the specific domain they originated from, and they may not necessarily provide a detailed understanding of dynamics in other fields. This divergence implies that different models serve as more coherent tools for analyzing distinct policy or strategic solutions: for instance, in order to assess the impact of different technologies in the energy supply, it should be consider a model that has a detailed representation of the energy system, while, if the goal is to project the impact of a different carbon prices, the model should be able to deliver a detailed representation of the economy and the interaction between carbon pricing and the underlying taxation framework.

In any case, the first and probably most important distinction that can be drawn is between *benefit-cost* models and *detailed-process* or *process-based* models. In general, **process-based** or **detailed-process** (PB or DP) IAMs feature (Wilson et al., 2021):

- Explicit representation of the drivers and processes of change in global energy and land-use systems, interconnected with the broader economy and they frequently provide a detailed technological breakdown of the energy supply as well.
- Incorporation of both biophysical and socioeconomic processes, including human preferences. Crucially, they typically don't incorporate future impacts or damages of climate change on these processes, which is a key difference when compared to benefit costs integrated models.

- They project cost-effective 'optimal' mitigation pathways based on hypothetical scenarios or predefined goals, such as limiting global warming to 2 °C.

Prominent models in this category include GCAM (see Iyer et al. 2015), MESSAGE (Krey et al. 2016) and IMAGE (Van Vuuren et al., 2015). Models used in **benefit-cost** (BC) analyses, on the other hand, are bound to present simplified representations of the energy system, land use, and other critical dynamics related to the field of earth science. As a result, these models are highly aggregated, and they generally aim at analyzing the trade-off between the investment in abatement and the benefits that stem from reducing a measure of risks or damages from future climate events. These models have also found extensive use in determining specific aspects of the transition to a net-zero economy, such as estimating the SCC (Social Cost of Carbon) or incorporating climate-related impacts into regulatory appraisal processes. Examples of these IAMs include DICE (Barrage and Nordhaus, 2023), FUND (2023), and PAGE (Alberth and Hope, 2007).

The difference in complexity between the two types of approaches can be observed in Figure 7 and 8, and Table 1 offers a glimpse of the heterogeneity in their features. Whereas the benefit-cost DICE model presents only a straightforward relationship between carbon emissions and the economy in its traditional variables, such as labor, capital and output, the process-based IMAGE model relies on a far more complex entanglement of distinct modules, that aim at specifying in a far more detailed fashion the relationships between human system, earth systems and the impacts of anthropogenic emissions.

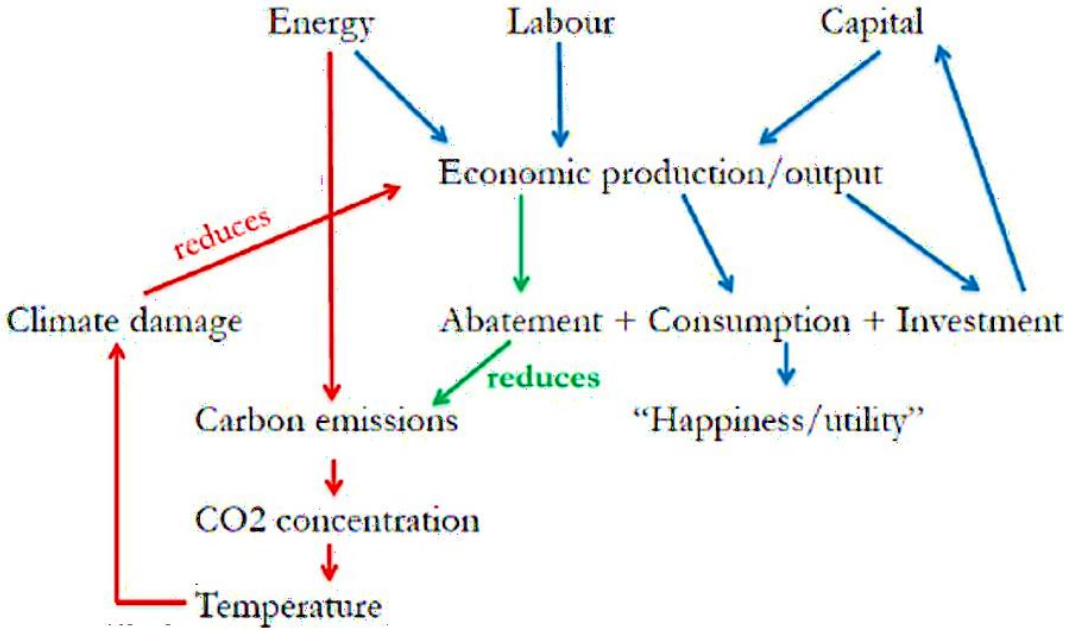


Figure 7. Schematic structure of DICE, a benefit cost model. (Gupta, 2020)

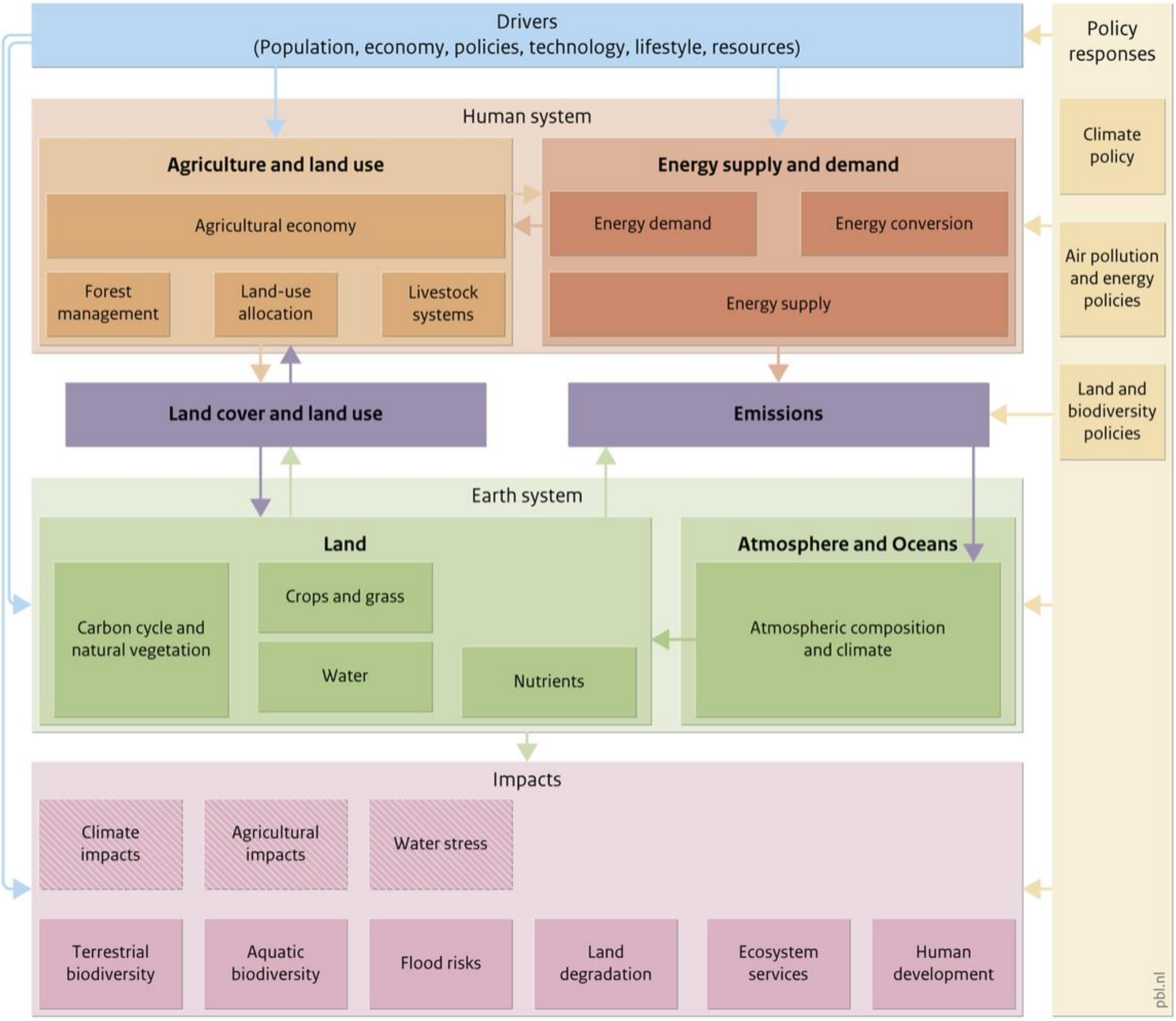


Figure 8. Schematic structure of IMAGE, a detailed process model. (PBL, 2014)

Moreover, other key distinctions in this space concern (Keppo et al., 2021):

- **Intertemporal optimization models**: they assume that a given agent, or society acts with perfect foresight, i.e., ruling out uncertainty in the framework. These assumptions are typical of benefit-cost models, although they are not featured in the entire category.
- **Recursive-dynamic models**: this type of integrated modelling acts myopically, accepting a measure of uncertainty within the framework. The projected values for each computed time step are solved without full knowledge of the future conditions.
- **Partial Equilibrium and General Equilibrium models:** the economy can be represented exogenously if there is a more detailed representation of, for instance, energy and land use (Partial Equilibrium) or the model can take into account different

relationships between the climate variables and the economy, computing a comprehensive endogenous solution for economic variables (General Equilibrium).

- **Simulation models:** as opposed to the more generally used optimization models, these frameworks aim at simulating how the system is projected to move forward, based on assumed or observed relationships.

Model	***Nature***	***Economic coverage****	***Solution method***	***Spatial dimension***	***Temporal dimension***
GCAM	Process based	PE	Recursive simulation	Global, 32 regions	Time steps 5 years, horizon 2100
DICE-2023	Benefit-cost	GE	Intertemporal optimization	Global, 1 region †	Time steps 5 years; horizon 2525
WITCH	Process based	Hybrid	Non-linear intertemporal optimization and game theoretic setup	Variable set of regions	Time steps variable, horizon 2100
IMAGE	Process based	PE	Hybrid	Global, 26 regions	1-year time steps, horizon 2100
FUND	Benefit-cost	GE	Intertemporal optimization	Global, 16 regions	1-year time steps, time spans from 1950 to 2300
PAGE	Benefit-cost	GE	Recursive intertemporal optimization	Global 8 regions	1-year time steps, horizon 2100

Table 1. Main features of some of the most common IAMs. Data from the IAMC (2023).
** Partial Equilibrium (PE) and General Equilibrium (GE).*
† Another iteration of the model, called RICE, has the option to analyze different regions.

2.3 Criticisms in IAMs: an overview

The previously discussed features as well as the extensive use of integrated modelling sparked a wide array of critiques and discussions. These debates can be encapsulated in four broad arguments (Gambhir et al., 2019; Keppo et al., 2021; IPCC, 2022b):

1. Inability to effectively represent prominent aspects of the climate issue.
2. Scarcity of transparency in the modelling process
3. Failure to adequately consider the socio-cultural dimension.
4. Narrow focus on a limited set of future pathways.

First of all, these tools may be **lacking** the capability of representing **crucial dynamics**. This argument is vitally tied to the weaknesses in effectively describing the climate change phenomenon from an economic standpoint, as explored in Chapter 1. Typically, the impact of failing to represent crucial dynamics is a lower social cost of carbon, or more generally a lower incentive to act swiftly and decisively to address the climate issue via curbing emissions or adapting to the changing climate. A common thread, in fact, is the failure to adequately represent the benefits stemming from policies that may produce economies of scale and the advantages that may be generated from structural and significant technological development in climate abatement and transitioning to a net-zero economy. Other prominent arguments concern the inability to include crucial dynamics such as the demand-side responses, Carbon Dioxide Removal (CDR) and the unpredictability of the long-term technological evolution in pivotal sectors, namely regarding renewable energy. As a matter of fact, most aspects of integrated modelling have been criticized in one way or another, and such critiques encompass the climate modules, with an array of arguments spanning from the consideration of specific gases to the calibration of the models, as well as the socio-economic and the technological aspects of IAMs. Yet, to be more accurate, it’s also worth noticing how effects that are seemingly more subtle, and may in turn be overlooked given the framework, could end up having major implications both in a socio-economic and in a climate-related perspective. In relation to this matter, in 2016 Stern additionally noticed how:

- The benefits from protecting biodiversity tend to be overlooked.
- IAMs struggle to incorporate crucial tipping points.
- These models neglect to include crucial indirect effects, e.g., large-scale human migration or wide-spread conflicts related to climate events.

This argument has been central to discussions concerning the credibility of IAMs, which, given their extensive use in crucial public policy, should aim both to be based on clear and well-defined assumptions and to be as reliable as possible. However, these critiques are notably at the heart of the continuous developments and advancements in the field, leading to improvements in the specifications of dynamics spanning from energy demand and renewables to CDR technologies and land management (IPCC, 2022b).

Another concern revolves around the **transparency** of the models and the way in which it's hard to understand their meaning and their results in a given context. This matter has played a pivotal role in the recent efforts by the IAMC to ensure comprehensive documentation of the most widely used models and the advancement of open-source models as well. Additional developments in this field may help the provision of findings that are more robust on account of cross-model comparisons (IPCC, 2022b). Besides, in an ideal setting, deep transformation pathways regarding energy and land usage should also be represented as closely related to **societal and cultural transitions**. Currently, even the most detailed integrated models lag behind in this regard (Weyant, 2017). Finally, some experts maintain that way in which the current discourse is articulated by the IPCC may steer policymakers toward specific pathways without sufficient scrutiny. This concern arises mainly because of the agency's shift in emphasis over the last two decades or so. Previously, the focus of IPCC discussions revolved much more around simply understanding the impacts of global emissions levels on the climate, yet since the late 2000s there has been a prominent shift toward establishing specific goals, such as the 2 °C and the 1.5°C target, and the actions that policymakers need to undertake in order to achieve such objectives.

The criticisms directed toward integrated modelling certainly hold at least some merit and, as discussed, they surely play a vital role in driving the field forward and fostering the development of increasingly detailed and consistent tools. Yet, especially concerning benefit-cost models, some critics have argued (e.g., Pindyck, 2013) that due to these weaknesses, IAMs possess limited or negligible value in achieving their fundamental objectives, namely assessing alternative climate change policies and estimating the social cost of carbon. This argument seems to overlook the actual purpose und utility behind the development of benefit-cost integrated models. In fact, these frameworks provide a significant contribution by offering valuable insights into climate change policy, arguably the most prominent debate of our time, which necessitates a thorough consideration of non-linear and highly complex relationships. Even without considering Detailed Process IAMs, which provide a more detailed account of, for instance, technological progress and encompass the entire ecosystem, it's worth recognizing that Benefit Cost models have played a crucial role in advancing the understanding of various aspects. As noticed by Weyant (2017) they have been fundamental in comprehending pivotal aspects in climate policy, namely:

- The significance of cost-effectiveness in designing policies
- The value of employing market-based policy instruments, such as carbon taxes.
- The importance of updated information on new technologies and advancements in climate science, greenhouse gas mitigation, and climate impacts
- The necessity of broad participation in mitigating carbon emissions
- The potential volatility in carbon prices that can arise from emission capping systems.
- The costs associated with alternative approaches to emission reduction.

In light of all these considerations, integrated models are hardly perfect instruments. Yet it's pivotal to emphasize that IAMs have been providing valuable insights for the last three decades, even though it's crucial to approach this information with careful interpretation and knowledge of its assumptions, as well as ensure its integration with diverse array of quantitative and qualitative inputs during the decision-making process.

2.4 Concluding remarks on IAMs and modelling choice

This chapter has provided an overview of the most essential aspects of integrated assessment modelling, as it touched upon its history, its objective and common features, and its most pressing limitations. The primary focus has revolved around the objectives of IAMs and their use in the scientific literature as well as in public policy decision-making. A key insight is that there exists a broad array of models and the selection of an IAM for a specific analysis shall be closely related to its features and particularly to its strengths in representing crucial dynamics for the examination. As the primary goal of this analysis concerns understanding the consequences of adopting different rationales for the choices of interest rates in the extremely long term, some considerations on the choice of the model can already be gathered.

Detailed Process models have the capability to offer an exceedingly detailed description of different dynamics in the energy system, in the land use, and in the different ways in which the climate and the planet as a whole reacts to anthropogenic emissions. Yet they would hardly be the optimal tool to perform the analysis: first of all, many of them lack the necessary focus to extract insights from an economic perspective, sometimes even assuming an exogenous evolution for economic variables. In contrast, this analysis will seek to streamline the aspects of integrated modeling concerning the complexities and dynamics of the physical and natural dimensions of climate science as much as possible. The examination should in fact be careful to avoid running the model just as a *black box*, which returns results that produce uninformative results on account of its exaggerate complexity (see, e.g., Wilson et al., 2021). A viable approach to achieve this, as it will be explored in Chapter 3, is relying upon the consideration of carbon budgets computed by the IPCC. Given these premises, it becomes clear how in order to pursue this line of reasoning, the choice of the modelling tool should be carefully weighed. The integrated model under consideration should, in fact, feature a well-defined economic module that enables the disentanglement of traditional discounting parameters, and, additionally, it should be able to represent a clear link with the climate module through a defined relationship between economic activity and GHG emissions.

Chapter 3 – Interest rate analysis

This chapter aims at verifying whether common discounting approaches proposed in the literature are compatible the carbon budget or if, even when considering different interest rates, the current trajectory of resource depletion is likely to exhaust the budget within this century.

To conduct this analysis, three main steps are taken. First of all, a literature review is conducted to explore various approaches for determining the discount rate and the parameters of the Ramsey formula, providing an overview of the different approached used and proposed in the field. Secondly, the carbon budget computed by the IPCC (2022b) is described, along with the necessary policies and economic measures identified by the agency to achieve the goal of limiting temperature changes. Finally, utilizing the DICE model, different scenarios are computed to assess whether the rates derived from the literature can effectively meet the carbon budget and to determine a measure of the necessary interest rate level to achieve it.

3.1 Literature review

At its most basic level, the crux of the matter lies in how society values the significance of the well-being of future generations. In accordance with Ramsey's formula, such dynamic is formalized via the definition of two of the three parameters constituting the real interest rate, i.e., the pure rate of social time preferences, ∂, that may be called "generational discounting" as well, and the elasticity of marginal utility of consumption, as previously discussed in more detail. In summary, the central issue relates to how the Social Rate of Time Preferences (STRP), as determined in Ramsey, has been considered from both an academic and policy perspective, the main representation of the Social Discounting Rate (SDR). The strict optimality form of the Ramsey rule also implies that the marginal productivity of capital equals the SRTP. All of these three approaches can be summarized in:

$$r = SDR = \underbrace{\delta + \eta g}_{SRTP} \tag{20}$$

Clearly, there is no consensus over a universal value that encompasses all of these definitions together. A similar issue relates to the different interpretations of the η parameter, as it's commonly understood as the marginal utility of consumption yet should also serve as relative risk aversion coefficient and reflect the aversion in intergenerational inequality. A more detailed discussion on the proposed values of all of these components is provided in Chapter 1. In the context of climate change, the complexity of finding a credible measure for these parameters is compounded by the extremely long life in the atmosphere of harmful gasses largely emitted since the industrial revolution, which are bound to produce damaging effects on the economy for an extremely long timeframe. As a side note, it's also worth noticing how this analysis will only consider CO2 emissions, which undoubtedly constitute the most pressing climate-related problem, yet hardly the only one. They are produced together with other gases which challenge policymakers, scientists, and economists with their own sets of issues and potential curbing rewards. This, for instance, holds true for methane, whose short atmospheric lifetime of 12 years circa creates a larger short-term curbing incentive, or fluorinated gases that, given their permanence in the atmosphere spanning millennia, originate a damage that resembles more a sunk cost.

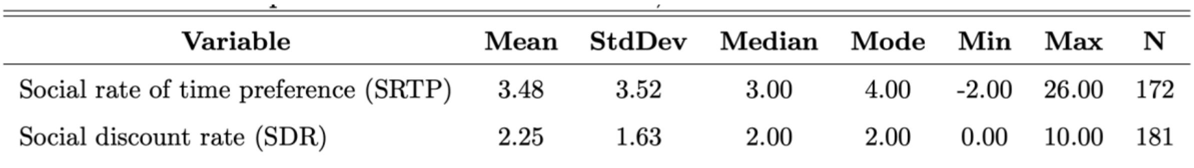
Various scenarios that will be run to verify the effect of different interest rates are based on some of the most influential proposals in the literature on this matter. While the centrality of discounting in contemporary discussions has led to a prolific number of publications, the selection of studies used to determine the parameters of the Ramsey equation in different scenarios is limited to some of those that offer the most relevant insights within the framework. The proposed discounting approaches to be considered include those by Drupp et al. (2015), Weitzman (2001), Stern (2007) and Nordhaus (Barrage and Nordhaus, 2023).

3.1.1 Expert survey on the Ramsey equation: Drupp et al. (2015)

A viable approach to challenge the common view on discounting consists in using estimates of the different components of the Ramsey formula according to a consensus drawn from a pool of experts in the field. Drupp et al. (2015) elicit responses on the individual components of the Ramsey's rule and therefore disentangle the expert opinions on the social rate of discounting into its fundamental constituent parts. By adopting this simple yet highly effective approach, it becomes possible to overcome the limitations of relying solely on normative or descriptive definitions of interest rates, and therefore it's possible for the modeler to refer to a representative account of expert opinions.

This pivotal survey provides insights into the specific values that can be used for the SDR, the STRP, the different components of the Ramsey rule, as well as how experts perceive the relationship between normative and empirical approaches. Probably the single most interesting finding is that the framework applied to retrieve long-run interest rates in models such as DICE needs to be updated, as it yields discounting parameters that significantly deviate from the consensus. According to the authors, in fact, the reported acceptable value for the SDR, that most of the surveyed individuals feel comfortable recommending, ranges from 1% to 3% for 92% of the respondents. Part of such difference is clearly a consequence of the disagreements over the exact role of the Ramsey Rule. The three distinct representations of the rule are likely to ignite debates not only over their determinants but also their individual components, as explored in Chapter 1. Yet, even taking into account the heterogeneity of the responses, it’s worth noting how, according to the same survey, much more experts, 30%, agreed upon the central value of SDR proposed by Stern, 1.4%, rather than Nordhaus’ central SDR of 4.5% or higher, which was deemed acceptable only by 9% of respondents. This figure is actually retrieved from the 2013 version of the DICE model, yet the current one presents only minor downward adjustments. The majority of respondents, 61%, still preferred a value in between those two points.

