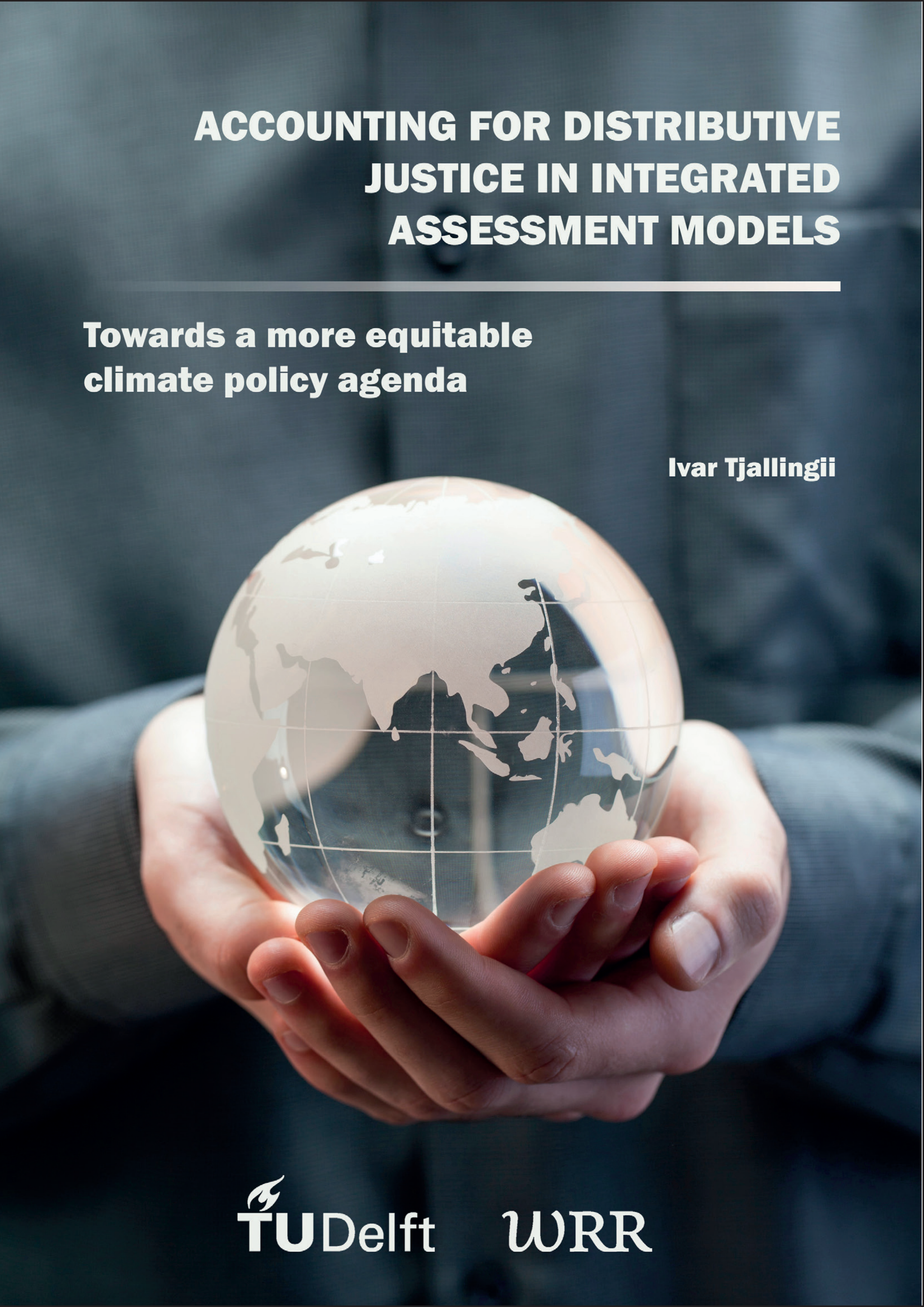
ACCOUNTING FOR DISTRIBUTIVE JUSTICE IN INTEGRATED ASSESSMENT MODELS

Towards a more equitable climate policy agenda

Ivar Tjallingii



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ACCOUNTING FOR DISTRIBUTIVE JUSTICE IN INTEGRATED ASSESSMENT MODELS

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https://github.com/itjallingii/PyRICE2020

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Ivar Tjallingii,
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SUMMARY

Without large scale emission reductions, atmospheric warming is expected to rise towards 2 - 5 °C at the end of this century [Masson-Delmotte et al., 2018]. Atmospheric warming of 2 °C and beyond will significantly negatively impact all life on earth, both on current and future generations. Economic inequalities are an indicator of exposure to environmental hazards. Therefore population groups at the lower end of the income hierarchy are more vulnerable to the changing climate [Hallegatte and Rozenberg, 2017].

Integrated Assessment Models (IAMs) are used to map the changing climate's impact on the economy. But these models have a limited ability to represent the impact on today's and future vulnerable people [Dennig et al., 2015]. Many influential IAMs use highly aggregated outcomes masking significant relative differences in economic effects across heterogeneous populations and time. This has resulted in that insufficient attention has been placed on the people's position at the bottom of the income hierarchy within current abatement strategies. Furthermore, current IAMs lack a thorough analysis of climate uncertainties to generate robust abatement strategies. Therefore many IAM studies undervalue the need for more stringent CO_2 abatement policies to prevent significant climate impacts on low-income countries and their future generations.

In previous literature, alternative distributive principles have been proposed for IAM optimization to overcome the inequities that arise due to the Utilitarian principle. However, no overarching and comparative study of the performance of various distributive principles under the effect of deep uncertainty has been carried out in previous research. Therefore the following main research question has been formulated for this thesis:

MAIN RESEARCH QUESTION

What is the effect of applying alternative distributive principles to the RICE model on global CO_2 abatement pathways under deep uncertainty?

This research has provided an overview of applying four of the most known distributive principles used by the IAM community; the Prioritarian, Egalitarian, Sufficitarian, and Utilitarian principle to the RICE model. The RICE model has been transformed into the stochastic simulation model PyRICE. The RICE model has been extended with a disaggregated income distribution within regions and climate uncertainties. The performance of alternative principles has been analyzed through the execution of the MORDM method. Using a Many Objective Evolutionary Algorithm, alternative abatement strategies have been generated. Generated strategies show big differences in abatement trajectories if more emphasis would be placed on the position of the worst-off (Prioritarian), minimizing climate extremes (Sufficitarian) and focusing on an equal distribution of climate impact and consumption (Egalitarian). Sufficitarian strategies have the most stringent abatement targets focusing on reaching net-zero emissions around 2065. Prioritarian strategies focus on reaching zero-emission in the range of 2055-2105. Egalitarian policies enforce slow climate abatement to decrease inequality. Utilitarian strategies focus on reaching net-zero emissions around 2135.

The uncertainty analysis results, based on the Shared Socioeconomic Pathways, have shown that the Nordhaus policy and Utilitarian policies have high exposure to climate change extremes in many scenarios. Furthermore, Utilitarian policies contribute to a widening of economic inequalities. Under the Nordhaus policy, the re-introduction of poverty levels present similar to the 20th-century is possible. Contrary to this, the Prioritarian and especially the Sufficitarian strategies have a good performance against extreme climate change. Furthermore, these principles deliver similar or higher average performance compared to Utilitarian policies. This means that income decline is prevented within these

strategies. Sufficitarian policies focus on preventing climate extremes, whereas Prioritarian policies perform better across optimistic economic scenarios. Thus, there is a trade-off between preventing the worst-cases of climate impact or allowing more economic growth for the worst-off. Most Egalitarian policies perform worse than Utilitarian policies. Because they are not economically optimal and lead to unacceptable risk to climate change.

The Sufficitarian principle is an example of a partly utilitarian-based principle with correction at the bottom of the income distribution. Therefore economic optimality is still an essential factor in obtaining effective abatement strategies. This means that the Utilitarian principle is not to be abandoned entirely within IAMs. Instead, three recommendations have been made to improve Integrated Assessment Models' future usage for the generation of emission abatement strategies. Together, these three reparations have the potential to overcome the problems of inequity arising within the utilitarian-led IAM. Furthermore, the results have shown that more robust pathways can be obtained.

- Make use of a variety of Sufficitarian and Prioritarian objectives within IAMs to correct the utilitarian principle at the bottom of the income distribution
- Expand the usage of IAMs towards evaluating the equity of emission abatement trajectories
- Utilize a wide variety of scenarios to choose robust and effective abatement strategies

If policymakers focused on Prioritarian and Sufficitarian goals, abatement strategies should aim to reach net zero-emission in 2055 - 2085. To achieve these targets, current pledges within the Paris Agreement are not sufficient. Therefore more extensive emission reduction pledges are needed, which should be implemented in the coming 10 years. This is because negative emission techniques have a limited capacity to prevent the impact of CO_2 overshoots. Once sea level rise is triggered, it will have a continued impact on lower-laying low-income regions. Therefore, more should be done to adhere to the emission pathway of *a global warming of 1.5* set out by the IPCC. This pathway is consistent with the most robust Sufficitarian and Prioritarian pathways found in this research.

The results have also shown that considerable climate impact is still a significant possibility even in the most robust policies. This indicates that only immediate emission reductions will not be enough to reach an equitable global climate strategy in all scenarios. The model results have shown that if policymakers succeed in strengthening the worst-off's resilience, this can prevent many of the worst-case outcomes. To protect the vulnerable, extra focus should be on reducing economic inequalities and improve the economic resilience at the bottom of the income hierarchy in all regions. The task at hand is broader than just the rich regions that have to support the low-income regions. Even in high-income countries, climate hazards such as hurricanes events magnify existing economic inequalities [Chancel, 2020].

To support the transition in low-income regions, the developed world needs to recognize its place in the global climate regime. The financial transfers called for by the IPCC are needed to reduce existing economic inequalities between and within regions [Masson-Delmotte et al., 2018]. With faster emission abatement in place and reduced economic inequalities, through international redistribution and equitable growth within nations, the world's starting position to withstand incoming climate impact will be significantly improved.