Another key insight of this survey is that, despite the theoretical expectation that the Social Discount Rate should be equal to the Social Rate of Pure Time Preferences, the results obtained from the individual components of the Ramsey Rule indicate significantly different values for these two parameters. Only 35 out of 197 experts offer identical values for both, and the correlation between them is a surprisingly low 34%, suggesting that the recommended SDR is often incompatible with the SRTP. It implies a difference exceeding 1%, which has significant implications when considering time frames spanning centuries.



Variable	Mean	StdDev	Median	Mode	Min	Max	N
Social rate of time preference (SRTP)	3.48	3.52	3.00	4.00	-2.00	26.00	172
Social discount rate (SDR)	2.25	1.63	2.00	2.00	0.00	10.00	181

Table 2. Descriptive statistics on the SRTP and SDR (Drupp et al., 2015)

Explanations of this disparity are legion. Some of the respondents provide elucidations on the divergence, such as:

- “The SDR should be equal to the risk-free interest rate”, thus resulting in values far lower than the SRTP.
- “Incomplete future markets justify SDR lower than the real markets rate”, that is often considered a proxy for the SRTP.
- “Uncertainty has to be incorporated in long-term growth”.
- “If the future benefits accrue to non-monetary goods, such as environmental amenities, a very low [and declining] discount rate is based on the expectation of increasing relative price for these goods”.

Moreover, the vast majority of respondents (80%) deems both the normative and descriptive dimensions as relevant, while 15% believe that only normative issues should be considered, and just the remaining 5% argue that only empirical issues should be taken into account when determining the SDR. These findings emphasize the complexity of separating normative and descriptive factors in determining the SDR: for most participants, estimating it requires consideration of both objective measurements and far more subjective ethical values.

As previously discussed, defining a single value for the elasticity of the marginal utility of consumption is exceedingly challenging, given that it encompasses vastly different concepts and thus lends itself to highly divergent interpretations and, in turn, estimated values. It has been suggested that this parameter may even exhibit temporal variations, with values ranging from almost null ones up to 4 and, for instance, estimates from Groom and Maddison (2013) indicate a value of approximately 1.6% when extrapolated as an inequality aversion parameter. This survey reveals that there is some consensus among experts that aligns quite closely with the previously discussed estimates: the average elasticity of consumption is 1.35, while the median value is 1 and, interestingly, the responses in the survey roughly cover the expected range, spanning from 0 up to 5.

Ultimately, the survey provides estimates for per capita consumption growth, which serves as the final parameter in disentangling the Ramsey formula. The global average growth rate of income per capita was 2.2% between 1950 and 1990 and it’s expected to range between 1.3% and 2.8% in the period leading to 2100 (IPCC, 2000). While this estimate covers a significant time frame, the durations used to analyze the impacts of climate change are notably longer, making it challenging to retrieve a universally shared estimate. This survey reports that respondents predominantly predict a positive value. While there is considerable heterogeneity in the responses, with some even estimating negative figures, overall, the survey indicates an average value of 1.7% and a relatively close median value of 1.6%, consistent with the DICE output.

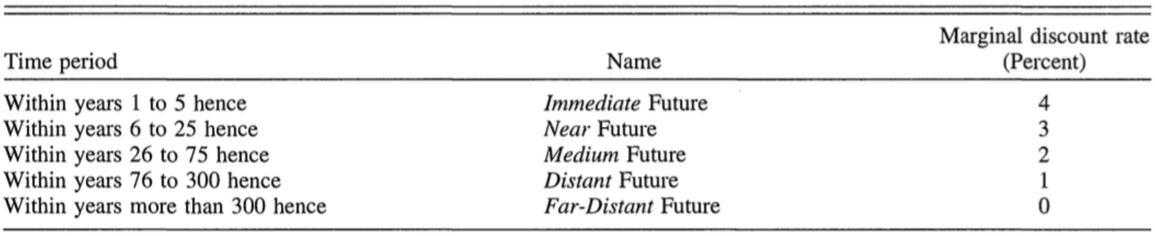
3.1.2 Sliding-scale discount rate: Weitzman (2001)

In 2001, Martin Weitzman published a study that had a significant impact on the design and policy framework of interest rate structures. This paper consisted of a survey of experts with a much larger sample size than the previous one, including 2160 respondents compared to the previous one's 262. Yet the most characteristic feature of Weitzman's study is that it retrieved a sharply declining interest rate structure from a combination of the expert responses and *gamma discounting*, which, at its most basic level, entails that uncertainty in rates implies that the certainty-equivalent discount rate is decreasing. The effective discount rate, according to Weitzman computations, evolves according to the following:

$$R(t) = \frac{\mu}{1 + \frac{t\sigma^2}{\mu}} \tag{21}$$

With the clear implication that R declines monotonically toward 0 as time increases.
This paper's significance is highlighted by its influence on the use of declining interest rates in public projects in countries including the UK, France, Norway, and Denmark. Over the last two decades such analysis has been supported by many economists working in the field, at least in its core concepts (e.g., Gollier 2012, Arrow et al., 2014) and has been criticized by others who pointed out how, for instance, its results may vary depending on whether the responses reflect forecasts of future risk-free interest rates or the ethics of intergenerational equity (Freeman and Groom, 2014).

Based on these premises, Weitzman retrieves an account of “approximate recommended” sliding-scale discount rates, which start at 4% in the most immediate future and exhibit a downward trend, eventually reaching null values for horizons exceeding 300 years.



Time period	Name	Marginal discount rate (Percent)
Within years 1 to 5 hence	*Immediate* Future	4
Within years 6 to 25 hence	*Near* Future	3
Within years 26 to 75 hence	*Medium* Future	2
Within years 76 to 300 hence	*Distant* Future	1
Within years more than 300 hence	*Far-Distant* Future	0

Table 3. Sliding-scale term structure retrieved in Weitzman's study (2001).

There are some crucial differences between the two surveys under examination. First of all, the most obvious one is that Weitzman requests the respondents to provide a single measure for an appropriate real discount rate. This survey is also more than 20 years old nowadays, and even expert opinions on discounting, a central and crucial debate, may have evolved over time: it may be, for instance, that the difference between the median discounting recommendation in Weitzman (3%) differs from the one from Drupp et al. on account of the distinct historical period, as the latter took place after some pivotal discussions sparked, for instance, by the Stern review. Moreover, this survey doesn't offer any insight into the components of the Ramsey formula, which means that if the sliding-scale discount rate has to be considered as one of the proposed interest rates for this analysis, there is a necessity to incorporate further assumptions. A declining interest rate effectively means that the future consumption will be assigned more weight, compared to a situation where a constant SDR applied at the beginning of the period and maintained throughout. This difference can also be resolved in the Weitzman's framework as a single SDR. The constant rate equivalent to the previous solution can be formalized as:

$$\bar{r} = \frac{1}{\int_0^\infty A(t)dt} \tag{22}$$

Where A(t) denotes the time-dependent weight suggested by the survey to aggregate the net benefits from various time intervals of the sliding scale. From Weitzman's gamma discounting analysis, it can also be drawn that these weights are determined as:

$$A(t) = \frac{1}{\left(1 + \frac{t\sigma^2}{\mu}\right)^{\frac{\mu^2}{\sigma^2}}} \tag{23}$$

Which, after substituting it into the previous equation and carrying out the integration, yields:

$$\bar{r} = \frac{(\mu - \sigma)(\mu + \sigma)}{\mu} \tag{24}$$

Based on the survey findings, with μ= 4.09% σ= 3.07%, it can be inferred the resulting equivalent real interest rate:

$$\boldsymbol{\bar{r} = 1.786\%} \tag{25}$$

3.1.3 Stern review

The Stern Review, published in 2006, is a seminal document that sparked fundamental debates about the nature of discount rates and their influence on quantifying the repercussions of climate change on the economy. According to Stern's analysis, a failure to swiftly implement mitigation strategies is bound to result in global warming causing economic damages that average 13.8% of global output by 2200 but can realistically be as high as 35%. These estimates encompass a wide range of factors, including standard dynamics such as infrastructure damages, increase in deaths from natural disasters, loss of environmental resources but also more subtle ones such as higher costs in air conditioning. Significantly, it also points out how the investment required in order to avoid some of the most severe impacts of climate change should account for less than 1% of global output per year. This report has been regarded as severely pessimistic by many critics, and sparked a debate predominantly centered not on the specific modeling details of the report[2], but rather on the nature of time preferences. In particular, the discounting parameters used by Stern fall, at the very least, within the lower range of figures commonly employed in the field. As previously discussed, one of the crucial factors to consider is the inclusion of an almost negligible pure rate of time preferences, estimated at 0.1%, reflecting the possibility of a fall in consumption due to catastrophic events leading to extinction, rather than simply because of lower weight assigned to future utility. Critics argue that the other parameters determining the marginal capital productivity are, likewise, quite low, as the elasticity of consumption is assumed to be only 1 and g is based on a projection of global real growth of 1.3%. As a result, the projected damages are significantly higher compared to other models: for instance, in the latest DICE-2023 model by Nordhaus, the optimal scenario predicts that damages will only amount to 2% of GDP by 2200, approximately one-seventh of the figure predicted by Stern.

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[2] There have been debates around the calibration of the model damages as well, particularly when it comes to the effects of very high temperature changes, whose estimates are generally deemed to be unreliable (see, e.g., Gollier 2007).

3.1.4 Final remarks

		DRUPP ET AL. (2015) Average (Median)	**WEITZMAN (2001)**	**STERN (2006)**
SOCIAL DISCOUNT RATE	ρ	2.25% (2%)	1.786%	1.4%
ELASTICITY OF CONSUMPTION	η	1.35 (1)	/	1
PURE RATE OF TIME PREFERENCES	∂	1.1% (0.5%)	/	0.1%
CONSUMPTION GROWTH	g	1.7% (1.6%)	/	1.3%

Table 4. Summary of discounting parameters retrieved from the literature.

As anticipated, a wide range of possibilities for the effective social rate of discounting has been proposed. Yet, even when accounting for the heterogeneity in values, the various proposed interest rates in question indicate a general consensus that the discounting approach should, for instance, adopt figures far below the yield of risky assets in financial markets. All of the studies being considered align with the recognition that a normative approach, which considers the ethical arguments for determining interest rates, should be employed at least to some extent. The result is that these selected measurements point out via three different lines of argument that future consumption should not be heavily discounted, particularly when the horizons considered are exceedingly long. The SDR produced by Stern, which is generally criticized as remarkably modest, does actually exhibit significant similarities in its constituent elements to the broader consensus among experts. The elasticity of consumption is the same as the resulting median value from Drupp et al. (2015) and it's not really far from the average one. Similarly, what is generally deemed to be the most unrealistic and purely ethically based assumption in the Stern review, the pure rate of time preferences, is closer to both the median and the average response to the one proposed by Barrage and Nordhaus in 2023 (2.2%). The value of consumption growth is somewhat lower, yet interestingly the more conservative level of the elasticity of consumption means that in turn the significance of this parameter in determining the effective SDR is not as pronounced.

3.2 Carbon budget

Carbon budget as a concept emerged in the late 2000s and gained significant attention and prominence with the publication of the AR4, the IPCC's Fourth Assessment Report (2007). At its fundamental level, the concept is remarkably simple: the AR4 introduced the global carbon budget as to represent the total amount of CO2 emissions that can be released into the atmosphere while still staying within a specific temperature target. Such goal is generally framed as limiting the increase in global average temperature to 2°C or 1.5°C above pre-industrial levels. To calculate a carbon budget, several key elements are taken into consideration including historical emissions, future emission scenarios, desired temperature targets, and the capacity of natural carbon sinks (e.g., forests and oceans) to absorb CO2. This approach is an intentionally simplistic and impactful way of communicating core scientific concepts and translating them in a way that can be easily accessed in climate policy debates. For instance, the budget has informed the establishment of international agreements such as the Paris Agreement, which aims to limit global warming "well below" 2°C and "pursue efforts" to limit the temperature increase to 1.5°C. The agreement effectively calls for countries to regularly assess and communicate their nationally determined contributions (NDCs), that should outline their specific emission reduction targets and actions to contribute to the global effort of staying within the carbon budget.

Yet its purpose goes well over the simple translation of scientific concepts into more understandable language: the carbon budget also represents the understanding that there is a finite amount of CO2 that can be emitted into the atmosphere before the global temperature rise becomes irreversible or exceeds certain thresholds with potentially catastrophic consequences. It's an adequate way to frame the finite capacity of the natural systems to absorb and sequester carbon emissions, and to represent a crucial limit that shouldn't be exceeded.

The latest AR6 defines remaining carbon budgets as the "maximum amount of cumulative net global anthropogenic CO2 emissions expressed from a recent specified date that would result in limiting global warming to a given level with a given probability, taking into account the effect of other anthropogenic climate forcers" (IPCC, 2022c). Estimates in the latest report are focused on the study of the TCRE, the transient climate response to cumulative emissions of carbon dioxide, which is the ratio of the globally averaged surface temperature change per unit of CO2 emitted (Figure 9).

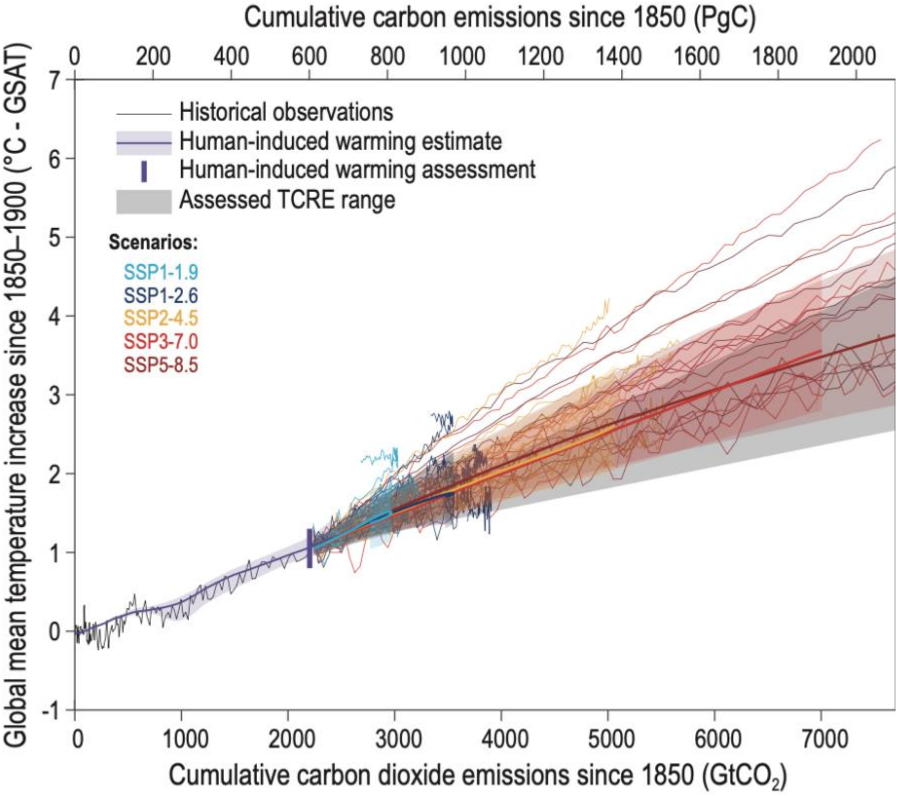

Figure 9. Illustration of the relationship between the cumulative emissions of carbon dioxide and global mean surface air temperature (GSAT). IPCC (2022c)

The evaluation of remaining carbon budgets (Table 5) acknowledges the uncertainties associated with quantifying the TCRE and provides estimations of the uncertainties surrounding each respective component. It is not feasible to formally combine all uncertainties as they are not all independent or they may represent choices rather than probabilistic uncertainties.

The IPCC also reports that due to all of the uncertainties related to mitigation and historical warming, there is a small probability that the remaining carbon budget for limiting warming to 1.5°C since pre-industrial is actually zero. However, when utilizing the best estimate values for remaining carbon budgets in accordance with the Paris Agreement, it's generally observed that the budget is relatively modest, even if not entirely null. In fact, the human-induced global temperature increase since pre-industrial is assessed to be at a 0.8–1.3°C likely range with a best estimate of 1.07°C. It implies that the current objective may involve limiting actual temperature rises to below 0.5°C, and it should also take into account that there is a lingering impact of already emitted GHGs on temperature.

Warming Since 1850–1900[a]	Remaining Carbon Budget[b] starting from 1 January 2020 and subject to variations and uncertainties quantified in the columns on the right					Scenario Variation	Geophysical Uncertainties			
°C	Percentiles of TCRE[c,d] PgC ($GtCO_2$)					Non-CO_2 scenario variation[e]	Non-CO_2 forcing and response uncertainty[f]	Historical temperature uncertainty[a]	Zero emissions commitment (ZEC) uncertainty[g]	Recent emissions uncertainty[h]
	17th	*33rd*	*50th*	*67th*	*83rd*	PgC ($GtCO_2$)	PgC ($GtCO_2$)	PgC ($GtCO_2$)	PgC ($GtCO_2$)	PgC ($GtCO_2$)
1.3	*100 (400)*	*60 (250)*	*40 (150)*	*30 (100)*	*10 (50)*	Values can vary by at least ±60 PgC (±220 $GtCO_2$) due to choices related to non-CO_2 emissions mitigation	Values can vary by at least ±60 PgC (±220 $GtCO_2$) due to uncertainty in the warming reponse to future non-CO_2 emissions	±150 PgC (±550 $GtCO_2$)	±115 PgC (±420 $GtCO_2$)	±6 PgC (±20 $GtCO_2$)
1.4	*180 (650)*	*120 (450)*	*90 (350)*	*70 (250)*	*50 (200)*					
1.5	*250 (900)*	*180 (650)*	*140 (500)*	*110 (400)*	*80 (300)*					
1.6	*330 (1200)*	*230 (850)*	*180 (650)*	*150 (550)*	*110 (400)*					
1.7	*400 (1450)*	*290 (1050)*	*230 (850)*	*190 (700)*	*150 (550)*					
1.8	*470 (1750)*	*350 (1250)*	*280 (1000)*	*230 (850)*	*180 (650)*					
1.9	*550 (2000)*	*400 (1450)*	*320 (1200)*	*270 (1000)*	*210 (800)*					
2	*620 (2300)*	*460 (1700)*	*370 (1350)*	*310 (1150)*	*250 (900)*					
2.1	*700 (2550)*	*510 (1900)*	*420 (1500)*	*350 (1250)*	*280 (1050)*					
2.2	*770 (2850)*	*570 (2100)*	*460 (1700)*	*390 (1400)*	*310 (1150)*					
2.3	*850 (3100)*	*630 (2300)*	*510 (1850)*	*430 (1550)*	*350 (1250)*					
2.4	*920 (3350)*	*680 (2500)*	*550 (2050)*	*470 (1700)*	*380 (1400)*					

Table 5. Measurements of the assessed remaining carbon budgets and relevant uncertainties. PgC values are rounded to the nearest 10, while GtCO2 ones (within parentheses) are rounded to the nearest 50. (IPCC, 2022c)

The task of maintaining temperature changes below the threshold of 1.5°C is indeed a daunting challenge. Even considering emission pathways in line with current pledges under the Paris Agreement global warming is projected to exceed 1.5°C above pre-industrial levels, and that holds true even if these commitments are supplemented with exceedingly ambitious efforts to scale up and enhance mitigation measures after 2030. As reported by the IPCC (2018), maintaining this limit, **1.5°C, requires** urgent action and **several critical conditions** need to be fulfilled:

- GHG emissions must **peak by 2030**.
- A **net-zero** level of global emissions should be reached by **2050** circa.
- The use of **non-CO2 GHGs**, such as methane, **must decline** swiftly as well.

- Economic policies that impose a **high price on emissions** are necessary to achieve cost-effective 1.5°C pathways. The discounted marginal abatement costs for limiting warming to 1.5°C is projected to be 3–4 times higher circa when compared to 2°C.
- Limiting warming to 1.5°C necessitates a significant **shift in investment patterns**, with additional investment estimated to be 830 billion USD2010 circa per year.

Moreover, these results are dependent on a range of assumptions, spanning from economic growth and technological development to changes in behaviors and lifestyle. Among these crucial assumptions it's fundamental to highlight how the policy and political dimensions play a pivotal role, particularly in fostering the necessary cooperation and in the reduction of particularly resource-intensive goods and services. In qualitative terms, the measures required to achieve the 2°C limit are quite similar, although less drastic and immediate in the coming decades when compared to the measures needed for the 1.5°C threshold. Consider, for instance, the necessary emission reduction level: in order to keep warming below 2°C with a consistent probability, emissions should decline by approximately a quarter by 2030 and eventually reach a global net zero level around 2070, as opposed to the previous target of 2050.

Finally, according to the IPCC, limiting warming to 1.5°C without the use of CRD (Carbon Dioxide Removal) is a hardly achievable task. This technology is expected to play a pivotal role, especially for GHG releases that currently lack identified mitigation measures and, as a result, significant reductions in these emissions are not expected in the near term. Yet, one of the key challenges is that large-scale deployment of CDR technologies is currently hindered by technological and economic obstacles and, as a consequence, placing excessive reliance on this unproven technology to achieve any carbon budget goal seems unconvincing and far-fetched, not even considering that it potentially incentivizes falling short of other necessary abatement initiatives.

3.3 Interest rate analysis

After discussing selected measurements of SDRs and their constituent elements as evidenced in the literature, as well as exploring the concept of the carbon budget and the necessary steps to achieve it, this section aims at examining the extent to which the previously reviewed interest rates impact emission reduction pathways. The primary objective of this analysis is to assess whether these rates align with some definitions of the carbon budget proposed by the IPCC and identify the transmission mechanisms through which different discount rate levels can either contribute to CO2 emissions reduction or fall short in doing so.