CONTENTS

III SIMULATION RESULTS

IV ETHICAL REFLECTION

V APPENDICES

LIST OF FIGURES

I

SETTING THE STAGE

1

INTRODUCTION

The current level of global warming has increased to around 1.0 °C. Without large scale emission reductions, atmospheric warming is expected to rise towards 2 - 5 °C at the end of this century [Masson-Delmotte et al., 2018]. As expressed by the IPCC in *a global warming of 1.5 °C*, atmospheric warming of 2 °C and beyond will result in a significant negative impact on all life on earth both on current and future generations.

Some effects of atmospheric warming will be felt in the near term, such as the intensifying of heatwaves and droughts [Masson-Delmotte et al., 2018]. There is consensus that the global South, consisting of the bulk of the low-income countries, will be hit hardest by the impacts of the changing climate [Edenhofer, 2015; Mendelsohn et al., 2006; Dennig et al., 2015]. Extreme weather events will become more intense and frequent as global warming evolves. Especially when droughts, floods, and heatwaves will occur in series, these weather extremes can push exposed populations further into poverty [Masson-Delmotte et al., 2018]. This injustice is amplified because 10% of today's wealthiest people cause more than 50% of current emissions [Gore, 2015]. Not only have high-income countries historically contributed most to climate change, they also possess most of the resources to mitigate and adapt to the changing climate. While poverty levels have been declining rapidly in the last 50 years, climate change has the potential to reverse these developments [Chancel, 2020; Masson-Delmotte et al., 2018]. To overcome these inequities, burden sharing principles have been proposed within climate negotiations [Dellink et al., 2008]. However, up to now, little has been done in current climate policies to implement redistributive policies on a significant scale [Okereke and Coventry, 2016].

The lack of emphasis on the low-income regions within the current climate policy regime is also reflected in how climate impacts are calculated in climate impact models. Models used to estimate the effect of the changing climate often have a limited ability to represent the impact on today's and future vulnerable people [Rao et al., 2017]. Integrated Assessment Models (IAMs) are used to map the impact of the changing climate on the economy [Weyant, 2017]. Many influential IAMs have aggregated outcomes masking significant relative differences in economic effects across heterogeneous populations and time [Aldy and Stavins, 2020; Dennig et al., 2015].

Some climate impacts, such as sea-level rise, will have a delayed effect. Until 2100, global sea-level rise will likely be limited to 0.1-0.7 meter. These effects can already be hazardous for lower laying nations such as the small island states [Wong, 2011]. But these effects seem marginal with the possible impacts of sea-level rise beyond 2100, where a sea-level rise of 1 to 5.5 meters is imaginable [Jevrejeva et al., 2012]. Furthermore, sea-level rise will potentially continue even when atmospheric warming is reduced [Masson-Delmotte et al., 2018]. Therefore, sea-level rise is an example of the unequal intergenerational distributed impacts of climate change [Kowarsch, 2016].

In all, this raises the question of how we, as the current global community, should mitigate our CO_2 emissions. Should the world reduce emissions as fast as possible, thereby giving up a significant part of our welfare to improve future generations' welfare? Or should the world follow a more moderate approach by mitigating at a slower pace preserving our welfare level but possibly risking extreme climate impacts for current and future generations? What to say that those who pay for climate action are mostly living in affluent countries. In contrast, the beneficiaries of climate actions are primarily people located in less well-off regions and generations who are not born yet?

1.1 INTEGRATED ASSESSMENT MODELS FOR CLIMATE POLICY

IAMs are used to estimate 'optimal' emission abatement pathways calibrated against more detailed climate change projections. Damage functions are used which model the estimated impact on the economic system [Frisch, 2013] relative to a certain level of warming. Within IAM analysis, 'optimal' abatement policies balance out the marginal damages per ton CO_2 against the marginal cost of CO_2 abatement policies. Climate policies are said to be 'optimal' when they maximize aggregated welfare by minimizing climate mitigation costs plus the damages resulting from the remaining climate change [Weyant, 2017]. Complex IAMs such as the IMAGE model are used to evaluate global emission abatement strategies' effectiveness within international climate governance. 'Simple' IAMs, such as the DICE model, have been used by the Obama administration to determine the internalized social cost of carbon [Aldy and Stavins, 2020]. This formed one of the inputs to draft CO_2 tax policies in the United States. In general, IAMs form a vital part of the scientific knowledge base used within international climate governance [Kowarsch, 2016].

1.2 CRITICS ON IAMS

Although their prominent place in climate governance, IAM's position within climate science is far from undisputed. Firstly, Kowarsch [2016]; Beck and Krueger [2016]; Jafino et al. [2020] have pointed out that IAMs hold strong normative assumptions within their model structure. Many of the problems in IAMs arise from the dominant use of the Utilitarian perspective. The Utilitarian principle aims at the maximization of aggregated welfare. The Utilitarian perspective is indifferent to the shape of the welfare distribution across time and space [Adler, 2019; Jafino et al., 2020]. High levels of inequality are still reflected in the distribution of consumption per capita across and within nations [Chancel, 2020]. The dominant Utilitarian perspective implies that these unequal distributions are not only accepted but also widened. Dennig et al. [2015] has shown that the welfare of the lowest income groups in the global South could eventually decline under the optimal Nordhaus pathway. This is the same policy that has been used by the Obama government to determine the 'optimal' social cost of carbon [Aldy and Stavins, 2020]. Thus 'optimal' Utilitarian climate policies possibly worsen the position of low-income countries by undervaluing the need for more stringent emission abatement pathways [Dennig et al., 2015].

Besides the issues with normative assumptions in IAMs, climate models are sensitive to model assumptions on the development of atmospheric warming and the resulting effect on the economy. Critics argue that there is little knowledge of the earth's climate sensitivity to higher GHG levels [Stanton et al., 2009; Beck and Krueger, 2016]. Furthermore, there is little knowledge of the level of damages that will occur because of a certain level of induced warming [Weyant, 2017; Weitzman, 2009; Frisch, 2013]. Many IAMs only use one scenario to base their recommendations, which exposes their results to uncertainty [Stanton et al., 2009]. Secondly, Keen [2020]; Storm [2017] point out that IAMs severely underestimate climate change impacts. Because in IAMs limited emphasis is placed on future generations' welfare due to the chosen discount rates. This practice provides a false sense of security towards economists, which in turn advocate for slow climate action. Therefore, estimates for the social cost of carbon vary widely between models [Weyant, 2017]. Thus, questions have been raised around IAMs regarding their usability to generate effective and robust climate policies [Beck and Krueger, 2016].

1.3 IMPROVING THE USAGE OF IAMS

Although Integrated Assessment Models face numerous problematic issues, they represent a significant part of the limited toolkit to evaluate climate change policies in a systematic way [Frisch, 2013; Beck and Krueger, 2016]. To overcome the inequities arising from using the Utilitarian distribution in models, IAMs should account for the population heterogeneity. This enables IAMs to properly represent the risks faced by vulnerable populations [Rao et al., 2017]. This implicates increasing the model resolution and broadening the aggregated utility perspective. Novel methods within IAM studies such as many objective exploratory algorithms could show trade-offs between policy objectives from different distributive objectives [Ciullo et al., 2020]. Furthermore, IAMs could be used in a less static way to obtain more robust climate pathways [Frisch, 2013]. Lingeswaran [2019]; Lamontagne et al. [2019] have shown that IAMs can be used for policy and scenario discovery to account for deep uncertainties present within climate change. Their research reveals insights that offer policymakers more than just one 'optimal' CO_2 trajectory [Lamontagne et al., 2018].

1.4 RESEARCH AIM AND OUTLINE

The previous paragraphs have indicated that IAMs face numerous challenges, such as the inequities arising from the Utilitarian perspective and the exposure to uncertainties. This thesis will explore novel methods to overcome both of these challenges. By using alternative distributive principles and robust decision making approaches in IAMs, more effective, robust, and equitable abatement strategies can be generated. This thesis aims to give a broad overview of which alternative distributive principles can be applied and what is their usability and performance for the generation of abatement pathways. This information can then be used by policymakers to reflect on current emission abatement pathways' distributive effects. Furthermore, it can show policymakers what they can do to make emission abatement pathways more equitable and robust.

This thesis is structured as follows, in chapters 2 and 3, the research gap and the research method are defined, including the main research question. This thesis is then structured in three parts: *Methods*, *Simulation results* and *Ethical reflection*. In *Methods*, alternative distributive principles are chosen to be implemented in the RICE model via a literature review. The model structure, extra model components, and the implementations of the alternative principles into PyRICE are highlighted in chapters 5, 6 & 7. Chapter 8 introduces the simulation methods used in this research. *Simulation results* entails generating alternative abatement strategies by using alternative principles in chapter 9. Generated strategies are stress-tested by applying them to an uncertainty analysis (chapter 10). Model outcomes of interest are identified by applying scenario discovery techniques in chapter 11. In *Ethical reflection*, a reflection on the model outcomes is performed. Chapter 12 sets out the limitations of this research. Next, the implications for Integrated Assessment Models (chapter 13) and implications for policymakers (chapter 14) will be highlighted. Chapter 15 consists of the conclusion, which includes answering the main research question.

2 BACKGROUND AND CONTEXT

This chapter entails the literature study that will identify the research gap. Section 2.1 states the usage of IAMs within global climate governance. Section 2.2 highlights the choice of the RICE model as example IAM in this research. Section 2.3 introduces concepts of distributive justice present within Integrated Assessment Models. Section 2.4 examines relevant issues within IAM-modelling related to spatial (section 2.4.1) and temporal distributive justice (section 2.4.2) while section 2.4.3 reviews literature that apply alternative distributive principles and robust approaches to IAMs. Section 2.5 entails the identified literature gap.