3.3.1 DICE model

The selected tool for conducting this examination is the latest iteration of Nordhaus' DICE. This analysis relies on the DICE-2023 version of the model, implemented with the General Algebraic Modeling Language (GAMS), which allows to solve the non-linear optimization problem without requiring licensing, via the use of NEOS server. The model presents some clear advantages when analyzing the impact of different rates structures: its simplified analytical and empirical framework provides a clear-cut representation of the scientific dynamics of climate change while allowing the user to directly investigate the economic and policy implications. On the other hand, the clearest shortcoming stems from the elementary structure of the model: while the use of small and comprehensive frameworks provides significant benefits, many major dynamics are not included within both the climate and the economic module. For instance, the output is simplified as production of one single commodity, that exemplifies the entirety of investment and consumption. While this assumption is commonly employed in many economic models, in this case it doesn’t allow for a comprehensive depiction of international trade, which is largely driven by the diversity of goods and services produced across regions. The structure of the tax system is completely overlooked as well, disregarding in this way its significance in determining the optimal level of carbon pricing, along with its interaction with existing taxes and possible regulatory distortions. The lack of these two features only scratches the surface of how limited the representation of reality in the model is: other pivotal dynamics, such as the impact of pollutants on health and the incorporation of endogenous technological change, are also overlooked, as discussed in Chapter 1. However, it should be noticed that no integrated assessment model offers a truly comprehensive representation of reality. In fact, the focus of this analysis is not on generating a perfectly realistic projection of carbon emissions, but rather on examining whether different rates can offer a consumption path that aligns with the carbon budgets. In this regard, it should also be noticed that, in spite of its simplistic structure, the DICE model in its previous iterations has been able to approximate to a large extent the evolution of emissions and CO2 concentration in the atmosphere (Barren and Nordhaus, 2023).

Another major limiting factor concerns the SDR structure: in order to perform analyses with declining term structures the model should allow for some measure of uncertainty, which is not feasible in a deterministic model such as DICE, as it would introduce issues of time inconsistency. Yet this analysis works with measurements of the different parameters for the SDR and the Ramsey formula components that that do not necessarily need to be employed in declining rate structures. Moreover, the overall outcome of the carbon budget examination is still bound to be probabilistic, as per the recent IPCC estimates. The ultimate goal is to leverage the simplicity and clarity of the framework provided by Nordhaus in order to examine the economic effects of different rates, while still harvesting the rigorous and more precise estimates available for the estimation of the effects of cumulative emissions on temperature changes.

3.3.1.1 Assumptions

Providing a clear explanation of the assumptions is crucial for ensuring a comprehensive understanding of the framework. First of all, the size of the labor force throughout time is central to the architecture of the model as growth in the number of workers directly imply a higher production level. The initial global population, as of 2022, is estimated to be 7.7529 billion, a figure drawn from approximations by the World Bank. The growth rate of the population, on the other hand, is calibrated in order to match the UN projections, which forecast the asymptotic limit of the global number of individuals that is likely to approximate 10.825 billion people in the long term, given current trends. Population growth is exogenously provided in the model and, thus, remains constant across different scenarios. Initial global output, on the other hand, relies on estimates from both the IMF and the World Bank. Aggregated production of every country is represented in PPP in 2019 US dollars and stands at $135.7 billion at the beginning of the modelling period.

Capital depreciation rate	10%
Initial level of TFP	5.84164
Initial 5-years TFP growth rate	0.082

Table 6. Selected figures assumed in the DICE-2023 model.

Initial cumulative emissions	633.5379
Initial emission control rate	50%
Initial cost of backstop technology (per tCO2, $2019)	707.7257

The model imposes a limit on the global cumulative level of fossil fuel extraction as well, that stands at 6000 GtCO2. Conceptually, reaching such threshold means to deplete the entirety of the fossil fuel resources in the planet. Yet this figure implies a cumulative level of CO2 extraction almost ten times higher than the current level of carbon emitted, which would in turn raise temperatures far beyond the thresholds considered in this analysis. To provide some context, the highest threshold that would be considered is 900 GtC02 emitted from 2020 onward, that, given DICE's assumptions, results in 1534 giga tons of carbon cumulatively released. Incidentally, such figures speak for a compelling argument in favor of regulation: there is no shortage of polluting energy resources in the planet, and therefore the sole role that markets are incentivized to play in this regard concerns damage prevention. In other words, since the supply of carbon-emitting energy resources will not be a constraint, the daunting task of limiting a damaging and relatively abundant resource should fall largely on policymakers' shoulders.

Clearly, the most relevant assumptions for this analysis concern the components of the Ramsey equation. As reported in Chapter 1, in using this relationship as a framework for discounting Nordhaus follows a descriptive approach, as opposed to a prescriptive one which entails deriving the interest rate from ethical considerations. Therefore, the model assumes that abatement costs have to compete with the yield generated by other investment opportunities in the economy. Such approach requires applying the Capital Asset Pricing Model to retrieve a measurement of the return on other investments to obtain a benchmark for projects aimed at curbing emissions. The most evident shortfall is that the risk features of climate investments are not guaranteed to be comparable to those of other "standard" assets. In the most recent models, Nordhaus tries to solve this issue via the application of a climate beta. Investigating the elasticity of climate damages with respect to variations in consumption using the C-CAPM suggests that abatement projects have a similar risk structure to other investment opportunities. As a result, estimates of such parameter range by and large between 0.6 and 1 (e.g., Diez et al., 2018). In the 2022 DICE model, the elasticity of marginal utility of consumption, μ, is assumed to be 1.5, which is a reasonable figure, in line for instance with the aforementioned estimates of Groom and Madison (2013). In order to define the rate of pure time preferences Nordhaus also assumes that the risk-free investment yield, ρ^F, is 1% and the time preference on risky capital, ρ^R, is 2%. Therefore, the return on a risky climate investment can be retrieved from some straightforward relationships.

$$r^{\mathrm{C}} = \rho^F + \beta^C(r^K - \rho^F) \tag{26}$$

The latter can be combined with the rate of return on risky capital from the Ramsey equation:

$$r^K = \rho^F + \rho^R + \eta_0 g \tag{27}$$

Which, in turns, results in:

$$\begin{gathered} r^{\mathrm{C}} = \rho^F + \beta^{\mathrm{C}}(\rho^F + \rho^R + \eta_0 g - \rho^F) \\ r^{\mathrm{C}} = \rho^F + \beta^{\mathrm{C}}\,(\rho^R + \eta_0 g) \end{gathered} \tag{28}$$

And therefore:

$$\begin{gathered} \partial = \rho^F + \beta^{\mathrm{C}}\rho^R \\ \eta = \beta^{\mathrm{C}}\,\eta_0 \end{gathered} \tag{29}$$

That, given β^{C} that is assumed to be at the lower end of the estimated range, i.e., equal to 0.6, results in:

$$\partial = 0.01 + 0.6 \times 0.02 = 0.022$$

Meaning that future utility has to be discounted at a 2.2% rate, and the figure for η adjusted for the climate beta is equal to:

$$\eta = 0.6 \times 1.5 = 0.9$$

This analysis seeks to question this definition. In many instances, the approach taken will be closer to a prescriptive one. In fact, one of the pivotal problems with the approach used by Nordhaus to retrieve these parameters concerns the simple use of the rate of return on capital as to determine the SDR. Among the most prominent concerns is that such parameter is estimated using data from the US financial markets and, thus, features an extremely high premium for risky assets. The literature provides various reasons for this prominent disparity, called the *equity premium puzzle*, which won't be extensively analyzed, yet it's crucial to the matter. In general, such controversy implies that the yield on equity assets is too large to be justified by standard measurement of risk aversion, as it can be as high 10 compared to a standard of about 2, let alone to be the basis of discounting the consumption of future generations. It should be also noticed how some explanations of the puzzle rely precisely on the rejection of the Ramsey model of optimal growth (Mehra, 2007), further undermining the applicability of this procedure in the given context. Therefore, it's appropriate to investigate the recent literature on extremely long interest rates and assess if it departs from Nordhaus's conjectures, and it can match the recent IPCC estimates on carbon budgets.

3.3.1.2 Relevant equations

The general framework of the model is consistent with the economic concepts and representations introduced in the initial chapter. Specifically, the core principle of the model is the optimization of a social welfare function, that is represented by the discounted sum of future per capita utility streams generated from consumption:

$$W = \sum_{t=1}^{T\max} U[c(t), L(t)]\Psi(t) \tag{30}$$

Under the same set of assumptions and implications outlined before, such as the constant elasticity of the marginal utility of consumption or the intergenerational nature of the preference. This dynamic, for our purposes, clearly results in the reiteration of the Ramsey rule.

As for the determination of the production level, the model stems from a standard approach to long-term economic growth. Consumption is represented by a single commodity, that includes also non-monetary goods, such as environmental amenities. The level of GDP is therefore computed via an adjusted version of the conventional neoclassical production function, such that:

$$Q(t) = [1 - \Lambda(t)][1 - \Omega(t)]A(t)K(t)^{\gamma}L(t)^{1-\gamma} \tag{31}$$

As output is positively influenced by the level of capital, labor, and productivity, yet it includes a representation of damages, $\Omega(t)$, and abatement costs, $\Lambda(t)$, as well. These two relationships effectively link the economic module with the climate one and, while the latter may not be the central focus of the analysis, it still holds a crucial importance within the model. It should be observed how the specification of environmental variables on the economic output omits or merely indirectly captures cumulative effects of climate, yet the updated calibration of the negative shocks on the economy closely overlaps global damage studies reviewed by the AR6 (see Barrage and Nordhaus, 2023). Moreover, the model is not calibrated to accurately account for damages in scenarios surpassing a 4°C temperature increase, yet such limitation is not concerning as all considered scenarios remain within this temperature range.

On the other hand, abatement costs over output are defined as follows:

$$\Lambda(\mathrm{t}) = \theta_1(t)\mu(t)^{\theta_2} \tag{32}$$

I.e., a polynomial function of $\mu(t)$, the emission control rate, that is the fraction of emissions that are reduced by the applied climate control policy, such that, for instance, when $\mu(t) = 1$ then the economy is in a carbon neutral position. The underlying assumption is that abatement costs are proportional to output and to an exponential function of the emission control rate, i.e., the reduction in emissions. In this framework $\theta_1(t)$ is the time-dependent measure of the fraction of production necessary to achieve total emission neutrality, around 11% at the beginning of the period, as $\theta_1(0) = 0.109062$. The relationship is also calibrated via the constant parameter $\theta_2 = 2.6$.

In this framework the optimization under different conditions is bound to yield different allocations of resources. Essentially, the output net of damages can be consumed, allocated toward investment, which grows capital stock and in turn future GDP, or allocated in abatement projects. Once taken into account the differences due to investment toward emission reduction and climate damages, the fundamental accounting relationships can be formalized in a conventional neoclassical fashion, defining the main macroeconomic categories as:

$$\begin{aligned} Q(t) &= C(t) + I(t) \\ c(t) &= C(t)/L(t) \\ K(t) &= I(t) - \delta_K K(t-1) \end{aligned} \tag{33}$$

Where Q(t) is the output net of both climate damages and abatement costs. In sum, the output is split into consumption and investment, per capita consumption is affected by labor supply, and the capital stock grows with investment and is subject to a depreciation measure proportional to the existing stock.

The social cost of carbon (SCC) is another significant variable, which is sometimes deemed as the "most important economic concept of climate change" (Barrage and Nordhaus, 2023). The estimation of this variable stems from the effort to quantify the economic cost associated with an incremental unit of carbon dioxide. Yet the computation of the SCC is inherently complex as it involves the consideration of both direct and indirect impacts resulting from carbon emissions. At a given time period, SCC is defined as:

$$SCC_t \equiv \frac{\frac{\partial W}{\partial E_t}}{\frac{\partial W}{\partial C_t}} \equiv \frac{\partial C_t}{\partial E_t} \tag{34}$$

That is, the impact of emissions on consumption can also be represented as the ratio between the marginal effect on welfare of an additional unit of emission and the marginal impact on welfare of an additional unit of consumption. The actual estimation in the model relies on a discrete approximation of the previous equation. Various IAMs attempt to define the SCC, and the process can be in general summarized in 4 main steps (IMF, 2023):

- Projection of future GHGs emission
- Computation of the effects of past and future emissions on the climate system
- Impact of the changes in climate on the physical and biological environment
- Translation of natural changes into a measure of discounted damages

Incidentally, it was estimated that in 2017 the SCC had already been used in climate projects accounting for more than 1$ TRN in benefits. (Nordhaus, 2017).

This framework allows for straightforward predictions on the direction of the impact of different assumptions regarding interest rates. The only exception concerns the effect on consumption, where the relationship is somewhat ambiguous: in a scenario with higher interest rates, the level of consumption is expected to increase in the initial decades, due to the lower saving rate, and then fall as the incentive to allocate more resources toward consumption yields lower levels of investment which diminish the capital stock, the largest driver of output growth.

Concerning the climate and policy variables, the level of emission control and abatement costs are anticipated to be inversely related to the interest rate level, as a lower interest rate implies a greater emphasis on future well-being and thus damages prevention, allowing for a larger allocation of resources towards abatement projects. This, in turn, leads to increased investment in the field of emissions reduction. Damages are expected to respond accordingly, as higher levels of emission control reduce the cumulative carbon emissions and mitigate the impact of anthropogenic emissions on output.

Clearly, these relationships are not linear, and it's essential to thoroughly test the actual impact of the different interest rates, and the effect of the determinants of the Ramsey formula as well. In general, it can be stated that lower discount rates have a positive impact on the climate agenda, leading to reduced damages and cumulative emissions. Yet it's not obvious that even some of the lower rates proposed, as well as some of the most "optimistic" parameters proposed, will produce consumption paths that align with the carbon budgets set by the IPCC. Further analysis and evaluation are necessary to determine the extent to which different interest rates align with the desired outcome.

Table 7. Expected impact of higher interest rates on selected variables, DICE model

Consumption	Positive in the short term Negative in the long term
Capital stock	Negative
Capital depreciation	Exogenous (constant)
Investment	Negative
Labor	Exogenous (dynamic)
Abatement costs	Negative
Damages	Positive
TFP	Exogenous (dynamic)
Cumulative carbon emissions	Positive
Social cost of carbon	Negative
Carbon price	Negative

3.3.2 Scenarios and carbon budget choice

The analysis explores the impact of various interest rate interpretations and parameters on carbon emissions in the economy via the construction of multiple scenarios based on the previously discussed insights from the literature. Clearly, such approach calls for a more detailed discussion concerning the computation of the discount rate and the various methods employed to estimate the parameters of the Ramsey formula.

Baseline: running this framework computes the projections of the levels and growth of several major economic and climate variables considering **current climate-change policies**. Evidently, neither announced policies nor aspirational ones are represented in this scenario. Nevertheless, it doesn't represent the typical no control scenario that would imply a constant null carbon price, but rather one where the latest policies, as of 2023, are kept indefinitely. It relies on a very low global carbon price level of 6$/tCO2 growing at just 1% per year, with an emission control rate of about 5%. This type of structure is appropriate to study a world of evolving climate policies, as simple tweaks in policy parameters allow for the representation of the constantly evolving policy architecture. Yet it's worth noticing how this framework is bound to produce the highest emissions among the ones that will be considered and, therefore, it generates the larger global temperature change.

Optimal C/B: the cost-benefit optimal scenario proposed by Nordhaus, on the other hand, is far more likely to deliver levels of carbon emission closer to the IPCC's thresholds. Such framework relies on some more optimistic assumptions when compared to the latter, as it stems from maximizing economic welfare according to a cost-benefit analysis and it implies full participation of all the global actors starting from the first period of the model, i.e., 2025. The fundamental difference with the BAU scenario is that in this one the maximization is not constrained by imposed values on policy variables such as the emission control rate and carbon pricing. Essentially, the C/B scenario entails striking, without any limiting factor, an optimal balance between the present value of the costs of abatement and its future benefits, in the form of subsequent climate damage reduction. Such framework will be also considered as the starting point for the following interest rate structure analysis, meaning that given these assumptions and this specification various interest rates will be tested to verify whether they can match different carbon budgets. The central SDR proposed in this scenario is the same as the baseline one, and it's the result of the retrieval process previously discussed.

DRUPP_avg: this scenario relies on the average values retrieved from Drupp et al. (2015).

DRUPP_med: this scenario relies on the median values retrieved from Drupp et al. (2015).

WTZ: this scenario reproduces the SDR retrieved from Weitzman (2001) via changes in the central normative parameter, ∂, assuming where needed parameters from median figures in Drupp et al. (2015).

Stern: this process uses the assumptions of the Stern review (2007) based on the same methodology provided in some of the previous iterations of the DICE model.

These scenarios will be compared, and an assessment will be made to determine whether they can meet the carbon budget computed by the IPCC (2022c) for several temperature changes with an **83% likelihood**, excluding the additional geophysical uncertainties (see Table 5 and Table 8). The choice of a single carbon budget to align to is clearly as crucial as it is arbitrary. Various factors can be taken into account when deciding on an appropriate level, and in some instances, the cumulative emissions will be evaluated against different likelihoods as well. Yet, selecting a specific likelihood measurement allows for the examination of a state of reality where there is a reasonable assurance of meeting the temperature thresholds and it also lays the ground for the determination of an optimal level of interest rate needed to fulfil the requirements needed to respect the budget. This task is to be accomplished via the construction of some other additional scenarios that retrieve what is the SDR that matches the cumulative emissions threshold indicated by the IPCC and adjusted for the model under consideration. In order to effectively retrieve a single SDR, some additional assumptions need to be made about the elasticity of consumption. In this case the analysis proceeds to consider an almost negligible value of the elasticity of consumption, which is achieved in the following scenarios via the application of an almost null value, i.e., $\eta = 0.001$. Although the latter may be a generous assumption even under a prescriptive approach, which generally prescribes that such parameter should fall within a range of 1 to 3, such conjecture allows for a full control of the interest rate level. The use of such procedure to analyze what-if scenarios, is effectively drawn from the additional modules proposed by Nordhaus in the latest DICE-2023. These scenarios are:

LIM2°C: this scenario retrieves the discount rate needed to stay within the 2°C threshold.

LIM1.7°C: this scenario retrieves the discount rate needed to stay within the 1.7°C threshold.

Moreover, this analysis found that **no positive interest rate** applied to this model allows for avoiding the depletion of the carbon budget for **1.5°C at 83%** likelihood. This insight is supported by the supplementary scenario proposed by Nordhaus which investigates the implication of capping the change in temperature endogenously computed in the model at 1.5°C: as reported by Barrage and Nordhaus (2023), "with current assumptions, the scenario limiting temperature to 1.5 °C is not feasible without an unrealistic increase in emissions reductions or a catastrophic reduction in output". That is to say that forcing the model to comply with this target brings about a negative interest rate and an exceedingly steep 77% drop in consumption levels between the first and the second period. At this point, not really much can be articulated about a scenario that allows to keep temperatures within 1.5°C with some certainty, and it's adequate to approach the issue with another perspective: How does this framework behave in a condition of extremely low interest rates? In order to achieve the most extreme projection, the considered scenario proposes a utility discount rate of zero ($\partial = 0$), on top of the negligible nature of the elasticity of consumption. While it's supported for instance by Ramsey based on the opposition to the notion of assigning less importance to the well-being of future generations, it significantly deviates from the discount rates currently employed in integrated assessment models, and in general in economic modelling. One may argue that some economists, such as Stern, consider a very low rate of pure time preferences of 0.1%, that effectively just reflects the possibility of extinction, and not a real difference in the value of intergenerational utility. Yet such strategy operates with a considerably higher value of the elasticity of consumption, which, in line with Nordhaus' approach, has been maintained at negligible levels in the optimal rate analysis. The result is evidently that even though Stern considers an almost null figure for the pure rate of time preferences, the actual central value for the SDR stands at 1.4%, whereas in this scenario it's close to zero. It results in the additional scenario:

R0: this framework retrieves the equilibrium resulting from applying an almost null level of SDR.

83% LIKELIHOOD CARBON BUDGETS

Temperature change limit	IPCC's estimated budget	DICE upper limit
2°C	900 GtCO2	1534
1.7°C	550 GtCO2	1184
1.5°C	300 GtCO2	934

Table 8. Carbon budget retrieved from the IPCC (2022c) and corresponding figures in DICE.

	Scenario	**Target SDR**	**Assumed η**	**Assumed ∂**
Nordhaus	*Baseline*	4%	1.5	2.2%
	Optimal C/B	4%	1.5	2.2%
Literature	*DRUPP_avg*	2.25%	1.35	1.1%
	DRUPP_med	2%	1	0.5%
	WTZ	1.786%	1	1.006%
	Stern	1.4%	1	0.1%
Optimal IR	*LIM2°C*	2.951%	/	/
	LIM1.7°C	1.867%	/	/
	R0	0%	/	/

Table 9. Parameters chosen in each scenario.

3.3.3 Results of the analysis

In order to conduct the analysis, the first step involves addressing the most pressing issue, whether the various frameworks proposed are effectively capable of meeting the required carbon budget parameters as identified by the IPCC. Subsequently, the analysis will proceed by describing the evolution of other relevant variables in the model to verify if the framework indeed provides a pathway that is compatible with the expected trajectory required to achieve these ambitious goals. Graphic details of the different scenarios are provided throughout the analysis, and a summary account of the evolution of variables is provided in the tables in each section. The analysis focuses on the dynamics projected in the next century, yet the full projection of each scenario up to 2300 can be consulted in Appendix B.

3.3.3.1 Meeting the IPCC requirements: carbon emissions

First of all, it's clear how the **business-as-usual scenario** doesn't deliver a path of consumption in line with keeping temperatures within the aforementioned limits. This is, in fact, the framework that due to its different specification is bound to deliver the highest emissions among the ones that will be considered (Figure 10), and in turn to generate the largest temperature change. Carbon emissions are indeed set to surpass the highest considered threshold, for the 2°C limit, within just 50 years (Figure 11). Cumulative emissions are set to peak at around 5200 GtCO2 by the early 23rd century, therefore almost reaching the complete depletion limit of fossil fuel energy resources specified in the model. This baseline approach impacts the long-term equilibrium in a catastrophic way and implies exceedingly low levels of emission control, abatement costs and in turn extremely high damages from climate change.

The **optimal C/B scenario**, as one would expect, envisions a significantly higher reduction in carbon emissions, attributable to the assumption of universal collaboration in pursuing the optimal long-term equilibrium.

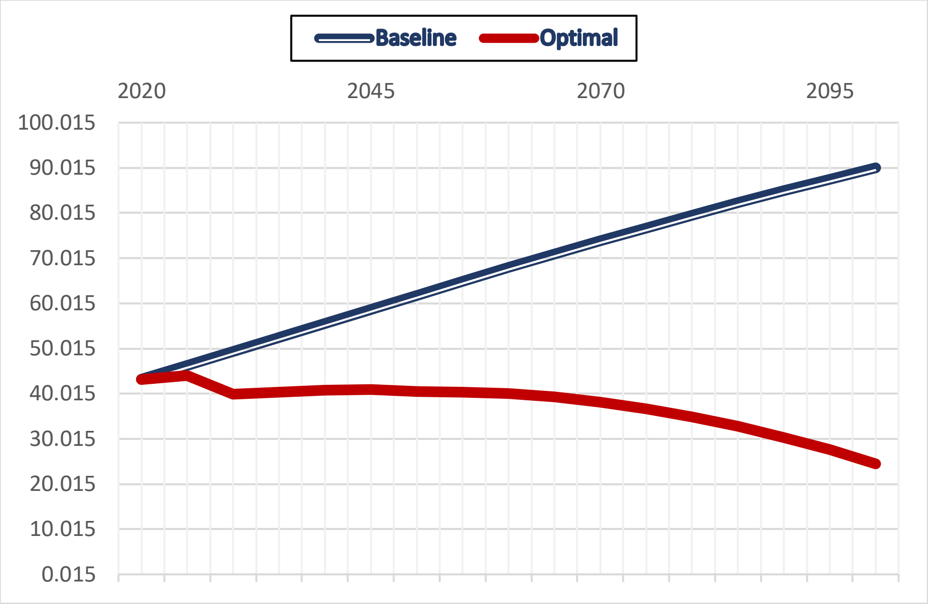

Figure 10. Own computations

Per year carbon emissions (GtCO2) under C/B and BAU scenarios.

The implication is that per year emissions are predicted to be curbed more decisively and in turn the level of temperature is bound to reach its far lower peak more quickly. Nordhaus' C/B allows for the system to stay within the carbon budget defined for 2°C at 83% likelihood, at least up until the end of the century. Slightly higher figures are reached at its peak, in the first decades of the 22nd century, yet levels are predicted to return within budget in a relatively swift fashion. Both of these frameworks rely upon the same assumptions on the discounting interest rate, and the major differences stem in fact from the divergencies in the specification of the model.

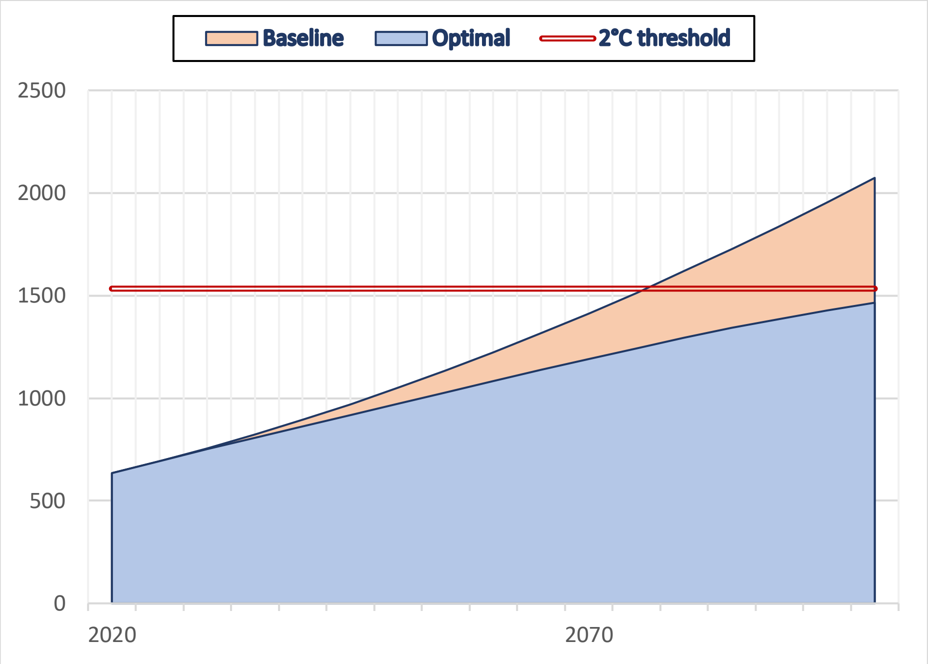

Figure 11. Own computations

Cumulative carbon emissions in GtCO2 under C/B and BAU scenarios and 2°C carbon budget threshold.

Such discounting approach is actually far less attentive to the well-being of future generations than others. The average SDR recommended by the experts in Drupp et al. (2015), is 2.25%, far lower than the lowest point in the structure described above. Each assumed value in the DICE model points out to a relatively high discounting rate. Therefore, even though the C/B DICE scenario is built over some "optimistic assumptions", the same cannot be said about how much weight is placed on the importance of generations yet to be born. A direct comparison can be conducted using more generally accepted estimates of the parameters of the Ramsey formula, as obtained from the average and median values reported in the aforementioned survey and computed in the **DRUPP_avg** and **DRUPP_med scenarios** (Figure 12 and 13).

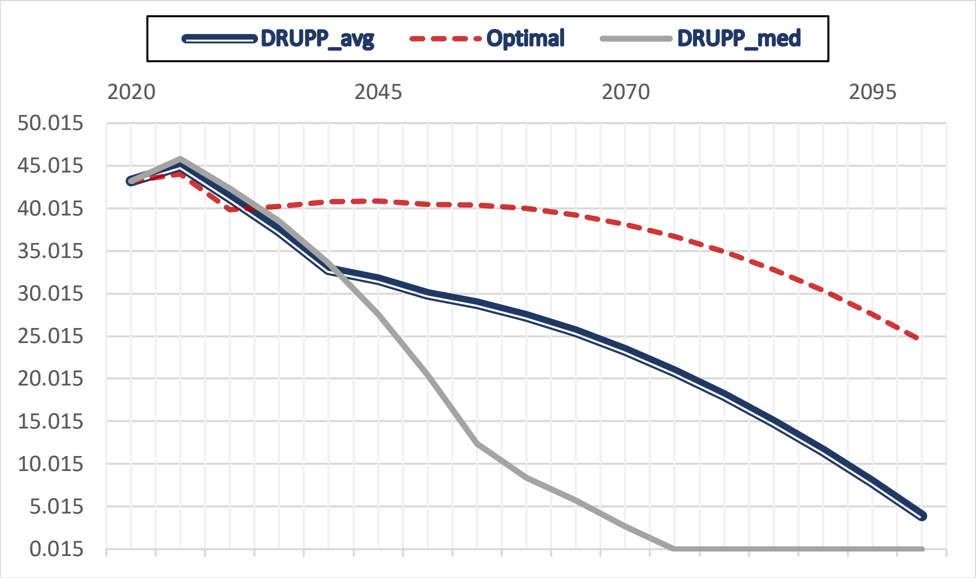

Figure 12. Own computations

Per year carbon emissions (GtCO2) under optimal scenario and scenarios drawn from average and median parameters in Drupp et al. (2015).

Each proposed scenario projects a peak in carbon emissions within the next ten years. The key difference clearly lies in the rate at which annual emissions are anticipated to decline as a result of the implemented emission control rate and in turn the scale of the abatement policy. The divergency between the scenarios is stark, at the very least: whereas the optimal scenario projects a reduction of approximately 40% in annual emissions over an 80-year period, DRUPP_avg predicts nearly carbon neutrality by the end of the century. The difference is even more pronounced in the scenario derived from median values, indicating carbon neutrality by the 2070s. Concerning the carbon budget, both scenarios are projected to align with the 2°C target, yet no framework indicates that emissions will meet the 1.5°C threshold. This is to be expected, as it has been previously estimated that no positive interest rate would allow the achievement of such a target. These findings are consistent with recent findings from the IPCC (2018): achieving temperature limitations with a reasonable level of certainty, including below the 2°C threshold, requires prompt measures and a swift reduction in the emission of greenhouse gases. The scenario derived from the median parameters, in particular, aligns with the objective of achieving carbon neutrality by the 2070s and offers projections that generously align with the target of limiting temperature increases to 2 degrees.

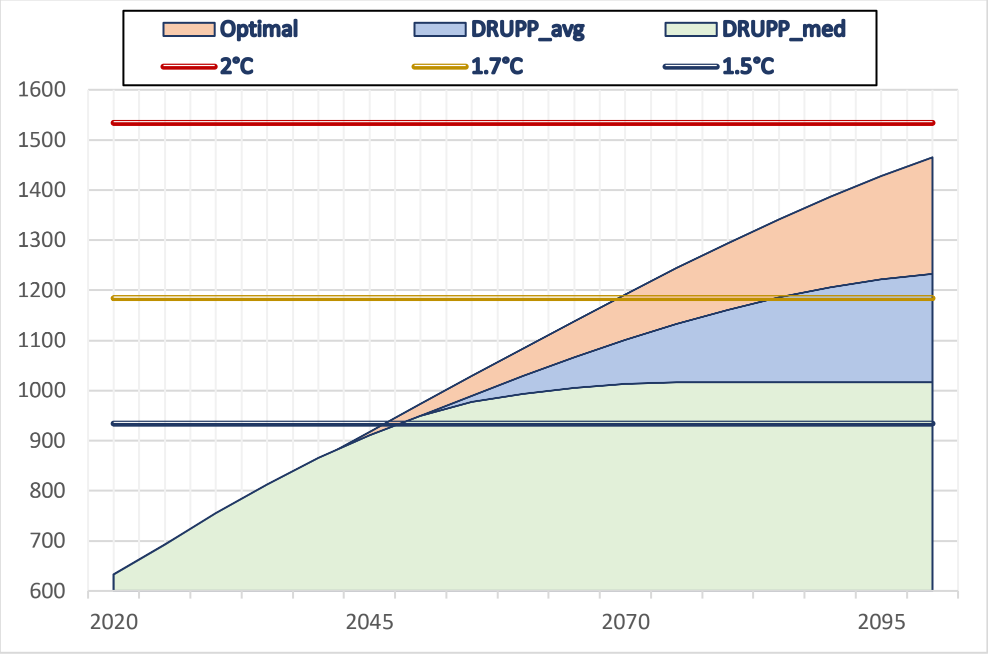

Figure 13. Own computations

Cumulative carbon emissions in GtCO2 under optimal, DRUPP_avg and DRUPP_med scenarios, compared with different carbon budget thresholds.

The other scenarios drawn from the literature are based on the estimated values in Weitzman (2001), **WTZ scenario**, and from the normative parameters assumed in Stern (2007), **Stern scenario**. In these instances as well, the significantly lower SDR is bound to deliver consumption trajectories that are more aligned with the IPCC's requirements. In fact, the scenario resulting from the discount rate drawn from Weitzman reaches carbon neutrality well within the end of the century.

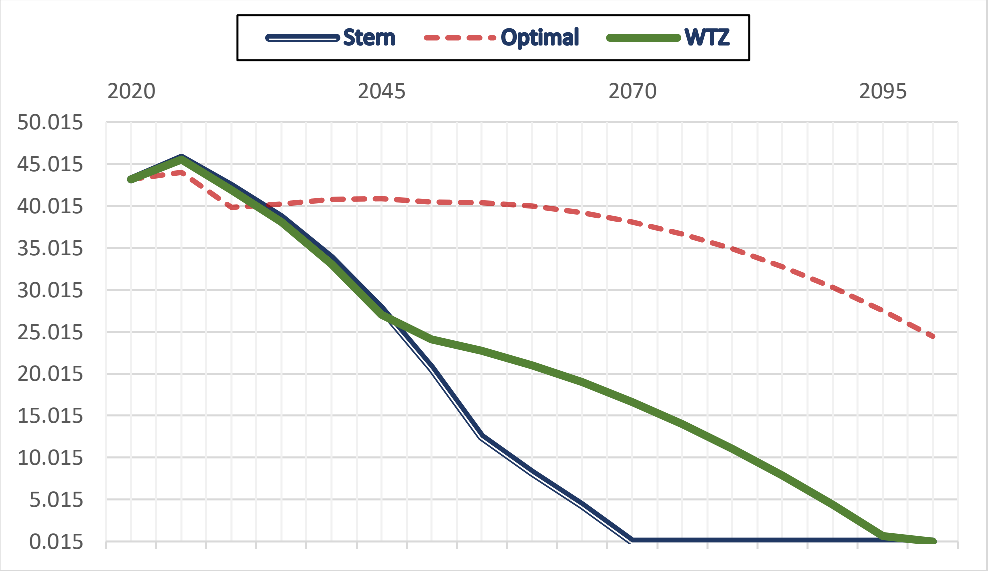

Figure 14. Own computations.

Per year carbon emissions (GtCO2) under optimal, Stern and WTZ scenarios.

The normative approach drawn from Stern proves to be even more effective, primarily due to the incorporation of a lower pure rate of time preferences. In this case carbon emissions follow a trajectory that is generally consistent with the previous DRUPP_avg scenario, reaching a higher peak in the upcoming decade and promptly decreasing until carbon neutrality is achieved in 2070. As a result, both of these scenarios also project the achievement of the carbon budget for the 2°C threshold. Yet the Stern scenario, with its remarkably low ∂ of 0.1%, proves to be the most effective in curbing emissions. It is worth noting that both the Stern scenario and the DRUPP_med scenario, which are effectively the most optimistic, do not fully achieve the aforementioned 1.5°C threshold target, yet they do project carbon emissions that align with the same threshold with still a relatively high 67% likelihood (See Table 5).

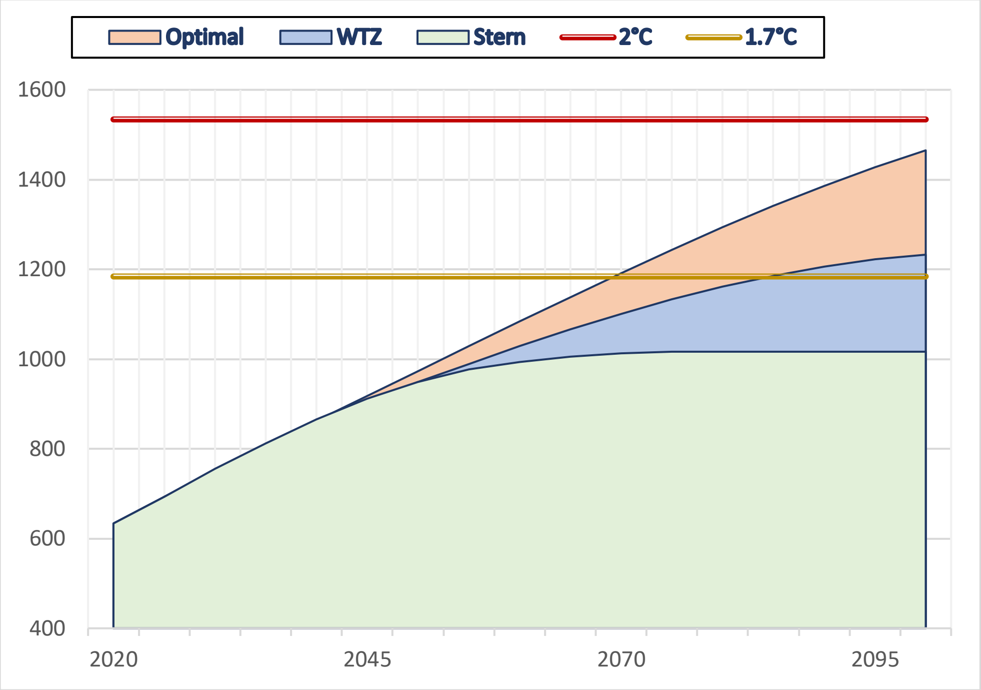

Figure 15. Own computations

Cumulative carbon emissions in GtCO2 under optimal, Weitzman and Stern scenarios, compared with different carbon budget thresholds.

Lastly, we consider the scenarios matching the carbon budgets and the zero-rate scenario. Both the **LIM2°C** and **LIM1.7°C** scenarios effectively establish an upper limit for the interest rate that meets the targets set by the IPCC. As a results, they deliver emission pathways somewhat close to the other scenarios meeting the respective limits, in spite of the distinct consideration of the elasticity of consumption. In contrast, the R0 scenario, as one would expect, exhibits a distinct behavior: it doesn't project a peak in emissions within the next decade, yet it rather anticipates a rapid decrease starting from the present time. The projected maximum cumulative CO2 emissions reach 997.77 GtCO2, resulting from an additional release of 364.3 GtCO2 from today. Although the more stringent 1.5°C limit is not met even under these extreme assumptions, this framework predicts cumulative emissions that are still within the range of a 50% likelihood of staying below 1.4°C of temperature change.

The examination of these scenarios, provided the framework, seems to point out that maintaining temperature changes within 2°C aligns with the preferences and ethical values of our society, or at least with the representation economists offer of it. The only instance where the consumption trajectory produces outcomes that deviate significantly from the estimated maximum carbon emissions is the scenario that diverges from the others in its specifications. In fact, the baseline doesn’t really allow for adjustments in the climate policy, i.e., it forces constant values for emission control and therefore share of output invested in abatement. The implication is that the uncertainty in achieving the 2-degree target is not primarily due to a failure in the way society values future consumption, but it rather stems from potential limitations in global collaboration to effectively curb emissions to desired levels. Given these premises, the nature of the interest rate employed, and particularly its alignment with either a normative or descriptive approach, has the potential to either enable or hinder the achievement of the more ambitious goals. Nordhaus' discounting rate leads to projections that may be somewhat likely to keep temperatures below the 2°C threshold in its optimal scenario, yet the parameters proposed by a considerable consensus of experts indicate trajectories that offer a much higher level of certainty in achieving the same goal. Moreover, the analysis reveals that extreme discounting rate parameters are not necessary to achieve sensible emission pathways that are likely to mitigate long-lasting damage to the planet. The extreme scenario (R0) and the highly normative consideration of parameters from the Stern review don’t significantly differ in terms of emission curbing when compared to discounting approaches that are arguably more justifiable, such as those derived from the expert consensus.

Finally, the alignment with the IPCC trajectory requirements validates the choice of the model. The majority of scenarios are projected to remain below the 2-degree threshold, aligning with the agency's prediction that in order to reach the goal, a peak in emissions is anticipated in the upcoming decade, followed by a rapid decline in carbon release. The inability of this model to effectively achieve cumulative emissions in line with the 1.5°C target, even under extreme circumstances, can be attributed to two major factors. Firstly, there is considerable uncertainty surrounding the target, and it necessitates extreme actions across various sectors. Secondly, this model does not account for two critical dynamics that could contribute to reducing the impact of anthropogenic emissions and reaching the most ambitious target: the use of Carbon Dioxide Removal (CDR) technologies and the dynamics associated with gases like methane that offer potential short-term mitigation benefits. For what concerns methane, reducing its emissions may be particularly crucial to ensuring greater certainty in mitigating the greenhouse effect in the upcoming decades, even though the majority of the overall effect is still attributable to CO2. In contrast, incorporating CDR in the modeling process is inherently very risks. The current technology is not sufficiently advanced to provide cost-effective results, and there is no guarantee that it will achieve such efficacy in the foreseeable future. Moreover, including it into the model risks incentivizing short-term consumption and the use of pollutants, which could have disastrous consequences if the technology eventually fails to deliver effective results.

Cumulative emissions, GtCO2	**2020**	**2030**	**2050**	**2070**	**2100**
Baseline	633.54	755.50	1050.13	1412.05	2073.40
Optimal	633.54	752.53	973.28	1191.72	1465.15
Stern	633.54	754.90	949.43	1011.90	1011.90
WTZ	633.54	754.61	945.82	1064.35	1138.86
DRUPP_avg	633.54	753.85	948.90	1101.01	1232.62
DRUPP_med	633.54	754.97	948.71	1012.69	1016.36
LIM2°C	633.54	755.82	966.81	1162.67	1402.55
LIM1.7°C	633.54	757.84	954.31	1075.92	1180.01
R0	633.54	746.33	932.87	997.77	997.77

Carbon emissions, per year, GtCO2	**2020**	**2030**	**2050**	**2070**	**2100**
Baseline	43.22	49.32	61.71	73.86	90.02
Optimal	43.22	39.87	40.50	38.15	24.48
Stern	43.22	42.37	20.70	0.00	0.00
WTZ	43.22	41.95	24.14	16.64	0.00
DRUPP_avg	43.22	41.23	29.91	23.34	3.92
DRUPP_med	43.22	42.35	20.46	2.70	0.00
LIM2°C	43.22	42.02	36.56	33.82	21.10
LIM1.7°C	43.22	43.48	23.99	18.55	3.10
R0	43.22	38.77	21.26	0.00	0.00

Table 10. Evolution of climate variables in different scenarios.

3.3.3.2 Remarks on other relevant variables

Examining the trajectory of other key variables in the model provides insights into both the successful and failed attempts to achieve the imposed targets. The first dynamics to be analyzed concern the macroeconomic projections. One major dynamic, population and labor growth, is exogenous in the model, thus it’s not a matter of concern. The same holds true for the TFP.

On the other hand, as expected, lower interest rates are bound to propel the GDP level in the long term, via an increase in the optimal saving rate. As a result, the beneficial effect of higher discount rates on current consumption levels, seen for instance in Nordhaus’ Optimal and BAU scenarios, is projected to exhaust by the end of the century. Indeed, in the same time frame, due to a combination of higher damages and lower saving rates, the scenarios that exhibit the lower value for per capita consumption are the BAU and Optimal (Table 11). Accordingly, the highest level of output is reached in the most extreme scenario, R0, which is projected to produce 21% and 18% more when compared to the BAU and the Optimal respectively. The compounded impact on the capital stock therefore allows for more future consumption in the long term, while at the same time retaining a broadly higher level of investment.