2.1 GOALS OF IAMS FOR POLICY MAKING

More than 20 IAMs exist within the climate change research [Beck and Krueger, 2016]. There are three main goals within IAM-analysis, namely policy optimization, policy evaluation, and policy guidance [Füssel, 2010]. Integrated assessment models differ in model resolution, e.g. the level of detail of the model outputs. This is related to the underlying model goal as policy optimization models require a low resolution for optimization purposes, whereas policy evaluation models offer high-resolution spatial outputs [Frisch, 2013]. Furthermore, models differ in how they treat uncertainty. Deterministic models use best-guess values for model parameters [Beck and Krueger, 2016] while stochastic models use probability distributions for uncertain parameters. Models with the most thorough adoption of uncertainty make use of multiple distributions to sample uncertainty inputs [Lingeswaran, 2019; Lamontagne et al., 2019]. This is known as the exploratory modelling approach [Walker et al., 2013]. Although this practice is underused within IAM modelling [Frisch, 2013; Weaver et al., 2013].

Within IAMs, a division can be made between 'simple' and 'complex' IAMs. The division is made regarding model complexity, e.g. the relative amount of model inputs and model parameters that are used within the model [Frisch, 2013]. Often complex IAMs use extensive sub-models to represent sub-systems, such as a climate model. Whereas simple IAMs only use a few parameters to represent similar sub-systems. Complex IAMs, like the IMAGE model developed by PBL, offer a significantly higher resolution of outputs such as local geospatial climate impacts [Stehfest et al., 2014]. Simple IAMs, like the DICE/RICE model, only offer aggregated outcomes for the whole world (DICE) or continental sub-regions (RICE) [Nordhaus, 2014].

The Intergovernmental Panel on Climate Change (IPCC) uses complex IAMs to evaluate the world's future state under climate change. Within the IPCC special report on 'Global warming of 1.5 °C', CO_2 abatement pathways of multiple global and regionally aggregated IAMs are summarized and statistically analysed. The ensemble of predictions is used to draft confident estimates for policy alternatives. For this purpose, the IPCC uses 'complex' IAM models such as the IMAGE model, the GCAM, and the REMIND model [Masson-Delmotte et al., 2018].

2.2 SELECTION OF INTEGRATED ASSESSMENT MODEL

A significant advantage of using a simple IAMs like the DICE/RICE model over complex IAMs is its short run time. This enables exploratory approaches where many different parameters are sampled as input for the model across many separate runs. Although the perceived 'predictive power' of DICE/RICE is limited compared to the complex models [Masson-Delmotte et al., 2018], many of the simple and complex models use the same structural elements such as discounting and utility functions to estimate optimal climate pathways [Beck and Krueger, 2016]. Therefore, using a 'simple' IAM as an example model in this thesis can still reveal the performance of alternative distributive principles. Similar model components could then be adopted in more detailed complex climate models.

Compared to other simple IAMs, extensive research on the DICE/RICE model and possible alternative applications exist. Compared to the DICE model, the RICE model offers regional disaggregated outputs, which enables analysis of the distribution of welfare across space. Due to the limited model complexity, the regional aggregated outcomes to assess distributive consequences of climate policies and the low computational burden and the wide usage of the RICE/DICE model in the IAM literature, the RICE model will be taken as example IAM for this thesis.

2.3 DISTRIBUTIVE JUSTICE AND IAMS

Within ethics, distributive justice focuses on the socially just allocation of resources [Lamont and Favor, 2017]. Distributive justice lies at the core of IAM studies as IAMs try to estimate an optimal distribution of climate benefits and burdens over time [Fleurbaey et al., 2019]. Within distributive justice, three essential questions are relevant when assessing the fairness of burdens and benefits [Jafino et al., 2020]:

1. What metric is being distributed e.g. *the unit of justice*, for example, the total economic damages as a result of climate change
2. Over which entities should the selected unit be distributed, e.g. *the scope of distribution*, for example, the whole world or specific groups of entities within regions
3. Who should receive which quantity of what is being distributed, e.g. climate benefits over time, referred to as *the shape of distribution*

Regarding the unit of justice, most IAMs estimate climate trajectories by balancing climate impacts and the investment burdens caused by mitigating CO_2 emissions [Kowarsch, 2016]. This approach is embedded in consequentialism, which assesses only the outcome of an action when passing a verdict on the rightness of that action [Konow, 2003]. Utilitarianism is a specific example of the consequentialistic approach, which assumes that the unit of justice can be represented by a single quantity such as utility or welfare to compare actions which each other [Jafino et al., 2020]. Estimating all 'real' impacts of climate change in one metric can be troublesome as it is difficult to monetize non-economic values. The result is that in current IAMs, the loss of nature due to climate change or economic development is omitted from the analysis [Kowarsch, 2016]. Although this issue is very relevant and must be addressed, it will not form the focus of this thesis work. Thus, this research takes economic metrics such welfare and economic consumption per capita (CPC) as a unit for analysing the distribution of climate burdens and benefits.

The scope of justice, to whom the distribution relates, can be split up in the temporal distribution (intergenerational) and the spatial distribution (intragenerational). Regarding the temporal distribution, the question is how climate change damages should be distributed across generations. This is also known as intergenerational distributive justice [Jafino et al., 2020]. Within IAMs, the climate change benefits and burdens are often divided across generations using discount methods with the appropriate discount rate [Fleurbaey et al., 2019]. To describe the spatial distribution of climate change impacts within generations (intra-generational justice) often groups are drawn using income ratios or geospatial divisions [Jafino et al., 2020].