The other scenarios behave according to their SDR level in a similar fashion. For instance, consider the scenario aligned with the 2-degree target. As it exhibits a discount rate of 2.951%, which is the highest among all scenarios except for BAU and Optimal, the other scenarios project higher GDP and increased investment by the end of the century. Similarly, the scenario matching the 1.7°C limit closely aligns with the one derived from the Weitzman survey, on account of their very similar SDRs. In spite of the different parameter values used to determine their respective discount rates, these scenarios result in barely distinguishable levels of output, per capita consumption, and gross investment by the end of the century.

Output net	2020	2030	2050	2070	2100
Baseline	135.14	187.53	322.49	492.81	797.02
Optimal	135.14	187.62	323.36	497.29	820.55
Stern	135.14	200.53	352.84	541.42	921.01
WTZ	135.14	198.35	342.86	528.06	878.96
DRUPP_avg	135.14	194.61	337.25	519.80	863.05
DRUPP_med	135.14	200.43	348.62	533.24	903.32
LIM2°C	135.14	198.71	337.81	514.57	840.29
LIM1.7°C	135.14	206.25	348.84	534.19	880.57
R0	135.14	181.94	363.03	575.24	969.35

Consumption per capita	2020	2030	2050	2070	2100
Baseline	12.79	16.38	25.53	37.08	58.03
Optimal	12.76	16.33	25.45	37.09	58.93
Stern	11.31	15.69	24.69	36.04	59.40
WTZ	11.50	16.00	25.24	36.88	59.31
DRUPP_avg	11.97	16.10	25.36	37.03	59.17
DRUPP_med	11.27	15.83	24.93	36.24	59.49
LIM2°C	10.72	16.54	25.73	37.49	59.53
LIM1.7°C	9.32	16.42	25.34	37.16	59.61

Gross investment	2020	2030	2050	2070	2100
Baseline	35.97	48.59	79.96	118.45	185.76
Optimal	36.25	49.10	81.58	122.79	199.76
Stern	47.42	67.43	118.24	177.51	295.25
WTZ	46.01	62.65	103.05	155.66	254.22
DRUPP_avg	42.32	58.04	96.27	145.89	239.77
DRUPP_med	47.76	66.14	111.71	167.35	276.61
LIM2°C	52.04	58.40	93.35	136.02	213.19
LIM1.7°C	62.87	66.99	108.05	159.04	252.61
R0	12.05	63.73	144.96	215.99	344.65

Table 11. Evolution of macroeconomic variables in different scenarios.

As output grows, it’s expected to impact positively various macroeconomic variables in the long run, including the growth of advantageous factors such as abatement costs and per capita consumption, yet it will also amplify the effects of damages, which are calculated in this framework as a proportion of output. In other words, in this framework as GDP expands, both the positive and negative consequences related to emissions will accrue or become more pronounced. As a result, it’s appropriate to assess the level of different variables relative to production, in this way disregarding the nominal impact but obtaining figures more suitable for understanding the evolution of a specific scenario.

When accounting for the difference in the level of output, the contrast in cumulative damages between the different scenarios is striking The BAU scenario exhibits the highest cumulative level of damages, with climate change-related damages amounting to nearly one-third of GDP. In the other scenarios the variable moves accordingly to the discount rate, as previously observed. Yet, the relationship between the SDR and damages is not linear, it rather appears that reducing the interest rate yields diminishing returns in terms of mitigating damages. In fact, while there is a significant difference between the levels observed in scenarios with the highest discounting rates like Optimal and LIM2°C, the other scenarios show similar figures, especially those with extremely low interest rates such as Stern and R0.

Cumulative damages/output	**2020**	**2030**	**2050**	**2070**	**2100**
Baseline	0.54%	1.87%	5.61%	11.78%	28.58%
Optimal	0.54%	1.84%	4.99%	9.16%	17.54%
Stern	0.54%	1.82%	4.79%	7.54%	10.43%
WTZ	0.54%	1.82%	4.81%	7.90%	12.41%
DRUPP_avg	0.54%	1.83%	4.81%	8.21%	13.79%
DRUPP_med	0.54%	1.82%	4.81%	7.56%	10.53%
LIM2°C	0.54%	1.84%	4.96%	8.89%	16.51%
LIM1.7°C	0.54%	1.83%	4.91%	8.08%	13.02%
R0	0.54%	1.78%	4.43%	7.08%	10.08%

Table 12. Cumulative damages/output in different scenarios

To provide an effective measure of the extent to which the costs resulting from GHG emissions are taken into account in each framework, the most appropriate metric is the social cost of carbon, as it represents the change in welfare, appropriately discounted, due to an additional unit of CO2-equivalent emissions. As a result, this parameter is particularly sensitive to the interest rate level chosen. Remarkably, the Optimal and BAU scenarios exhibit minimal differences, which is particularly striking given their significantly divergent levels of climate policy. Due to the direct impact of the interest rate on discounting welfare changes to calculate it, scenarios with very low interest rates result in exceptionally high levels of SCC, which can be attributed to the profound reduction in the discounting of future damages, rather than being driven by any other sound economic principle.

Social cost of carbon	**2020**	**2030**	**2050**	**2070**	**2100**
Baseline	60.90	84.49	150.13	237.03	395.32
Optimal	52.67	72.70	126.59	197.73	329.39
Stern	428.33	548.54	699.83	836.39	1018.60
WTZ	160.44	212.59	307.01	409.01	561.88
Drupp average	113.53	153.49	240.04	340.49	500.69
Drupp median	253.46	330.32	445.43	556.74	720.17
LIM2°C	89.81	117.95	174.42	242.22	358.26
LIM1.7°C	187.83	238.23	311.70	390.62	507.67
R0	1874.83	2199.36	2158.82	2095.98	1963.05

Table 13. Evolution of SCC in different scenarios

Finally, we turn our attention to analyzing the variables that determine the level of climate policy implemented, i.e., the allocation of resources towards abatement and the emission control rate. As previously observed, the former is directly dependent on the latter. As expected, the Baseline scenario stands out in this case as well, with a significantly lower allocation of resources towards climate policies. Yet there is also considerable heterogeneity among the other scenarios. Higher interest rates, reflecting a reduced emphasis on future consumption, lead to decreased incentives for future damage reduction, and in turn lower emission control rate and lower abatement. In the Optimal scenario, the projection for emission abatement only slightly surpasses the 1% mark by the end of the century, which is the main reason it falls short of the level required to achieve carbon neutrality in a short timeframe. On the other hand, the scenarios that are effectively capable of delivering net zero emissions by 2070, namely Stern, DRUPP_avg, and R0, exhibit a higher emission abatement/output of around 4%, by the time they reach such target.

Abatement/ Output	**2020**	**2030**	**2050**	**2070**	**2100**
Baseline	0.00%	0.01%	0.01%	0.01%	0.01%
Optimal	0.00%	0.21%	0.46%	0.77%	1.38%
Stern	0.00%	0.21%	2.25%	4.07%	2.81%
WTZ	0.00%	0.21%	1.81%	2.31%	2.82%
DRUPP_avg	0.00%	0.21%	1.23%	1.74%	2.56%
DRUPP_med	0.00%	0.21%	2.25%	3.75%	2.81%
LIM2°C	0.00%	0.21%	0.76%	1.05%	1.57%
LIM1.7°C	0.00%	0.21%	1.86%	2.17%	2.62%
R0	0.00%	0.21%	2.25%	4.07%	2.81%

Emission Control Rate	**2020**	**2030**	**2050**	**2070**	**2100**
Baseline	0.05	0.06	0.07	0.09	0.10
Optimal	0.05	0.24	0.40	0.53	0.76
Stern	0.05	0.24	0.72	1.00	1.00
WTZ	0.05	0.24	0.66	0.81	1.00
DRUPP_Avg	0.05	0.24	0.57	0.73	0.96
DRUPP_Med	0.05	0.24	0.72	0.97	1.00
Lim2°C	0.05	0.24	0.48	0.60	0.80
Lim1.7°C	0.05	0.24	0.67	0.79	0.97
R0	0.05	0.24	0.72	1.00	1.00

Table 14. Emission reduction variables in different scenarios

3.4 Concluding remarks on interest rate analysis

This chapter began with a literature review that provided some valuable insights concerning the appropriate interest rate level for analyzing extremely long-term scenarios, such as those projected in Integrated Assessment Models. First of all, it revealed that the commonly used discounting approaches exhibit significant heterogeneity mainly due to distinct considerations of the fundamental components of the Ramsey equation. The different views on the discounting parameters can be broadly classified as *normative* (or *prescriptive*) approaches, and *descriptive* ones. The former approach involves incorporating components of the formula based on ethical considerations, while the latter aims at estimating the same parameters by comparing them to the yield on other investments or using anchors from other fields of economics, such as measures of risk aversion or utility discounting. The consensus view suggests that the determination of these parameters should consider some insights from both approaches, with a general rejection of relying exclusively on the descriptive approach, which was found to be advocated by only one in twenty economists (Drupp et al., 2015).

The amount of research published on this matter is undeniably extensive and therefore, as to encompass a range of commonly employed frameworks, we considered four distinct methodologies drawn from the literature:

- Nordhaus (2023): utilizing the assumptions of the influential DICE model, which adopts a decisively descriptive approach and incorporates data from the US financial markets along with an estimated figure for the extremely long-term risk-free investment yield.
- Stern (2006): relying on the parameter estimations of what is deemed to be one of the most resolutely normative determinations of the SDR.
- Drupp et al. (2015): leveraging insights from a large-scale survey that disentangles the various parameters of the Ramsey formula and uncovers the commonly shared narrative regarding the descriptive and prescriptive approaches.
- Weitzman (2001): relying on an influential analysis on the appropriate discount rate that not only incorporates the opinions of a large pool of respondents but also enables the determination of a single SDR from a sliding-scale interest rate structure.

As to provide a quantitative measure of impact of discounting on the output of the model, the analysis considers the estimates of the carbon budget as reported in the latest AR6, released by the IPCC (2022c), focusing on the cumulative carbon limits necessary to maintain temperature changes within different thresholds with an 83% likelihood.

In order to conduct a quantitative assessment, multiple scenarios corresponding to different assumptions on parameters that define the interest rate need to be generated by an IAM.

The choice of the model is both crucial and somewhat arbitrary, as even minor differences in the model's specifications can lead to significantly different outcomes for long-term equilibria (as discussed in Chapter 1). The most significant factor in the model selection is the objective that the examination aims at achieving. This analysis relies on the latest iteration of the DICE, the seminal IAM that introduced the use of integrated models with economic modules in the 1990ies. The main reason for choosing DICE as the tool for this analysis lies in its ability to provide a clear representation of the economy and the climate, while requiring minimal assumptions on the evolution of other variables. In fact, while using a model that, for instance, incorporates uncertainty could enable to represent declining interest rates within the Ramsey framework, it should be noticed how such a model would necessitate additional assumptions, particularly concerning the variability of consumption growth. Moreover, it would not necessarily guarantee more accurate outcomes, as uncertainty itself may introduce additional complexities and potential sources of error. The primary objective of this analysis is not to establish a specific interest rate structure that guarantees the achievement of the carbon budget, but rather to examine the consequences of different common assumptions of the Ramsey components on the long-term economic and climate equilibrium. Therefore, a straightforward representation of the influence of different parameters is the most effective approach for this purpose.

3.4.1 Summary of the results

Overall, the analysis highlights that:

1st	The scenarios that take into account normative issues are in line with delivering a pathway compatible with meeting the carbon budgets computed by the IPCC.
2nd	The optimal interest rates required to ensure the economy stays within the carbon budgets fall well within the range of commonly employed discounting approaches and align with what surveyed experts would “feel comfortable recommending”.
3rd	No positive interest rate allows for achieving the reduction in emissions necessary to comply with the 1.5°C target within this framework.

4th	As to ensure a high level of confidence in keeping long-term temperature changes within the 2°C threshold, it’s not necessary to rely on excessively low interest rates or extreme scenarios. Yet, it’s crucial to incorporate a certain degree of normative considerations when determining the discounting approach.
5th	Meeting the carbon budget strongly relies on global and effective collaborations.
6th	The analysis confirms the urgency emphasized by the IPCC (2018), highlighting the need for immediate action to limit cumulative emissions within levels that prevent temperatures from exceeding the aforementioned thresholds.

[1] Although Nordhaus’ optimal scenario, which relies on a descriptive approach, comes close to meeting the budget, every other framework assessed projects emission pathways that are far more likely to deliver temperature changes below 2°C, if not significantly lower. This holds true not only for the Stern approach, which represents an almost-extreme case, but also for scenarios that derive the social SDR and the parameters of the Ramsey equation from a consensus among economists.

[2] The interest rates that meet the 2°C and the 1.7°C budget are respectively 2.95% and 1.86%, which are consistent with the 1% to 3% range 92% of the respondents in Drupp et al. (2015) would recommend.

[3] This result stems from the challenges associated with achieving such an ambitious objective with a high level of certainty, as well as the absence of certain crucial dynamics in the model, including carbon dioxide removal (CDR) and emissions of non-CO2 greenhouse gases.

[4] Many approaches to discounting deliver results in abatement projections and damage reduction very close to the most extreme scenarios, namely Stern and R0, without generating the same distortions in the computation of, for instance, the Social Cost of Carbon and the optimal saving rate.

[5] Highlighted by the results from the BAU scenario.

[6] The results, in fact, are consistent with the projections by the agency. The scenarios’ inability to reach carbon neutrality within 2030 align with the failure in achieving the most ambitious

1.5°C target. On the other hand, as predicted, scenarios that do achieve carbon neutrality by 2070 are successful in meeting the 2°C target. Additionally, a considerable allocation of resources is necessary to facilitate the transition towards a carbon neutral economy. The scenarios that support carbon neutrality predict that abatement costs will need to approximate around 4% of the total output.

Conclusions

This review discussed the long-term implications of discounting choices in Integrated Assessment Models (IAMs) and the influence of different parameter selections within the Ramsey formula in effectively achieving the climate transition objectives outlined by the IPCC in its most recent assessment cycle (IPCC, 2022b).

The initial stage of this analysis entailed offering a qualitative overview of the potential impacts of climate change on the economy. It has been observed that climate change is expected to introduce various challenges within an economic analysis due to the way in which it may impact economic activity at different levels: this includes increased probabilities and intensities of extreme weather events, which can inflict damage on the economy (*physical risk*), as well as the associated risks and potential damages that arise as society adapts to climate change (*transition risk*). A commonly employed approach to formalize the climate issue has been discussed, involving the adoption of the Ramsey-Koopmans-Cass framework, thus allowing for the incorporation of climate damage within a conventional neoclassical economic framework, while also serving as the basic principle for the choice of discounting, as it's presented in most of the currently used models.

The analysis proceeded to examine the various components of the Ramsey equation and the distinct approaches employed to derive the discount rate, with particular attention to the divergences stemming from the two opposite methods used to define the parameters of the equation, namely the normative and descriptive approaches. It has been found that there exists a substantial lack of consensus in the field regarding the selection of these parameters, which can be attributed to two primary reasons:

1. The parameters are susceptible to multiple interpretations, making it exceedingly difficult to agree upon a single measure that satisfies all the intended meanings they should encompass. The parameter η should capture three distinct concepts (e.g., Arrow et al., 2014), while the pure rate of time preferences, δ, is the subject of extensive debates and it's heavily influenced by subjective beliefs or interpretations, (e.g., Pindyck, 2013).
2. The very meaning of the Ramsey equation is prone to different explanations as well, as it's commonly intended as the Social Rate of Discount, but it should also encompass the

> Social Rate of Time Preferences, and, by definition, it should reflect the marginal productivity of capital (Drupp et al., 2015).

In order to disentangle the effects of the parameter selection and the different interpretations of the Ramsey formula, this analysis included a comparison of outcomes associated with different interest rates and parameters proposed in the literature. The aim was to assess whether these different interpretations would result in divergent outcomes and whether they would have the potential to significantly influence the long-term equilibrium of the model, thus impacting the feasibility of achieving the carbon budget calculated by the IPCC in its latest assessment cycle. The range of proposals considered spanned from the highly normative approach adopted in the Stern Review (2007) to the distinctly descriptive approach taken by Nordhaus (Barrage and Nordhaus, 2023). Moreover, the analysis incorporated findings from influential studies such as the surveys conducted by Drupp et al. (2015) and Weitzman (2001). The analysis was conducted using the latest version of the DICE model, which offers a comprehensive architecture that integrates a climate module with the previously discussed framework. This integration allows for the examination of the relationship between economic activity and carbon emissions, providing a structured approach to assess the implications of different parameter choices and interpretations. The model selection was based on its ability to provide a transparent and straightforward approach to evaluate the effects of different parameters, without being influenced by other assumptions, for instance regarding the level of uncertainty in the framework. Moreover, the model is sufficiently aggregated to prevent it from being treated as a *black box*, allowing for meaningful insights to be derived from the analysis. Multiple scenarios were developed, with some specifically targeting the alignment of the optimal interest rate level required to meet the cumulative emission thresholds as determined by the IPCC.

The analysis found that in this framework all of the approaches incorporating normative considerations in the discounting choice were in line with the objective of limiting temperature increases to below 2°C, with an 83% level of likelihood. The discounting proposal from Nordhaus, which features a descriptive approach, emerged as the only one that struggled in achieving such result. Within this framework, it is feasible to meet both temperature thresholds of 2°C and 1.7°C, with discount rates falling largely within the range of what most experts would feel comfortable recommending. On the other hand, the analysis found that no positive interest rate would enable the achievement of the 1.5°C target. The significance of these results also lies in their implications for the feasibility of the carbon budget under other interest rate proposals. In this way, we may shed light and provide some considerations on the level of interest rate that is generally required to meet the targets set by the IPCC. Take for instance Giglio et al. (2021), who retrieve long-term discount rate from the climate risk in housing markets and found the upper limit of such rate to be around 2.6% under a modelling framework comparable to the one used in this analysis. Based on this analysis, that would result in an SDR capable of achieving the carbon budget, at least for the 2°C threshold with an 83% likelihood. Moreover, the authors also determine that the lower bound for the long-term interest rate corresponds to the risk-free rate, estimated in this study to be around 1%. This suggests that employing such a discounting approach is likely to yield cumulative carbon emissions that at least align with a temperature range between 1.7°C and 2°C.

Finally, the examination of the other relevant variables highlighted how the evolution of this framework is in line with the estimates computed by the IPCC in its latest publications (IPCC, 2022b; IPCC, 2018). The scenarios' failure to achieve carbon neutrality by 2050, as outlined in the Paris Agreement (UN, 2015), corresponds to the inability to meet the ambitious 1.5°C target. Conversely, scenarios that do achieve carbon neutrality by 2070 successfully meet the 2°C target. Moreover, a substantial reallocation of resources is required to effectively decarbonize the economy and significantly depress carbon emissions in order to achieve the 2°C target with a reasonable level of certainty.

Overall, this analysis has shed some light on the crucial role of the discounting rationale in shaping the assumptions and frameworks used to project extremely long-term equilibria, and its potential to significantly impact the achievement of critical climate goals. The Ramsey formula remains the standard discounting approach in the field, yet it’s pivotal to acknowledge that this framework has significant limitations when it comes to generating discounting parameters that produce consensus among experts. Moreover, while the model selection in this analysis has clear advantages for examining the effects of parameter choices, it does not address other challenging aspects of climate modeling beyond this specific focus. This is partly attributable to the very nature of IAMs, especially in the context of Benefit Cost models, which may not prioritize providing detailed dynamics yet, precisely for this reason, they are valuable for generating insights into specific matters, such as climate policy. The most consequential implication of this choice, however, is the absence of uncertainty within the framework, which features deterministic projections. As a result, the integration of Declining Discount Rates (DDR) into the model becomes unfeasible, as they would cause issues of time inconsistency, despite their alignment with the evidence from the last 20 years regarding decision-making under incomplete preferences or ambiguity (Weitzman, 2001; Gollier, 2012). However, the existing literature on the impact of uncertainty in discounting within Benefit Cost models is already extensive (e.g., Anthoff et al., 2009; Traeger, 2013), and it generally focuses on measuring and implementing uncertainty rather than specifically addressing the selection of parameters within the Ramsey equation.

Moreover, additional research is necessary to explore the various ramifications of discounting rationales within long-term equilibria. Other dynamics that are not explicitly addressed in the framework but may be worth exploring include the impact of interest rate choices on models that incorporate measures of equality and assess how climate change affects the most vulnerable fringes of society or how the choice of interest rates may also have implications for non-CO2 GHGs with different atmospheric lifetimes, creating different incentives to mitigate their emissions. The comparison between the different scenarios also assumes extensive global collaboration, with the implicit expectation that each government aligns with the long-term optimal solution and actively cooperate in reducing emissions and implementing optimal climate change policies. Given the potential, if not evident, disparity between this assumption and real-world conditions, there is also scope for further examination of the discounting rationale while considering different levels of global cooperation.

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Appendix A – GAMS code

The following code allows to run the modified version of the DICE-2023 model used to compute the scenarios discussed in the analysis. It’s possible to run this code without licensing via the NEOS server, available natively in the latest version of GAMS Studio.

```
$ontext
DICE application of different SDRs in the model
$offtext

$title        Discount rate analysis in DICE model

set        t  Time periods (5 years per period)                     /1*101/

PARAMETERS
** If optimal control
        ifopt    Indicator where optimized is 1 and base is 0        /1/

** Population and technology
        gama     Capital elasticity in production function        /.300    /
        pop0     Initial world population 2020 (millions)         /7752.9  /
        popadj   Growth rate to calibrate to 2050 pop projection  /0.145   /
        popasym  Asymptotic population (millions)                 /10825.  /
        dk       Depreciation rate on capital (per year)          /.100    /
        q0       Initial world output 2020 (trill 2019 USD)       /135.7   /
        A0       Initial level of total factor productivity       /5.84164 /
        gA0      Initial growth rate for TFP per 5 years          /0.082   /
        delA     Decline rate of TFP per 5 years                  /0.0072  /
        k0       Initial K 2020 for beta = 0.6 (trill 2019 USD)   / 302  /
** Emissions parameters and Non-CO2 GHG
        gsigma1   Initial growth of sigma (per year)                   / -0.015 /
        delgsig   Decline rate of gsigma per period                    /.96/
        asymgsig   Asympototic gsigma                                  /-.005/
        e0        Industrial emissions 2020 (GtCO2 per year)           / 37.56  /
        miu0      Emissions control rate historical 2020               / .05    /
        fosslim   Maximum cumulative extraction fossil fuels (GtC)     / 6000   /
        CumEmiss0 Cumulative emissions 2020 (GtC)                      / 633.5379/
* Climate damage parameters
        a10       Initial damage intercept                            /0      /
        a1        Damage intercept                                    /0      /
        a2base    Damage quadratic term rev 01-13-23                  /0.003467/
        a3        Damage exponent                                     /2.00   /
** Abatement cost
        expcost2  Exponent of control cost function                   / 2.6  /
        pback2050 Cost of backstop 2019$ per tCO2 2050                / 515.  /
        gback     Initial cost decline backstop cost per year         / -.012 /
        delgback  Decline factor of gback per period                  /.95/
        cprice0   Carbon price 2020 2019$ per tCO2                    / 6    /
        gcprice   Growth rate of base carbon price per year           /.01   /
** Limits on emissions controls
        limmiu2070
        limmiu2120
        delmiumax
** Preferences and timing
        betaclim                                                    / 0.6  /
        elasmu    Elasticity of marginal utility of consumption     / 0.9  /
        rhof      Riskfree real rate per year                       / .001 /
        rhok      Rate of risky social time preference per year     / .035 /
        prstp
** For redefinitions, not numerical
        a20       Initial damage quadratic term
        a2        Damage in program
        sig0      Carbon intensity 2020 (kgCO2 per output 2020 USD 2019 no policy)
** Scaling so that MU(C(1)) = 1 and objective function = PV consumption
        tstep       Years per Period                               / 5  /
        scale1      Multiplicative scaling coefficient             /0.009889 /
        scale2      Additive scaling coefficient                   /-7776.944399/ ;
** Other calibration parameters
        a2 = a2base;
        prstp = rhof+rhoK*betaclim;
* Program control variables
sets     tfirst(t), tlast(t), tearly(t), tlate(t);

PARAMETERS
```

```
        L(t)           Level of population and labor
        aL(t)          Level of total factor productivity
        sigma(t)       CO2-emissions output ratio
        sigmatot(t)    GHG-output ratio
        RR(t)          Average utility social discount rate
        gA(t)          Growth rate of productivity from
        gL(t)          Growth rate of labor and population
        gcost1         Growth of cost factor
        gsig(t)        Change in sigma (rate of decarbonization)
        eland(t)       Emissions from deforestation (GtCO2 per year)
        cost1tot(T)    Abatement cost adjusted for backstop and sigma
        pbacktime(t)   Backstop price 2019$ per ton CO2
        optlrsav       Optimal long-run savings rate used for transversality
        scc(t)         Social cost of carbon
        cpricebase(t)  Carbon price in base case
        photel(t)      Carbon Price under no damages (Hotelling rent condition)
        ppm(t)         Atmospheric concentrations parts per million
        atfrac2020(t)  Atmospheric share since 2020
        atfrac1765(t)  Atmospheric fraction of emissions since 1765
        abaterat(t)    Abatement cost per net output
        miuup(t)       Upper bound on miu
        gbacktime(t)   Decline rate of backstop price
;
** Dynamic parameter values
        L("1") = pop0; loop(t, L(t+1)=L(t););
        loop(t, L(t+1)=L(t)*(popasym/L(t))**popadj ;);
        gA(t)=gA0*exp(-delA*5*((t.val-1)));
        aL("1") = A0; loop(t, aL(t+1)=aL(t)/((1-gA(t))););
        RR(t) = 1/((1+prstp)**(tstep*(t.val-1)));
        optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;
        cpricebase(t)= cprice0*(1+gcprice)**(5*(t.val-1));

        gbacktime(t)=gback*delgback**((t.val-1));
        pbacktime(t)=pback2050*exp(-5*(.01)*(t.val-7));
        pbacktime(t)$(t.val > 7) = pback2050*exp(-5*(.001)*(t.val-7));
        sig0 = e0/(q0*(1-miu0));
        sigma("1")=sig0;
        gsig(t)=min(gsigma1*delgsig **((t.val-1)),asymgsig);
        loop(t, sigma(t+1)=sigma(t)*exp(5*gsig(t)););
** Emissions limits
        limmiu2070 = 1;
        limmiu2120 = 1.1;
        delmiumax = 0.12;
        miuup('1')= .05;
        miuup('2')= .10;
        miuup(t)$(t.val > 2) = ( delmiumax*(t.val-1));
        miuup(t)$(t.val > 8) = 0.85+.05*(t.val-8);
        miuup(t)$(t.val > 11) = limmiu2070;
        miuup(t)$(t.val > 20) = limmiu2120;
** Include file for non-CO2 GHGs
$include Include/Nonco2-b-3-17.gms

* Program control definitions
        tfirst(t) = yes$(t.val eq 1);
        tlast(t)  = yes$(t.val eq card(t));

VARIABLES
        MIU(t)          Emission control rate GHGs
        C(t)            Consumption (trillions 2019 US dollars per year)
        K(t)            Capital stock (trillions 2019 US dollars)
        CPC(t)          Per capita consumption (thousands 2019 USD per year)
        I(t)            Investment (trillions 2019 USD per year)
        S(t)            Gross savings rate as fraction of gross world product
        RI(t)           Real interest rate (per annum)
        Y(t)            Gross world product net of abatement and damages (trillions 2019 USD per year)
        YGROSS(t)       Gross world product GROSS of abatement and damages (trillions 2019 USD per year)
        YNET(t)         Output net of damages equation (trillions 2019 USD per year)
        DAMAGES(t)      Damages (trillions 2019 USD per year)
        DAMFRAC(t)      Damages as fraction of gross output
        ABATECOST(t)    Cost of emissions reductions  (trillions 2019 USD per year)
        MCABATE(t)      Marginal cost of abatement (2019$ per ton CO2)
        CCATOT(t)       Total carbon emissions (GtC)
        PERIODU(t)      One period utility function
        CPRICE(t)       Carbon price (2019$ per ton of CO2)
        CEMUTOTPER(t)   Period utility
        UTILITY         Welfare function
;
NONNEGATIVE VARIABLES  MIU, TATM, MAT, MU, ML, Y, YNET, YGROSS, C, K, I;
EQUATIONS
*Emissions and Damages
        CCATOTEQ(t)      Cumulative total carbon emissions
        DAMFRACEQ(t)     Equation for damage fraction
```

```
        DAMEQ(t)         Damage equation
        ABATEEQ(t)       Cost of emissions reductions equation
        MCABATEEQ(t)     Equation for MC abatement
        CARBPRICEEQ(t)   Carbon price equation from abatement
*Economic variables
        YGROSSEQ(t)      Output gross equation
        YNETEQ(t)        Output net of damages equation
        YY(t)            Output net equation
        CC(t)            Consumption equation
        CPCE(t)          Per capita consumption definition
        SEQ(t)           Savings rate equation
        KK(t)            Capital balance equation
        RIEQ(t)          Interest rate equation
* Utility
        CEMUTOTPEREQ(t)  Period utility
        PERIODUEQ(t)     Instantaneous utility function equation
        UTIL             Objective function      ;

** Include file for DFAIR model and climate equations
** Equals old FAIR with recalibrated parameters for revised F2xco2 and Millar model.
** Deletes nonnegative reservoirs. See explanation below


sets     tfirst(t), tlast(t);

PARAMETERS
         yr0     Calendar year that corresponds to model year zero         /2020/
        emshare0 Carbon emissions share into Reservoir 0   /0.2173/
        emshare1 Carbon emissions share into Reservoir 1    /0.224/
        emshare2 Carbon emissions share into Reservoir 2    /0.2824/
        emshare3 Carbon emissions share into Reservoir 3    /0.2763/
        tau0    Decay time constant for R0  (year)                            /1000000/
        tau1    Decay time constant for R1  (year)                            /394.4/
        tau2    Decay time constant for R2  (year)       /36.53/
        tau3    Decay time constant for R3  (year) /4.304/

        teq1    Thermal equilibration parameter for box 1 (m^2 per KW)         /0.324/
        teq2    Thermal equilibration parameter for box 2 (m^2 per KW)        /0.44/
        d1      Thermal response timescale for deep ocean (year)               /236/
        d2      Thermal response timescale for upper ocean (year)              /4.07/

        irf0    Pre-industrial IRF100 (year)                                        /32.4/
        irC      Increase in IRF100 with cumulative carbon uptake (years per GtC)    /0.019/
        irT      Increase in IRF100 with warming (years per degree K)                /4.165/
        fco22x   Forcings of equilibrium CO2 doubling (Wm-2)                        /3.93/

** INITIAL CONDITIONS TO BE CALIBRATED TO HISTORY
** CALIBRATION
       mat0   Initial concentration in atmosphere in 2020 (GtC)       /886.5128014/

       res00  Initial concentration in Reservoir 0 in 2020 (GtC)      /150.093 /
       res10  Initial concentration in Reservior 1 in 2020 (GtC)      /102.698 /
       res20  Initial concentration in Reservoir 2 in 2020 (GtC)      /39.534  /
       res30  Initial concentration in Reservoir 3 in 2020 (GtC)      / 6.1865 /



       mateq      Equilibrium concentration atmosphere  (GtC)            /588   /
       tbox10    Initial temperature box 1 change in 2020 (C from 1765)  /0.1477  /
       tbox20    Initial temperature box 2 change in 2020 (C from 1765)  /1.099454/
       tatm0     Initial atmospheric temperature change in 2020          /1.24715 /

;
VARIABLES
*Note: Stock variables correspond to levels at the END of the period
        FORC(t)        Increase in radiative forcing (watts per m2 from 1765)
        TATM(t)        Increase temperature of atmosphere (degrees C from 1765)
        TBOX1(t)       Increase temperature of box 1 (degrees C from 1765)
        TBOX2(t)       Increase temperature of box 2 (degrees C from 1765)
        RES0(t)        Carbon concentration in Reservoir 0 (GtC from 1765)
        RES1(t)        Carbon concentration in Reservoir 1 (GtC from 1765)
        RES2(t)        Carbon concentration in Reservoir 2 (GtC from 1765)
        RES3(t)        Carbon concentration in Reservoir 3 (GtC from 1765)
        MAT(t)         Carbon concentration increase in atmosphere (GtC from 1765)
        CACC(t)        Accumulated carbon in ocean and other sinks (GtC)
        IRFt(t)        IRF100 at time t
        alpha(t)       Carbon decay time scaling factor
        SumAlpha      Placeholder variable for objective function;

**** IMPORTANT PROGRAMMING NOTE. Earlier implementations has reservoirs as non-negative.
**** However, these are not physical but mathematical solutions.
**** So, they need to be unconstrained so that can have negative emissions.
```

```
NONNEGATIVE VARIABLES   TATM, MAT,  IRFt, alpha

EQUATIONS
        FORCE(t)        Radiative forcing equation
        RES0LOM(t)      Reservoir 0 law of motion
        RES1LOM(t)      Reservoir 1 law of motion
        RES2LOM(t)      Reservoir 2 law of motion
        RES3LOM(t)      Reservoir 3 law of motion
        MMAT(t)         Atmospheric concentration equation
        Cacceq(t)       Accumulated carbon in sinks equation
        TATMEQ(t)       Temperature-climate equation for atmosphere
        TBOX1EQ(t)      Temperature box 1 law of motion
        TBOX2EQ(t)      Temperature box 2 law of motion
        IRFeqLHS(t)     Left-hand side of IRF100 equation
        IRFeqRHS(t)     Right-hand side of IRF100 equation
;
** Equations of the model
    res0lom(t+1)..   RES0(t+1) =E=  (emshare0*tau0*alpha(t+1)*(Eco2(t+1)/3.667))*(1-exp(-
tstep/(tau0*alpha(t+1))))+Res0(t)*exp(-tstep/(tau0*alpha(t+1)));
    res1lom(t+1)..   RES1(t+1) =E=  (emshare1*tau1*alpha(t+1)*(Eco2(t+1)/3.667))*(1-exp(-
tstep/(tau1*alpha(t+1))))+Res1(t)*exp(-tstep/(tau1*alpha(t+1)));
    res2lom(t+1)..   RES2(t+1) =E=  (emshare2*tau2*alpha(t+1)*(Eco2(t+1)/3.667))*(1-exp(-
tstep/(tau2*alpha(t+1))))+Res2(t)*exp(-tstep/(tau2*alpha(t+1)));
    res3lom(t+1)..   RES3(t+1) =E=  (emshare3*tau3*alpha(t+1)*(Eco2(t+1)/3.667))*(1-exp(-
tstep/(tau3*alpha(t+1))))+Res3(t)*exp(-tstep/(tau3*alpha(t+1)));
    mmat(t+1)..      MAT(t+1)  =E=   mateq+Res0(t+1)+Res1(t+1)+Res2(t+1)+Res3(t+1);
    cacceq(t)..      Cacc(t)   =E=  (CCATOT(t)-(MAT(t)-mateq));
    force(t)..       FORC(t)    =E=  fco22x*((log((MAT(t)/mateq))/log(2))) + F_Misc(t)+F_GHGabate(t);

    tbox1eq(t+1)..   Tbox1(t+1) =E=  Tbox1(t)*exp(-tstep/d1)+teq1*Forc(t+1)*(1-exp(-tstep/d1));
    tbox2eq(t+1)..   Tbox2(t+1) =E=  Tbox2(t)*exp(-tstep/d2)+teq2*Forc(t+1)*(1-exp(-tstep/d2));
    tatmeq(t+1)..    TATM(t+1)  =E=   Tbox1(t+1)+Tbox2(t+1);
    irfeqlhs(t)..    IRFt(t)   =E=  ((alpha(t)*emshare0*tau0*(1-exp(-
100/(alpha(t)*tau0))))+(alpha(t)*emshare1*tau1*(1-exp(-100/(alpha(t)*tau1))))+(alpha(t)*emshare2*tau2*(1-
exp(-100/(alpha(t)*tau2))))+(alpha(t)*emshare3*tau3*(1-exp(-100/(alpha(t)*tau3)))));
    irfeqrhs(t)..    IRFt(t)   =E=  irf0+irC*Cacc(t)+irT*TATM(t);

**  Upper and lower bounds for stability
MAT.LO(t)       = 10;
TATM.UP(t)      = 20;
TATM.lo(t)      = .5;
alpha.up(t) = 100;
alpha.lo(t) = 0.1;

* Initial conditions
MAT.FX(tfirst)    = mat0;
TATM.FX(tfirst)   = tatm0;
Res0.fx(tfirst) = Res00;
Res1.fx(tfirst) = Res10;
Res2.fx(tfirst) = Res20;
Res3.fx(tfirst) = Res30;
Tbox1.fx(tfirst) = Tbox10;
Tbox2.fx(tfirst) = Tbox20;

** Solution options
option iterlim = 99900;
option reslim = 99999;
option solprint = on;
option limrow = 0;
option limcol = 0;


** Equations of the model
**Emissions and Damages
 eco2eq(t)..          ECO2(t)        =E= (sigma(t)*YGROSS(t) + eland(t))*(1-(MIU(t)));
 eindeq(t)..          EIND(t)        =E= (sigma(t)*YGROSS(t))*(1-(MIU(t)));
 eco2Eeq(t)..         ECO2E(t)       =E= (sigma(t)*YGROSS(t) + eland(t) + CO2E_GHGabateB(t))*(1-(MIU(t)));
 F_GHGabateEQ(t+1)..  F_GHGabate(t+1) =E= Fcoef2*F_GHGabate(t)+ Fcoef1*CO2E_GHGabateB(t)*(1-(MIU(t)));
 ccatoteq(t+1)..      CCATOT(t+1)    =E= CCATOT(t) +  ECO2(T)*(5/3.666) ;
 damfraceq(t) ..      DAMFRAC(t)     =E= (a1*(TATM(t)))+(a2*(TATM(t))**a3) ;
 dameq(t)..           DAMAGES(t)     =E= YGROSS(t) * DAMFRAC(t);
 abateeq(T)..         ABATECOST(T)   =E= YGROSS(T) * COST1TOT(T) * (MIU(T)**EXPCOST2);
 mcabateeq(t)..       MCABATE(t)     =E= pbacktime(t) * MIU(t)**(expcost2-1);
 carbpriceeq(t)..     CPRICE(t)      =E= pbacktime(t) * (MIU(t))**(expcost2-1);
**Economic variables
 ygrosseq(t)..        YGROSS(t)      =E= (aL(t)*(L(t)/1000)**(1-gama))*(K(t)**gama);
 yneteq(t)..          YNET(t)        =E= YGROSS(t)*(1-damfrac(t));
 yy(t)..              Y(t)           =E= YNET(t) - ABATECOST(t);
 cc(t)..              C(t)           =E= Y(t) - I(t);
 cpce(t)..            CPC(t)         =E= 1000 * C(t) / L(t);
 seq(t)..             I(t)           =E= S(t) * Y(t);
 kk(t+1)..            K(t+1)         =L= (1-dk)**tstep * K(t) + tstep * I(t);
```

```
 rieq(t+1)..          RI(t)          =E= (1+prstp) * (CPC(t+1)/CPC(t))**(elasmu/tstep) - 1;
**Utility and objective function
 cemutotpereq(t)..    CEMUTOTPER(t)  =E= PERIODU(t) * L(t) * RR(t);
 periodueq(t)..       PERIODU(t)     =E= ((C(T)*1000/L(T))**(1-elasmu)-1)/(1-elasmu)-1;
 util..               UTILITY        =E= tstep * scale1 * sum(t,  CEMUTOTPER(t)) + scale2 ;

* Ccntrol rate limits
miu.up(t) = miuup(t);
K.LO(t)         = 1;
C.LO(t)         = 2;
CPC.LO(t)       = .01;

*Control for terminal savings rate
set lag10(t) ;
lag10(t) =  yes$(t.val gt card(t)-10);
S.FX(lag10(t)) = optlrsav;
ri.fx(tlast) = .014;

* Initial conditions
ccatot.fx(tfirst) = CumEmiss0;
k.FX(tfirst)      = k0;
F_GHGabate.fx(tfirst) = F_GHGabate2020;

** Solution options
option iterlim = 99900;
option reslim = 99999;
option solprint = on;
option limrow = 0;
option limcol = 0;
model  CO2 /all/;

* Initialize with optimal run
ifopt=1;
solve CO2 maximizing UTILITY using nlp ;

**** STATMENTS FOR DEFINITIONS AND PUT STATEMENTS FOR SCENARIOS

*                                          OPTIMAL

ifopt=1;

* Solve
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));
file resLARGE2022 /DICE2022-b-3-16-1p.csv/; resLARGE2022.nd = 10 ; resLARGE2022.nw = 0 ;
resLARGE2022.pw=20000; resLARGE2022.pc=5;
put resLARGE2022;
put /”Results of DICE2022-b-3-16-1p.csv with final results: February 14, 2023”;
put /”SCENARIO: OPTIMAL”
put /”Results of DICE2022-opt-b-3-1p”;
put /”OPTIMAL”;

$include Include/put_list_module-b-3-17.gms


*                                 BASELINE WITH CURRENT LEVEL OF POLICY
* Solve equations for base (low policy) case

ifopt=0;
tatm.up(t)=15;
cprice.up(t)$(t.val < 38)=cpricebase(t);

*miu.fx(t)=0;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment
scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
ppm(t)    = mat.l(t)/2.13;
```

```
abaterat(t)=abatecost.l(t)/y.l(t);
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));
cprice.up(t)=500;
put /”SCENARIO: BASE”;
put /”Results of DICE2022-base-b-3-1p”;
put /”BASE”;
$include Include/put_list_module-b-3-17.gms

*                                                    WEITZMAN
* Discount program

ifopt=1;
elasmu   = 1*0.6;
*marginal mutliplied by bclim
prstp    = .00186;
*retrieved from Drupp median and elasmu matching SDR from Weitzman

rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;
cprice.up(t) = 1000;

solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

* $include Include\put-DISC5%-b-3-16.gms
put /”SCENARIO: Weitzman”
put /”Results of Weitzman single SDR”;
put /”Weitzman”;

$include Include/put_list_module-b-3-17.gms

*                                           DRUPP ET AL. MEDIAN
* Discount program

ifopt=1;
elasmu   = 1*0.6;
prstp    = .005;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;
cprice.up(t) = 1000;

solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

* $include Include\put-DISC5%-b-3-16.gms
put /"Drupp et al. median"
put /"Results of median discounting parameters from Drupp et al. (2015)";
put /"Drupp et al median";

$include Include/put_list_module-b-3-17.gms
```

```
*                                                 STERN
* Discount program

ifopt=1;
elasmu   = 1*0.6;
prstp    = .001;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;
cprice.up(t) = 1000;

solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

put /"SCENARIO: Stern"
put /"Results of Stern parameters";
put /"Stern";

$include Include/put_list_module-b-3-17.gms

*                                                 DRUPP AVERAGE
* Discount program

ifopt=1;
elasmu   = 1.35*0.6;
prstp    = .011;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;
cprice.up(t) = 1000;

solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

put /"SCENARIO: Drupp average"
put /"Results of average discounting parameters from Drupp et al. (2015)";
put /"Drupp average parameter";

$include Include/put_list_module-b-3-17.gms


*                                         1.7°C THRESHOLD
* Discount program

ifopt=1;
elasmu   = .001;
prstp    = .01867;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

solve CO2 maximizing UTILITY using nlp ;
```

```
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

put /"SCENARIO Optimal 1.7°C discount"
put /"Results of the optimal discount for 1.7°C threshold";
put /"1.7°C threshold optimal";
$include Include/put_list_module-b-3-17.gms


*                                           2°C THRESHOLD
* Discount program

ifopt=1;
elasmu   = .001;
prstp    = .02951;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

put /"SCENARIO Optimal 2°C discount"
put /"Results of the optimal discount for 2°C threshold";
put /"2°C threshold optimal";
$include Include/put_list_module-b-3-17.gms

*                                           0 RATES
* Discount program

ifopt=1;
elasmu   = .0001;
prstp    = .0001;
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;
solve CO2 maximizing UTILITY using nlp ;

*Post-Solution Parameter-Assignment

scc(t) = -1000*eco2eq.m(t)/(.00001+cc.m(t));
ppm(t)    = mat.l(t)/2.13;
abaterat(t) = abatecost.l(t)/y.l(t);
atfrac2020(t) = ((mat.l(t)-mat0)/(ccatot.l(t)+.00001-CumEmiss0  ));
atfrac1765(t) = ((mat.l(t)-mateq)/(.00001+ccatot.l(t)  ));
FORC_CO2(t) = fco22x*((log((MAT.l(t)/mateq))/log(2)));

ifopt=1;
elasmu   = 1.5;
prstp    = .01;
```

```
rr(t) = 1/((1+prstp)**(tstep*(t.val-1)));
optlrsav = (dk + .004)/(dk + .004*elasmu + prstp)*gama;

put /"SCENARIO 0 rates"
put /"Results of DICE2022";
put /"Zero rates";
$include Include/put_list_module-b-3-17.gms
```