The third question, the shape of the distribution, regards the normative question of what should be a rightness division of what is being distributed [Konow, 2003]. There are an extensive amount of distributive principles that prescribe a just division, examples are maximizing total utility, prioritizing the worst-off (the Rawlsian approach) and enforcing a minimum level of welfare (the Sufficitarian approach) [Caney, 2020; Fleurbaey et al., 2019]. There is no objective way to decide which distribution principle is most fair. This is an example of conceptual normative uncertainty Jafino et al. [2020].

2.4 NORMATIVE ASSUMPTION WITHIN IAMS

The assumptions packed in IAMs shape the need for global policymakers for speeding up or slowing down global climate change mitigation efforts. For example regarding intergenerational justice, assumptions such as chosen discount rates determine how pressing the future climate impact weighs on the speed of our current emission abatement efforts [Dasgupta, 2008]. The next paragraphs explore relevant concepts related to temporal and spatial distributive justice. Section 2.3.1 focuses on issues related to temporal distributive justice or intergenerational justice. Within section 2.3.2, concepts related to spatial or intragenerational justice are explored. Section 2.3.3 focuses on how recent IAM studies try to improve distributive justice within IAMs by applying alternative distributive principles to IAMs.

2.4.1 Issues regarding intergenerational justice

The most important and disputed parameter regarding intergenerational justice within IAMs is the discount rate [Frisch, 2013; Kowarsch, 2016; Weyant, 2017]. In short, discount rates are used to evaluate current investments' economic efficiency relative to climate damages in the future. The social discount rate R set by using formula (2.1).

$$R = \delta + \eta * g \tag{2.1}$$

Where g is the expected future growth rate per capita consumption, δ forms the pure time preference, and η is the elasticity of utility [Weyant, 2017]. Discounting is normative because the selected parameter values reflect the relative importance of those living in the future compared to generations living now [Kowarsch, 2016]. Setting the discount rate proves to be difficult: if we do care about future generations, then to what extent? Do we value them significantly lower because we face the problem of climate mitigation now, and they mostly reap the benefits of climate mitigation? Or do we value them as equal to ourselves because they had no influence on the state of the world as they inherited it? In the former, we should pick a high discount rate to highly discount their utility in the future. Whereas in the latter, we should pick the discount carefully to reflect the relative value of present and future consumption [Fleurbaey et al., 2019]. Therefore, there is no objective way to set the discount rate [Kowarsch, 2016].

2.4.2 Issues regarding intragenerational justice

The most significant root of criticism based on intragenerational justice is the dominant use of the aggregated Utilitarian perspective within climate impact modelling. The general Utilitarian welfare function in IAMs has the following shape:

$$W = \sum_{t=0}^{T} \sum_{i=1}^{I} U(C_i t)(1+\rho)^{-t} \tag{2.2}$$

The Utilitarian welfare function used in most IAMs consists of a term that devalues welfare over time via discounting and another part that evaluates increases in consumption with marginal utility weights [Adler et al., 2017]. This perspective neglects differences in economic impacts across heterogeneous populations [Aldy and Stavins, 2020]. What is optimal in an aggregated perspective is not necessarily optimal for people at the bottom of the income hierarchy [Adler et al., 2017; Dennig et al., 2015]. These problems are often ignored by the persuasion of many IAM economist that distributional issues belong to a different realm of science [Arrow et al., 2014]. A third problem relates to the economic accounting logic within disaggregated IAMs, which implies that each 'dollar' is valued equally. This implicates that climate damage in low-income countries is valued significantly lower than damages occurring in high-income countries [Frisch, 2013]. These problems of distributive justice are often not made transparent when using these models to formulate climate policies [Kowarsch, 2016].

2.4.3 Alternative distributive principles within IAMs

In the preceding paragraphs, multiple issues of spatial and temporal distributive justice have been identified. The problems of neglecting spatial and temporal distributive justice within IAMs are often interlinked. Attempts to improve spatial and temporal distributive justice are therefore often implemented in conjunction with each other like done by Adler et al. [2017]; Dietz and Asheim [2012]; Arrow et al. [2014]; Freeman et al. [2015]. Adler et al. [2017] implemented a non-discounted Prioritarian social welfare function (SWF) which resulted in substantially different social cost of carbon (SCC) rates compared to the normal discounted SCC. Dietz and Asheim [2012] proposes a form of conditional discounting, namely Sustainable Discounted Utility (SDU), which only considers discounting when future welfare is higher than the present utility. Arrow et al. [2014] proposes that we should use Declining Discount Rates (DDR) to account for uncertainty and adverse shocks of consumption in the future. Freeman et al. [2015] implemented DDR-schemes in the DICE model and found an increase of the Social Cost of Carbon (SCC) from 10 $ to 26 $. Although some research focuses on dealing with uncertainty within approaches for discounting. Little research has been found that considers the robustness of alternative distributive principles.