A.1 Print CSV results

The following code has to be saved as

put_list_module-b-3-17.gms

and produces a CSV file in the base directory with the resulting output from each scenario.

```
put /"This is optimal if ifopt = 1 and baseline if ifopt = 0";
put /"ifopt =" ifopt;
put // "Period";
Loop (T, put T.val);
put / "Year" ;
Loop (T, put (2015+(TSTEP*T.val) ));
put / "Objective function (2019$)" ;
put utility.l;
put / "Industrial CO2 GtCO2/yr" ;
Loop (T, put EIND.l(T));
put / "Atmospheric concentration C (ppm)" ;
Loop (T, put (MAT.l(T)/2.13));
put / "Atmospheric concentrations GtC" ;
Loop (T, put mat.l(t));
put / "Atmospheric temperaturer (deg c above preind) " ;
Loop (T, put TATM.l(T));
put / "Total forcings w/m2" ;
Loop (T, put forc.l(t));
put / "Forcings, exogenous w/m2" ;
Loop (T, put F_Misc(t) );
put / "CO2 forcings w/m2" ;
Loop (T, put FORC_CO2(t) );
put / "Actual other abatable GHG forcings w/m2" ;
Loop (T, put F_GHGabate.L(t) );
put / "Carbon price (2019 $ per t CO2)" ;
Loop (T, put cprice.l(T));
put / "Emissions control rate" ;
Loop (T, put MIU.l(T));
put / "Social cost of carbon $/tCO2" ;
scc('1')=scc('2')*.85;
Loop (T, put scc(T));
put / "Output, net net trill 2019$" ;
Loop (T, put Y.l(T));
put / "Interest rate, %/yr" ;
Loop (T, put RI.l(T));
put / "Population" ;
Loop (T, put L(T));
put / "TFP" ;
Loop (T, put AL(T));
put / "Output, gross-gross, 2019$" ;
Loop (T, put YGROSS.L(t));
put / "Change TFP, %/year" ;
Loop (T, put ga(t));
put / "Capital stock, 2019$" ;
Loop (T, put k.l(t));
 put / "Savings rate, fraction gross output" ;
Loop (T, put s.l(t));
  put / "Gross investment, 2019$" ;
Loop (T, put I.l(t));
   put / "Y gross-net, 2019$" ;
Loop (T, put ynet.l(t));
put / "Consumption per capita, 2019$ " ;
Loop (T, put CPC.l(T));
put / "Consumption" ;
Loop (T, put C.l(t));
put / "Climate damages, fraction of output" ;
Loop (T, put DAMFRAC.l(T));
put / "Damages, 2019$" ;
Loop (T, put damages.l(t));
put / "Abatement, 2019$" ;
Loop (T, put abatecost.l(t));
put / "Abatement/0utput" ;
Loop (T, put  abaterat(t) );
put / "Sigmabase (CO2/output, no controls, industrial CO2)" ;
Loop (T, put sigma(t));
put / "Sigmatot,(CO2/output, no controls, all CO2)" ;
Loop (T, put sigmaTOT(t));
put / "Cost, backstop technology ($/tCO2)" ;
```

```
Loop (T, put pbacktime(T));
put / "Total CO2 Emissions, GTCO2/year" ;
Loop (T, put Eco2.l(T));
put / "Total CO2e Emissions, GTCO2-E/year" ;
Loop (T, put Eco2e.l(T));
put / "Industrial CO2 Emissions, GTCO2/year" ;
Loop (T, put EIND.l(T));
put / "Base abateable non-CO2 emission, GTCO2-E/year" ;
Loop (T, put CO2E_GHGabateB(t));
put / "Land emissions, GtCO2/year" ;
Loop (T, put eland(t));
put / "Cumulative CO2 emissions, GtC " ;
Loop (T, put ccatot.l(t));
put / "Atmospheric fraction CO2 since 1765 " ;
Loop (T, put  atfrac1765(t) );
put / "Atmospheric fraction CO2 since 2020 " ;
Loop (T, put  atfrac2020(t) );
put / "Permanent C box"
Loop (T, put res0.L(t) );
put / "Slow C box"
Loop (T, put res1.L(t)   );
put / "Medium C box"
Loop (T, put res2.L(t)  );
put / "Fast C box"
Loop (T, put res3.L(t) );
put / "Temp Box 1"
Loop (T, put TBOX1.L(t) );
put / "Temp Box 2"
Loop (T, put TBOX2.L(t) );
put / "Alpha"
Loop (T, put alpha.L(t)  );
put / "IFR"
Loop (T, put irft.L(t) );
put / "cacc"
Loop (T, put cacc.L(t) );
put / "ccatot"
Loop (T, put ccatot.L(t) );
put / "Share of output net zero emissions"
Loop (T, put cost1tot(t) );
put /"  yr0 ="  yr0 ; put " emshare0    ="  emshare0    ;put "  emshare1    ="  emshare1    ; put " emshare2
="  emshare2    ;
put "   emshare3    ="  emshare3    ;
put "   tau0    ="  tau0    ;
put "   tau1    ="  tau1    ;
put "   tau2    ="  tau2    ;
put "   tau3    ="  tau3    ;
put "   teq1    ="  teq1    ;
put "   teq2    ="  teq2    ;
put "   d1  ="  d1  ;
put "   d2  ="  d2  ;
put "IRF0   ="  irf0;
put "   irC ="  irC ;
put "   irT ="  irT ;
put /"  fco22x  ="  fco22x  ;
put "   mat0    ="  mat0    ;
put "   res00   ="  res00   ;
put "   res10   ="  res10   ;
put "   res20   ="  res20   ;
put "   res30   ="  res30   ;
put "   mateq   ="  mateq   ;
put "   tbox10  ="  tbox10  ;
put "   tbox20  ="  tbox20  ;
put "   tatm0   ="  tatm0   ;
put /"  a2  ="  a2  ;
put "   elasmu  ="  elasmu  ;
put "   prstp   ="  prstp   ;
put "gsigma1        ="  gsigma1     ;
put "    e0     ="    e0    ;
put "expcost2       ="   expcost2   ;
put "pback      ="   pback  ;
put "   gback   ="   gback  ;
put "   limmiu2050  ="   limmiu2070 ;
put "   limmiu2100  ="  limmiu2120  ;
put "   cprice0     ="   cprice0    ;
put "   gcprice     ="   gcprice  ;
put /;
```

Appendix B – Scenarios' output

This Appendix presents the long-term outcomes of the DICE model scenarios, extending the analysis horizon up to 2300. The time step considered in this section is 20 years, and the selected variables represent the most relevant ones. They don't encompass the entirety of the variables computed in the model.

For more comprehensive information and the ability to customize time steps, it is recommended to execute the code provided in Appendix A.

B.1 Baseline

Year	**2020**	**2040**	**2060**	**2080**	**2100**	**2120**	**2140**	**2160**	**2180**	**2200**	**2220**	**2240**	**2260**	**2280**	**2300**
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	7.321	8.933	10.900	13.300	16.229	19.802	24.163	29.483	35.975	506.064	496.043	486.221	476.593	467.156
Emissions control rate	0.050	0.066	0.080	0.092	0.105	0.120	0.138	0.158	0.182	0.208	1.100	1.100	1.100	1.100	1.100
Social cost of carbon $/tCO2	60.899	114.453	191.177	286.937	395.322	509.948	627.603	746.257	866.156	972.404	1129.403	1297.786	1466.173	1628.130	1778.382
Output, net net trill 2019$	135.143	250.194	403.657	588.903	797.017	1018.768	1244.095	1463.073	1668.264	1869.800	2090.982	2350.654	2596.239	2825.146	3037.434
Population	7752.900	9056.484	9840.769	10287.372	10534.288	10668.660	10741.169	10780.120	10800.993	10812.164	10818.139	10821.333	10823.040	10823.953	10824.440
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	253.242	412.341	609.466	839.182	1094.554	1367.843	1650.501	1935.345	2234.612	2546.901	2848.257	3137.273	3408.729	3661.190
Capital stock, 2019$	302.000	568.893	939.693	1399.034	1926.966	2499.370	3091.834	3677.350	4239.926	4902.313	5684.364	6435.821	7165.431	7847.900	8481.439
Savings rate, fraction gross output	0.266	0.253	0.244	0.238	0.233	0.230	0.227	0.225	0.225	0.247	0.240	0.240	0.240	0.239	0.239
Gross investment, 2019$	35.972	63.298	98.404	139.878	185.765	234.171	282.827	329.740	375.399	462.031	502.573	564.384	621.902	675.351	724.804
Y gross-net, 2019$	135.149	250.208	403.683	588.944	797.082	1018.869	1244.252	1463.312	1668.619	1870.318	2130.689	2390.037	2634.714	2862.222	3072.753
Consumption per capita, 2019$	12.791	20.637	31.019	43.648	58.025	73.542	89.494	105.132	119.699	130.202	146.828	165.069	182.420	198.615	213.649
Consumption	99.171	186.895	305.253	449.025	611.252	784.597	961.267	1133.334	1292.865	1407.769	1588.409	1786.270	1974.337	2149.794	2312.630
Damages, 2019$	0.733	3.034	8.658	20.521	42.101	75.685	123.591	187.189	266.727	364.294	416.213	458.220	502.560	546.508	588.437
Abatement, 2019$	0.006	0.014	0.026	0.041	0.065	0.102	0.157	0.239	0.354	0.518	39.706	39.383	38.474	37.076	35.319
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	55.581	67.902	79.551	90.016	99.163	106.904	113.111	116.598	117.791	-15.335	-15.515	-15.461	-15.199	-14.770
Cumulative CO2 emissions, GtC	633.538	894.302	1222.721	1617.455	2073.400	2583.770	3141.221	3737.832	4363.443	5002.151	5100.671	5016.545	4931.916	4848.025	4765.921
Atmospheric concentrations GtC	886.513	1034.880	1232.755	1485.185	1795.309	2163.475	2586.192	3057.691	3568.953	4108.341	3975.488	3851.449	3735.455	3627.024	3525.664
Atmospheric temperaturer (deg c above preind)	1.247	1.859	2.461	3.116	3.804	4.466	5.105	5.719	6.305	6.857	6.866	6.812	6.797	6.800	6.809
Industrial CO2 GtCO2/yr	37.610	51.965	65.565	78.037	89.038	98.532	106.499	112.851	116.432	117.686	-15.327	-15.509	-15.457	-15.196	-14.769

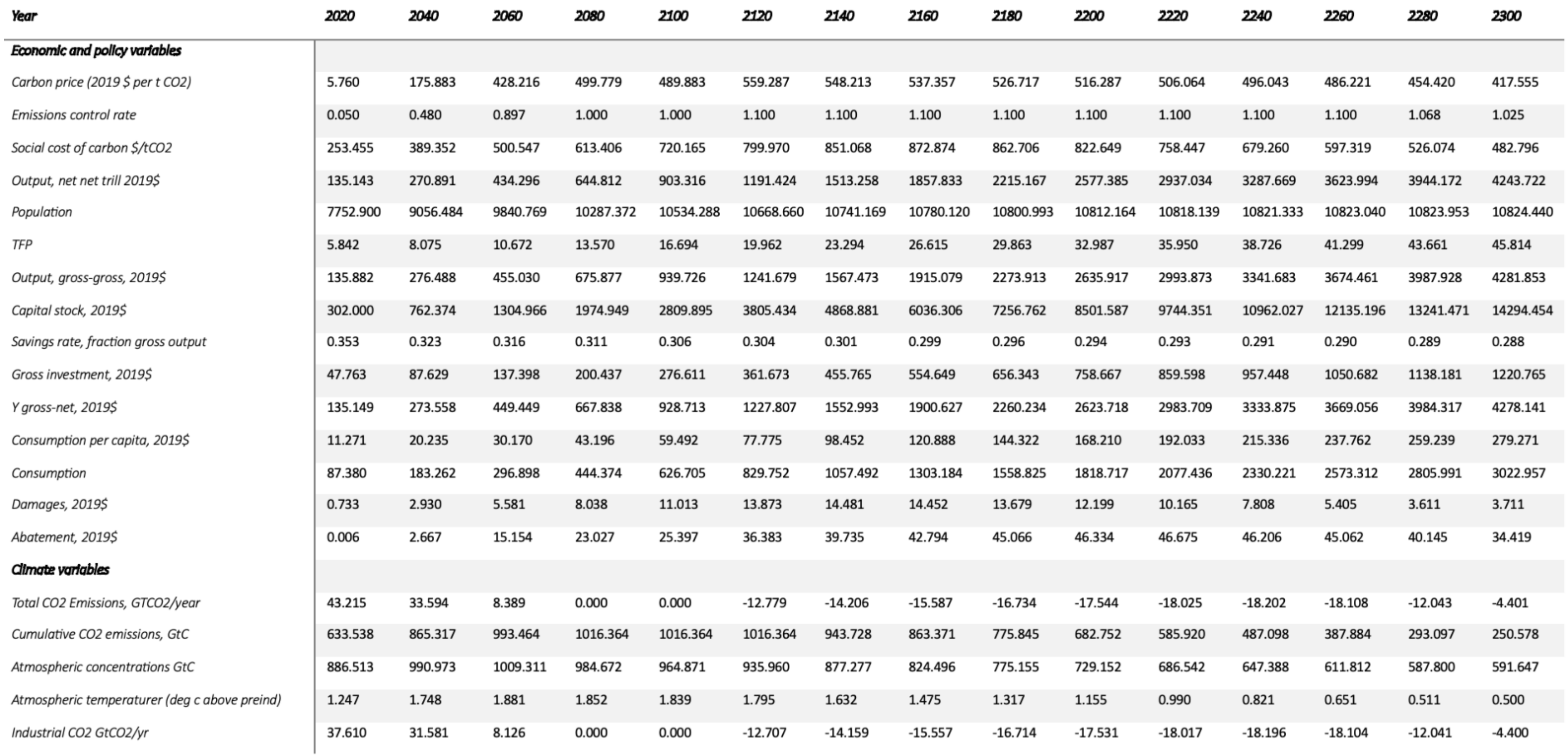
B.2 Optimal

Year	2020	2040	2060	2080	2100	2120	2140	2160	2180	2200	2220	2240	2260	2280	2300
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	90.178	147.758	223.900	316.287	400.722	485.198	537.357	526.717	516.287	506.064	496.043	486.221	476.593	467.156
Emissions control rate	0.050	0.316	0.461	0.605	0.761	0.893	1.019	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
Social cost of carbon $/tCO2	52.667	97.389	160.145	238.889	329.386	426.503	526.032	624.326	719.613	805.522	877.105	930.992	965.191	978.887	972.067
Output, net net trill 2019$	135.143	250.484	405.814	597.258	820.547	1073.038	1350.818	1652.114	1975.856	2306.375	2636.259	2959.584	3271.417	3567.900	3846.267
Population	7752.900	9056.484	9840.769	10287.372	10534.288	10668.660	10741.169	10780.120	10800.993	10812.164	10818.139	10821.333	10823.040	10823.953	10824.440
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	254.039	414.850	616.032	853.903	1123.675	1419.961	1734.910	2063.457	2396.811	2727.341	3049.260	3357.949	3649.949	3922.898
Capital stock, 2019$	302.000	574.883	958.892	1449.917	2041.966	2727.985	3502.271	4342.486	5249.870	6192.127	7141.233	8078.326	8987.694	9856.764	10676.242
Savings rate, fraction gross output	0.268	0.256	0.249	0.245	0.243	0.243	0.243	0.242	0.241	0.240	0.240	0.239	0.239	0.238	0.238
Gross investment, 2019$	36.252	64.226	101.120	146.518	199.756	260.584	327.960	399.825	476.719	554.634	632.094	707.729	780.403	849.251	913.673
Y gross-net, 2019$	135.149	251.311	408.265	602.951	831.882	1092.191	1380.336	1690.881	2016.752	2348.506	2678.778	3001.746	3312.598	3607.599	3884.111
Consumption per capita, 2019$	12.755	20.566	30.962	43.815	58.930	76.153	95.228	116.166	138.796	162.016	185.260	208.094	230.158	251.170	270.923
Consumption	98.891	186.258	304.694	450.741	620.791	812.454	1022.858	1252.288	1499.138	1751.741	2004.165	2251.855	2491.014	2718.649	2932.594
Damages, 2019$	0.733	2.728	6.585	13.082	22.022	31.484	39.625	44.028	46.706	48.305	48.563	47.513	45.351	42.350	38.787
Abatement, 2019$	0.006	0.828	2.451	5.692	11.335	19.153	29.517	38.768	40.895	42.131	42.519	42.163	41.180	39.700	37.844
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	40.806	40.000	34.919	24.480	12.370	-2.469	-14.124	-15.187	-15.954	-16.421	-16.609	-16.548	-16.274	-15.826
Cumulative CO2 emissions, GtC	633.538	861.844	1083.644	1293.807	1465.154	1575.264	1613.387	1567.672	1488.324	1403.773	1315.655	1225.570	1134.984	1045.182	957.248
Atmospheric concentrations GtC	886.513	996.974	1107.223	1207.714	1277.499	1304.401	1279.511	1203.712	1129.502	1061.239	998.079	940.394	888.503	842.442	801.920
Atmospheric temperaturer (deg c above preind)	1.247	1.760	2.140	2.475	2.727	2.843	2.837	2.706	2.555	2.411	2.266	2.120	1.974	1.829	1.689
Industrial CO2 GtCO2/yr	37.610	38.159	38.631	34.261	24.218	12.294	-2.459	-14.093	-15.167	-15.940	-16.413	-16.604	-16.544	-16.272	-15.824

B.3 Stern

Year	***2020***	***2040***	***2060***	***2080***	***2100***	***2120***	***2140***	***2160***	***2180***	***2200***	***2220***	***2240***	***2260***	***2280***	***2300***
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	175.883	430.777	499.779	489.883	559.287	548.213	537.357	526.717	516.287	506.064	496.043	486.221	436.478	415.456
Emissions control rate	0.050	0.480	0.900	1.000	1.000	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.041	1.022
Social cost of carbon $/tCO2	428.329	627.621	768.682	903.124	1018.596	1090.298	1121.726	1113.277	1065.221	982.986	875.416	753.808	629.811	511.261	486.330
Output, net net trill 2019$	135.143	272.593	441.265	656.984	921.013	1215.941	1544.949	1896.649	2261.281	2630.830	2997.707	3355.341	3698.270	4026.836	4330.430
Population	7752.900	9056.484	9840.769	10287.372	10534.288	10668.660	10741.169	10780.120	10800.993	10812.164	10818.139	10821.333	10823.040	10823.953	10824.440
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	278.228	462.501	688.541	958.023	1267.086	1600.084	1954.792	2320.862	2690.108	3055.193	3409.913	3749.236	4068.725	4369.050
Capital stock, 2019$	302.000	778.483	1377.757	2101.020	2996.442	4071.233	5214.804	6463.738	7768.332	9098.291	10425.662	11726.029	12978.076	14157.057	15288.046
Savings rate, fraction gross output	0.351	0.335	0.332	0.325	0.321	0.319	0.316	0.313	0.311	0.309	0.307	0.305	0.304	0.302	0.302
Gross investment, 2019$	47.423	91.307	146.454	213.704	295.246	387.563	488.108	593.827	702.492	811.790	919.580	1024.060	1123.425	1218.075	1305.634
Y gross-net, 2019$	135.149	275.277	456.817	680.443	946.905	1253.068	1585.510	1940.331	2307.278	2678.116	3045.337	3402.490	3744.249	4065.199	4365.263
Consumption per capita, 2019$	11.314	20.017	29.958	43.090	59.403	77.646	98.392	120.854	144.319	168.240	192.096	215.434	237.904	259.495	279.441
Consumption	87.720	181.286	294.810	443.280	625.767	828.378	1056.841	1302.822	1558.789	1819.040	2078.127	2331.281	2574.844	2808.761	3024.795
Damages, 2019$	0.733	2.951	5.684	8.098	11.118	14.018	14.574	14.461	13.584	11.992	9.856	7.423	4.987	3.527	3.787
Abatement, 2019$	0.006	2.684	15.552	23.458	25.892	37.127	40.562	43.681	45.997	47.286	47.631	47.149	45.979	38.363	34.834
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	33.793	8.246	0.000	0.000	-13.039	-14.500	-15.910	-17.079	-17.904	-18.394	-18.573	-18.476	-7.471	-3.922
Cumulative CO2 emissions, GtC	633.538	865.433	994.744	1011.896	1011.896	1011.896	937.764	855.742	766.407	671.397	572.578	471.736	370.499	277.065	245.410
Atmospheric concentrations GtC	886.513	991.277	1009.963	981.690	962.309	933.331	873.876	820.406	770.453	723.927	680.884	641.382	605.560	588.148	592.424
Atmospheric temperaturer (deg c above preind)	1.247	1.749	1.883	1.842	1.830	1.786	1.621	1.461	1.299	1.134	0.965	0.792	0.619	0.500	0.500
Industrial CO2 GtCO2/yr	37.610	31.780	7.992	0.000	0.000	-12.967	-14.453	-15.879	-17.059	-17.891	-18.386	-18.567	-18.472	-7.470	-3.921