Another approach is to implement disaggregated model outputs within IAMs to serve as an extra objective function. This can have a significant effect on the estimated optimal CO2 abatement trajectories. Dennig et al. [2015] extended the RICE model with a quintile population distribution for every region. Dennig et al. [2015] showed that when emission pathways are optimized for the lowest income group, optimal climate pathways deviated significantly from Nordhaus [2014] estimates. The resulting trajectories are so conservative that they approach the trajectories of the Stern Review Stern [2007], which uses a much lower discount rate. Little research has been found that effectively compares a broad range of distributive principles.

Lastly, the generation process of abatement strategies can be improved using Many Objective Evolutionary Algorithms to determine Pareto optimal climate abatement strategies. Traditionally, IAMs use social welfare functions with a one-dimensional unit of justice, e.g., aggregated utility. This is problematic because aggregation can result in an unknown a priori biased decision problem [Ciullo et al., 2020; Franssen, 2005]. Through aggregation, one objective becomes dictatorial without knowing in advance which one. To overcome this, Many Objective Evolutionary Algorithms (MOEAs) can be used that do not aggregate over multiple objectives. Instead, MOEAs optimize multiple objectives. The advantage is that MOEAs can show the underlying trade-offs structures within decision problems. This is one reason why MOEAs are frequently used in water management risk studies [Ciullo et al., 2020]. Within IAM studies, multi-objective approaches are still heavily underused. Most IAMs' only objective is to maximize aggregated utility, or in the case of a more equitable approach, to maximize a single metric resulting from an alternative social welfare function Adler et al. [2017]; Dietz and Asheim [2012]. Within the literature, only one study was found which implemented a multi-objective version of the DICE model, which minimized temperature deviations while maximizing social welfare Heris and Rahnamayan [2020].

One benefit of the multi-objective approach is the possibility of combining multiple different distributive principles in one objective function. For example, to combine Sustainable Discounting by Dietz and Asheim [2012] and the Prioritarian SWF by Adler et al. [2017]. Or to minimize intragenerational inequality while prioritizing the intergenerational distribution of climate impact. Other objectives are also possible, for example, to prioritize regions with the relative highest climate damage [Ciullo et al., 2020]. Furthermore, an important benefit of the MOEA based approach is that the alternative principles can be assessed independently on robustness. But in the research mentioned, no approach has been found that uses MOEAs to combine multiple distributive principles.

2.5 KNOWLEDGE GAP

In the previous sections, several issues of IAMs related to distributional justice have been discussed. To derive more equitable climate abatement trajectories Adler et al. [2017]; Dennig et al. [2015] have proposed various approaches to account for distributional issues within the RICE model and found significant different abatement trajectories. Dietz and Asheim [2012]; Arrow et al. [2014]; Freeman et al. [2015] have shown alternative ways to improve justness within the intergenerational distribution of climate impact, for example, by implementing Sustainable Discounting Utility functions. Fundamental modeling issues related to deep uncertainty can be overcome by the robust sampling of model inputs. For instance, by not handpicking a mid-center estimate of the IPCC range of temperature increases like Nordhaus [2014], but by sampling over a range of temperature projections [Lamontagne et al., 2019].

Although previous literature has delivered various ideas for improving Integrated Assessment Models, no study has combined alternative distributive principles with robustness considerations. First, the identified gap consists of the effects of using various different distributive principles within IAMs. And second, what are the effects of using alternative distributive principles under deep uncertainty. Furthermore, comparing alternative principles' performance was difficult using previous literature like [Dennig et al., 2015; Adler et al., 2017; Lamontagne et al., 2018; Arrow et al., 2014; Dietz and Asheim, 2012]. This is because of the heterogeneous models and parameters used within this literature. Little research exists that compares multiple distributive principles within the same study.

Therefore, this research overcomes both gaps by reflecting on multiple alternative distributive principles' performance to generate emission pathways under uncertainty. Because of the variety of analyzed alternative principles, the performance of alternative principles can be compared. The usage of the SSP-framework enables comparison with established Utilitarian CO_2 abatement trajectories like Nordhaus [2014] policy and the IPCC pathways within Masson-Delmotte et al. [2018]. This could offer practical insights into how alternative principles can be used within IAMs to generate more equitable global abatement pathways. Furthermore, it can deliver meaningful insights to policymakers on what can be done to strive for a more equitable global climate strategy.

3 RESEARCH DEFINITION

Based on the knowledge gap stated in the previous chapter, e.g., the absence of an integral overview of the effects of implementing spatial and temporal distributive principles within the RICE model under deep uncertainty, the following main research question has been formulated:

MAIN RESEARCH QUESTION

What is the effect of applying alternative distributive principles to the RICE model on global CO_2 abatement pathways under deep uncertainty?

To answer the main research question, an exploratory modelling approach has been selected. Exploratory modelling is a research methodology that makes use of computational experiments for the analysis of complex and uncertain systems [Bankes, 1993]. Therefore, exploratory modelling is especially useful in the case of long term climate change where large uncertainty exists. Not only is there scientific uncertainty about the precise effects of climate change. It is also unknown what frameworks should be applied to solve the ethical questions within the climate change debate (e.g., the ethical uncertainty) [Beck and Krueger, 2016]. The aim of exploratory modelling is not to predict the future. Instead, it entails using models to learn about the outcomes of policies under the world's possible future states. The goal is to learn through what-if scenario-generation on system behaviour and critical combinations of policy inputs [Kwakkel, 2017]. To answer the main research question, seven research sub-questions have been identified that will be introduced in the following paragraphs.