B.4 Drupp_med



Year	**2020**	**2040**	**2060**	**2080**	**2100**	**2120**	**2140**	**2160**	**2180**	**2200**	**2220**	**2240**	**2260**	**2280**	**2300**
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	175.883	428.216	499.779	489.883	559.287	548.213	537.357	526.717	516.287	506.064	496.043	486.221	454.420	417.555
Emissions control rate	0.050	0.480	0.897	1.000	1.000	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.068	1.025
Social cost of carbon $/tCO2	253.455	389.352	500.547	613.406	720.165	799.970	851.068	872.874	862.706	822.649	758.447	679.260	597.319	526.074	482.796
Output, net net trill 2019$	135.143	270.891	434.296	644.812	903.316	1191.424	1513.258	1857.833	2215.167	2577.385	2937.034	3287.669	3623.994	3944.172	4243.722
Population	7752.900	9056.484	9840.769	10287.372	10534.288	10668.660	10741.169	10780.120	10800.993	10812.164	10818.139	10821.333	10823.040	10823.953	10824.440
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	276.488	455.030	675.877	939.726	1241.679	1567.473	1915.079	2273.913	2635.917	2993.873	3341.683	3674.461	3987.928	4281.853
Capital stock, 2019$	302.000	762.374	1304.966	1974.949	2809.895	3805.434	4868.881	6036.306	7256.762	8501.587	9744.351	10962.027	12135.196	13241.471	14294.454
Savings rate, fraction gross output	0.353	0.323	0.316	0.311	0.306	0.304	0.301	0.299	0.296	0.294	0.293	0.291	0.290	0.289	0.288
Gross investment, 2019$	47.763	87.629	137.398	200.437	276.611	361.673	455.765	554.649	656.343	758.667	859.598	957.448	1050.682	1138.181	1220.765
Y gross-net, 2019$	135.149	273.558	449.449	667.838	928.713	1227.807	1552.993	1900.627	2260.234	2623.718	2983.709	3333.875	3669.056	3984.317	4278.141
Consumption per capita, 2019$	11.271	20.235	30.170	43.196	59.492	77.775	98.452	120.888	144.322	168.210	192.033	215.336	237.762	259.239	279.271
Consumption	87.380	183.262	296.898	444.374	626.705	829.752	1057.492	1303.184	1558.825	1818.717	2077.436	2330.221	2573.312	2805.991	3022.957
Damages, 2019$	0.733	2.930	5.581	8.038	11.013	13.873	14.481	14.452	13.679	12.199	10.165	7.808	5.405	3.611	3.711
Abatement, 2019$	0.006	2.667	15.154	23.027	25.397	36.383	39.735	42.794	45.066	46.334	46.675	46.206	45.062	40.145	34.419
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	33.594	8.389	0.000	0.000	-12.779	-14.206	-15.587	-16.734	-17.544	-18.025	-18.202	-18.108	-12.043	-4.401
Cumulative CO2 emissions, GtC	633.538	865.317	993.464	1016.364	1016.364	1016.364	943.728	863.371	775.845	682.752	585.920	487.098	387.884	293.097	250.578
Atmospheric concentrations GtC	886.513	990.973	1009.311	984.672	964.871	935.960	877.277	824.496	775.155	729.152	686.542	647.388	611.812	587.800	591.647
Atmospheric temperaturer (deg c above preind)	1.247	1.748	1.881	1.852	1.839	1.795	1.632	1.475	1.317	1.155	0.990	0.821	0.651	0.511	0.500
Industrial CO2 GtCO2/yr	37.610	31.581	8.126	0.000	0.000	-12.707	-14.159	-15.557	-16.714	-17.531	-18.017	-18.196	-18.104	-12.041	-4.400

B.5 Drupp_avg

Year	2020	2040	2060	2080	2100	2120	2140	2160	2180	2200	2220	2240	2260	2280	2300
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	172.456	255.396	354.148	461.751	545.181	548.213	537.357	526.717	516.287	506.064	496.043	486.221	476.593	467.156
Emissions control rate	0.050	0.474	0.649	0.806	0.964	1.083	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
Social cost of carbon $/tCO2	113.530	194.933	288.856	393.795	500.690	601.438	692.065	767.544	820.054	845.424	842.164	811.616	757.908	687.828	610.737
Output, net net trill 2019$	135.143	260.934	423.653	625.331	863.053	1135.705	1443.181	1775.467	2121.033	2472.155	2821.569	3162.945	3491.130	3802.208	4093.436
Population	7752.900	9056.484	9840.769	10287.372	10534.28	10668.66	10741.16	10780.12	10800.99	10812.16	10818.13	10821.33	10823.04	10823.95	10824.44
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	266.213	435.953	648.695	901.152	1189.094	1502.877	1839.137	2187.042	2538.592	2886.679	3225.262	3549.544	3855.987	4142.221
Capital stock, 2019$	302.000	671.963	1131.353	1722.398	2443.503	3294.277	4231.617	5274.672	6373.148	7499.584	8629.182	9739.952	10813.75	11836.69	12798.90
Savings rate, fraction gross output	0.313	0.290	0.283	0.279	0.278	0.277	0.275	0.274	0.272	0.271	0.270	0.269	0.269	0.268	0.267
Gross investment, 2019$	42.320	75.633	119.713	174.757	239.767	314.113	397.295	486.124	577.971	670.835	762.795	852.228	937.859	1018.759	1094.300
Y gross-net, 2019$	135.149	263.421	429.922	637.959	885.176	1169.130	1481.279	1816.564	2164.378	2516.778	2866.572	3207.542	3534.661	3844.149	4133.396
Consumption per capita, 2019$	11.973	20.461	30.886	43.799	59.167	77.010	97.372	119.604	142.863	166.601	190.308	213.534	235.911	257.156	277.071
Consumption	92.824	185.301	303.940	450.574	623.286	821.592	1045.886	1289.343	1543.062	1801.320	2058.774	2310.717	2553.271	2783.449	2999.136
Damages, 2019$	0.733	2.793	6.032	10.737	15.976	19.964	21.598	22.573	22.665	21.814	20.107	17.721	14.884	11.838	8.825
Abatement, 2019$	0.006	2.487	6.269	12.627	22.123	33.425	38.098	41.097	43.345	44.623	45.004	44.596	43.530	41.941	39.959
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	32.786	27.322	18.032	3.916	-10.108	-13.622	-14.971	-16.095	-16.897	-17.380	-17.568	-17.492	-17.193	-16.711
Cumulative CO2 emissions, GtC	633.538	861.008	1028.971	1161.271	1232.620	1238.737	1172.039	1094.937	1010.827	921.240	827.939	732.617	636.826	541.922	449.043
Atmospheric concentrations GtC	886.513	987.303	1055.990	1100.093	1100.172	1061.542	993.446	933.021	876.711	824.524	776.601	732.947	693.383	657.625	625.452
Atmospheric temperaturer (deg c above preind)	1.247	1.739	1.998	2.185	2.261	2.201	2.036	1.882	1.729	1.574	1.417	1.259	1.100	0.941	0.784
Industrial CO2 GtCO2/yr	37.610	30.750	26.431	17.709	3.877	-10.049	-13.575	-14.940	-16.075	-16.883	-17.371	-17.562	-17.488	-17.190	-16.709

B.6 WTZ

Year	***2020***	***2040***	***2060***	***2080***	***2100***	***2120***	***2140***	***2160***	***2180***	***2200***	***2220***	***2240***	***2260***	***2280***	***2300***
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	175.883	311.772	409.892	489.883	559.287	548.213	537.357	526.717	516.287	506.064	496.043	486.221	476.593	462.023
Emissions control rate	0.050	0.480	0.735	0.883	1.000	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.092
Social cost of carbon $/tCO2	160.442	259.178	357.278	460.980	561.879	650.972	722.966	774.750	800.873	799.498	771.737	721.791	656.936	587.616	528.535
Output, net net trill 2019$	135.143	266.618	430.401	635.412	878.956	1157.969	1470.981	1806.557	2154.753	2507.924	2858.810	3201.126	3529.775	3840.882	4132.076
Population	7752.900	9056.484	9840.769	10287.37	10534.28	10668.66	10741.16	10780.12	10800.99	10812.16	10818.13	10821.33	10823.04	10823.95	10824.44
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	272.114	445.073	661.474	917.432	1210.482	1527.871	1866.909	2216.981	2570.216	2919.544	3258.987	3583.819	3890.562	4176.577
Capital stock, 2019$	302.000	722.909	1212.185	1838.119	2593.774	3495.967	4470.787	5544.888	6668.632	7815.548	8961.040	10083.59	11165.75	12194.18	13156.18
Savings rate, fraction gross output	0.340	0.307	0.297	0.293	0.289	0.287	0.285	0.282	0.280	0.278	0.277	0.275	0.274	0.273	0.272
Gross investment, 2019$	46.006	81.754	127.939	186.140	254.220	331.927	418.586	509.610	603.285	697.591	790.636	880.850	967.015	1048.212	1123.394
Y gross-net, 2019$	135.149	269.242	439.251	651.741	903.751	1193.437	1509.712	1848.274	2198.691	2553.102	2904.326	3246.188	3573.725	3883.199	4171.650
Consumption per capita, 2019$	11.497	20.412	30.736	43.672	59.305	77.427	97.978	120.309	143.641	167.435	191.177	214.417	236.787	258.008	277.953
Consumption	89.137	184.863	302.462	449.272	624.737	826.042	1052.394	1296.947	1551.468	1810.332	2068.174	2320.276	2562.760	2792.670	3008.682
Damages, 2019$	0.733	2.872	5.822	9.733	13.681	17.045	18.159	18.635	18.290	17.114	15.218	12.799	10.094	7.363	4.927
Abatement, 2019$	0.006	2.625	8.850	16.329	24.795	35.468	38.731	41.717	43.938	45.179	45.516	45.063	43.950	42.317	39.574
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	33.094	21.028	11.060	0.000	-12.460	-13.848	-15.196	-16.315	-17.107	-17.578	-17.751	-17.661	-17.347	-15.574
Cumulative CO2 emissions, GtC	633.538	863.761	1009.768	1106.122	1138.859	1138.859	1068.048	989.712	904.381	813.612	719.188	622.816	526.053	430.258	336.569
Atmospheric concentrations GtC	886.513	989.412	1035.524	1055.958	1036.796	1001.779	938.556	881.923	829.144	780.168	735.049	693.757	656.167	622.194	593.254
Atmospheric temperaturer (deg c above preind)	1.247	1.745	1.942	2.060	2.074	2.015	1.852	1.697	1.543	1.386	1.226	1.064	0.901	0.739	0.583
Industrial CO2 GtCO2/yr	37.610	31.081	20.356	10.866	0.000	-12.388	-13.801	-15.165	-16.295	-17.094	-17.569	-17.746	-17.657	-17.345	-15.572

B.7 R0

Year	2020	2040	2060	2080	2100	2120	2140	2160	2180	2200	2220	2240	2260	2280	2300
Economic And Policy Variables															
Carbon Price (2019 $ Per T Co2)	5.760	175.883	430.777	499.779	489.883	559.287	548.213	537.357	526.717	516.287	506.064	496.043	486.221	430.518	412.791
Emissions Control Rate	0.050	0.480	0.900	1.000	1.000	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.032	1.018
Social Cost Of Carbon $/Tco2	1874.830	2181.924	2130.022	2056.885	1963.047	1841.895	1694.388	1529.578	1350.476	1162.393	972.588	788.778	614.133	509.737	488.220
Output, Net Net Trill 2019$	135.144	267.537	464.778	696.565	969.345	1274.704	1611.593	1967.902	2335.646	2706.941	3074.336	3431.443	3773.059	4100.714	4400.497
Population	7752.90	9056.48	9840.77	10287.37	10534.29	10668.66	10741.17	10780.12	10800.99	10812.16	10818.14	10821.33	10823.04	10823.95	10824.44
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, Gross-Gross, 2019$	135.882	272.974	486.996	729.808	1008.002	1327.908	1668.500	2027.431	2396.226	2766.861	3132.172	3486.163	3824.082	4142.500	4439.371
Capital Stock, 2019$	302.003	730.545	1636.377	2550.893	3549.964	4759.921	5995.832	7299.659	8641.507	9992.754	11327.311	12623.090	13861.980	15030.959	16123.772
Savings Rate, Fraction Gross Output	0.089	0.379	0.387	0.368	0.356	0.353	0.345	0.338	0.332	0.327	0.323	0.320	0.317	0.314	0.312
Gross Investment, 2019$	12.054	101.478	179.739	256.229	344.652	450.031	555.232	664.462	775.359	885.654	993.399	1096.994	1195.123	1287.218	1372.638
Y Gross-Net, 2019$	135.150	270.171	481.154	721.429	996.588	1313.613	1653.889	2013.206	2383.136	2755.576	3123.167	3479.647	3819.956	4138.909	4435.523
Consumption Per Capita, 2019$	15.877	18.336	28.965	42.804	59.301	77.299	98.347	120.911	144.458	168.448	192.356	215.727	238.190	259.932	279.724
Consumption	123.089	166.059	285.039	440.336	624.693	824.673	1056.360	1303.440	1560.287	1821.286	2080.937	2334.449	2577.936	2813.496	3027.859
Damages, 2019$	0.733	2.803	5.842	8.379	11.414	14.295	14.612	14.225	13.090	11.285	9.005	6.516	4.127	3.591	3.848
Abatement, 2019$	0.006	2.633	16.376	24.864	27.243	38.909	42.296	45.304	47.490	48.635	48.831	48.204	46.897	38.195	35.026
Climate Variables															
Total Co2 Emissions, Gtco2/Year	43.215	33.192	8.669	0.000	0.000	-13.661	-15.118	-16.500	-17.633	-18.415	-18.858	-18.988	-18.845	-5.961	-3.250
Cumulative Co2 Emissions, Gtc	633.538	849.425	979.703	997.766	997.766	997.766	920.224	834.884	742.400	644.455	542.947	439.676	336.270	264.122	238.227
Atmospheric Concentrations Gtc	886.513	980.624	1002.157	974.443	955.395	925.980	864.798	810.174	759.511	712.615	669.444	629.994	594.410	590.833	594.290
Atmospheric Temperaturer (Deg C Above Preind)	1.247	1.721	1.860	1.820	1.807	1.762	1.589	1.423	1.255	1.085	0.911	0.734	0.558	0.500	0.500
Industrial Co2 Gtco2/Yr	37.610	31.179	8.415	0.000	0.000	-13.590	-15.071	-16.469	-17.613	-18.402	-18.849	-18.983	-18.841	-5.960	-3.250

B.8 LIM_2C

Year	2020	2040	2060	2080	2100	2120	2140	2160	2180	2200	2220	2240	2260	2280	2300
Economic And Policy Variables															
Carbon Price (2019 $ Per T Co2)	5.760	131.183	188.321	259.400	341.759	410.710	476.888	537.336	526.717	516.287	506.064	496.043	486.221	476.593	467.156
Emissions Control Rate	0.050	0.400	0.537	0.664	0.798	0.907	1.008	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100
Social Cost Of Carbon $/Tco2	89.815	144.675	207.041	279.519	358.262	438.644	517.565	591.126	656.387	711.894	755.005	784.015	798.294	798.092	784.249
Output, Net Net Trill 2019$	135.144	263.129	421.809	615.573	840.287	1093.364	1370.031	1666.333	1983.510	2304.667	2623.630	2934.915	3233.987	3517.379	3782.693
Population	7752.90	9056.48	9840.77	10287.37	10534.29	10668.66	10741.17	10780.12	10800.99	10812.16	10818.14	10821.33	10823.04	10823.95	10824.44
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, Gross-Gross, 2019$	135.882	267.590	432.129	635.542	874.006	1142.634	1435.505	1746.229	2067.280	2390.389	2709.291	3018.673	3314.323	3593.150	3853.118
Capital Stock, 2019$	302.003	683.614	1098.609	1608.712	2206.657	2884.450	3631.708	4437.643	5282.361	6136.999	6984.901	7811.364	8604.333	9354.697	10056.251
Savings Rate, Fraction Gross Output	0.385	0.285	0.270	0.260	0.254	0.249	0.246	0.243	0.240	0.237	0.234	0.232	0.230	0.228	0.227
Gross Investment, 2019$	52.043	74.871	113.754	160.064	213.191	272.386	336.727	405.299	475.317	545.277	613.906	680.124	743.087	802.198	857.085
Y Gross-Net, 2019$	135.150	264.732	425.596	623.032	853.445	1113.635	1399.046	1705.352	2024.482	2346.685	2665.868	2976.655	3274.632	3556.461	3819.864
Consumption Per Capita, 2019$	10.719	20.787	31.304	44.278	59.529	76.952	96.200	116.978	139.635	162.723	185.774	208.365	230.148	250.849	270.278
Consumption	83.101	188.258	308.055	455.508	627.096	820.977	1033.304	1261.035	1508.193	1759.391	2009.724	2254.791	2490.899	2715.181	2925.608
Damages, 2019$	0.733	2.858	6.533	12.510	20.561	28.999	36.459	40.877	42.799	43.704	43.422	42.018	39.691	36.690	33.254
Abatement, 2019$	0.006	1.603	3.787	7.459	13.158	20.271	29.014	39.018	40.971	42.018	42.238	41.740	40.645	39.082	37.171
Climate Variables															
Total Co2 Emissions, Gtco2/Year	43.215	37.613	35.781	30.682	21.099	10.948	-1.071	-14.212	-15.215	-15.911	-16.313	-16.443	-16.333	-16.021	-15.545
Cumulative Co2 Emissions, Gtc	633.538	864.599	1066.201	1252.970	1402.550	1497.851	1533.615	1501.243	1421.521	1336.962	1249.215	1159.845	1070.270	981.724	895.233
Atmospheric Concentrations Gtc	886.513	994.901	1090.235	1175.172	1231.803	1252.418	1232.009	1166.800	1093.294	1026.874	966.012	910.878	861.597	818.016	779.689
Atmospheric Temperaturer (Deg C Above Preind)	1.247	1.755	2.088	2.383	2.605	2.706	2.707	2.598	2.444	2.296	2.150	2.004	1.859	1.716	1.578
Industrial Co2 Gtco2/Yr	37.610	35.289	34.604	30.121	20.879	10.882	-1.067	-14.181	-15.195	-15.898	-16.304	-16.437	-16.330	-16.019	-15.543

B.9 LIM_1.7C

Year	**2020**	**2040**	**2060**	**2080**	**2100**	**2120**	**2140**	**2160**	**2180**	**2200**	**2220**	**2240**	**2260**	**2280**	**2300**
Economic and policy variables															
Carbon price (2019 $ per t CO2)	5.760	175.883	307.604	385.896	467.988	522.072	548.213	537.357	526.717	516.287	506.064	496.043	486.221	476.593	457.332
Emissions control rate	0.050	0.480	0.729	0.851	0.972	1.054	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.100	1.085
Social cost of carbon $/tCO2	187.833	274.083	350.683	430.714	507.673	574.838	628.943	668.682	691.701	696.095	681.816	650.908	607.796	560.004	519.584
Output, net net trill 2019$	135.144	272.995	436.695	640.922	880.567	1153.078	1455.214	1779.875	2115.423	2454.714	2790.917	3118.176	3431.789	3728.236	4006.154
Population	7752.90	9056.48	9840.77	10287.37	10534.29	10668.66	10741.17	10780.12	10800.99	10812.16	10818.14	10821.33	10823.04	10823.95	10824.44
TFP	5.842	8.075	10.672	13.570	16.694	19.962	23.294	26.615	29.863	32.987	35.950	38.726	41.299	43.661	45.814
Output, gross-gross, 2019$	135.882	278.667	451.475	665.982	918.435	1203.189	1513.832	1841.897	2179.292	2518.637	2853.281	3177.654	3487.397	3779.353	4051.417
Capital stock, 2019$	302.003	782.588	1271.285	1880.213	2603.239	3426.249	4335.317	5301.103	6298.173	7304.875	8300.864	9268.915	10195.44	11070.56	11887.35
Savings rate, fraction gross output	0.465	0.316	0.303	0.293	0.287	0.282	0.277	0.272	0.268	0.264	0.261	0.259	0.256	0.254	0.253
Gross investment, 2019$	62.873	86.234	132.346	188.067	252.615	324.618	402.547	483.603	566.156	648.431	728.903	806.337	879.808	948.689	1012.416
Y gross-net, 2019$	135.150	275.683	445.478	655.827	903.612	1184.600	1493.589	1821.033	2158.614	2498.986	2835.399	3162.114	3474.557	3769.343	4043.910
Consumption per capita, 2019$	9.322	20.622	30.927	44.020	59.610	77.654	98.003	120.247	143.438	167.060	190.607	213.637	235.791	256.796	276.572
Consumption	72.270	186.761	304.349	452.855	627.952	828.460	1052.667	1296.272	1549.268	1806.283	2062.014	2311.839	2551.980	2779.547	2993.738
Damages, 2019$	0.733	2.984	5.996	10.156	14.823	18.589	20.243	20.863	20.677	19.652	17.881	15.540	12.841	10.010	7.507
Abatement, 2019$	0.006	2.688	8.783	14.905	23.045	31.523	38.375	41.158	43.191	44.272	44.483	43.938	42.768	41.107	37.757
Climate variables															
Total CO2 Emissions, GTCO2/year	43.215	33.843	21.817	14.257	3.098	-6.646	-13.721	-14.993	-16.038	-16.764	-17.179	-17.308	-17.186	-16.851	-13.972
Cumulative CO2 emissions, GtC	633.538	870.519	1018.453	1123.748	1180.007	1185.219	1129.579	1052.089	968.020	878.902	786.468	692.366	598.091	504.935	415.555
Atmospheric concentrations GtC	886.513	994.500	1041.500	1070.625	1066.495	1035.214	972.234	912.838	858.034	807.541	761.341	719.316	681.223	646.800	619.338
Atmospheric temperaturer (deg c above preind)	1.247	1.758	1.957	2.097	2.158	2.111	1.964	1.808	1.654	1.500	1.344	1.188	1.031	0.874	0.731
Industrial CO2 GtCO2/yr	37.610	31.830	21.129	14.009	3.067	-6.608	-13.674	-14.962	-16.018	-16.751	-17.170	-17.303	-17.182	-16.849	-13.971