A literature study will be executed on which temporal and spatial distributive principles should be selected. The distributive justice literature offers a magnitude of possible alternative principles as a guide for the chosen distribution of climate impacts and benefits. Principles will be selected on their usefulness to generate more equitable abatement pathways and diversity.

Research question 1

Which spatial and temporal distributive principles can contribute to overcome inequities within CO_2 abatement trajectories?

One spatial example is applying the Prioritarian principle by prioritizing the worst-of when optimizing for utility [Adler, 2019; Dennig et al., 2015] or to optimise for the number of people living under the Sufficitarian threshold [Dietz and Asheim, 2012]. A temporal example is applying a Sufficitarian approach which only discounts when future contemporaries are above a certain utility threshold [Greaves, 2017]. To limit the scope of the research, this thesis will not assess how spatial distributive justice can be improved with financial policy means, such as capital transfers, like researched by Orlov et al. [2017]. The focus will lie on using distributive principles for the optimization of abatement trajectories.

Within exploratory modelling, there are multiple approaches, namely robust decision making (RDM), many-objective robust decision making (MORDM), multi-scenario MORDM and lastly many-objective robust optimization (MORO). All of these approaches make use of sampling, data analysis and clustering to draft policies and sample the policy outcomes over a wide range of possible futures [Kwakkel et al., 2016]. The approaches differ in how comprehensive policies are generated. Within the MORDM framework, multiple objectives are used to evaluate candidate policies. Policies are generated using a search algorithm and checked for their outcomes relative to the objectives. Policies that score the highest on one or multiple of the objectives are kept and stored within the Pareto optimal set [Kasprzyk et al., 2013]. Therefore, the MORDM approach offers the possibility to show trade-offs between policies, which can improve policy evaluation towards stakeholders [Hall et al., 2012]. Multi-scenario MORDM extends robustness as policies are generated on multiple possible futures which challenge the outcomes of the reference scenario. MORO goes one step further by optimizing for robustness when generating the policy alternatives [Bartholomew and Kwakkel, 2020].

Although MORO offers the highest potential to generate robust policies, the computational burden becomes exponentially high with the number of uncertainty sources [Bartholomew and Kwakkel, 2020]. Also, the multi-scenario MORDM can become computationally expensive for the DICE/RICE model. Therefore the single scenario MORDM has been chosen as method within the exploratory approach. MORDM has been chosen over RDM because of the ability to include multiple distributive principles as objectives in the optimization problem. This makes it possible to show trade-off structures within alternative distributive principles. During the execution of the MOEA, candidate climate trajectories will be sampled using a single reference scenario similar to Lamontagne et al. [2019]. The robustness of generated policies in the MOEA will still be assessed via Uncertainty Analysis and Scenario Discovery.

Research question 2

How can deep uncertainty parameters and disaggregated model components be implemented within the PyRICE model?

This thesis will build further on the work of Lingeswaran [2019] which implemented an open-source version of the DICE model in Python, named the PyDICE model. The original PyDICE model constructed by Lingeswaran [2019] will be extended into the PyRICE model. Python is chosen as a programming language due to the wide variety of simulation and data-analyzing tools such as the EMA-workbench [Kwakkel et al., 2013]. The RICE2010 version of Nordhaus [2017] will be used as a template for PyRICE. The RICE2010 is the newest and most used regionally disaggregated version of the DICE2016 model. The RICE2010 model consists of 12 regions that use an identical economic structure to the DICE model. After model conceptualization, formalization and implementation the PyRICE model will be validated against the original RICE2010 output by Nordhaus [2014]. This ensures the comparability of the results when alternative distributive principles are implemented. The data that is needed for running the PyRICE model will mainly be derived from Nordhaus [2014]. Additional sources for data on damage functions, model uncertainties and model relations will be derived from the Lingeswaran [2019]; Riahi et al. [2017]; Lamontagne et al. [2019]; Weitzman [2009]; Dennig et al. [2015]. Using programming in Python, concepts will be developed on how distributive principles can be implemented as optimization objectives within the PyRICE model. The development and implementation of the PyRICE model will lead to answering sub-question 3.

Research question 3

How can the operationalized alternative principles be implemented as objectives for the generation of abatement strategies in the PyRICE model?

To answer sub-question 4, this thesis will follow the iterative MORDM method, which consists of four steps and is an iterative process. First, the model specification will be done setting-up the model input-parameters in the PyRICE model following the XLRM framework. The XLRM framework consists of the uncertainties (X), the policy levers (L), the outcomes of interest (M) and relationships within the model (R). Within the MOEA, the objectives are part of the outcomes of interest. These will correspond to the principles found in sub-question 1. A many-objective evolutionary algorithm (MOEA) will be used to search for CO_2 trajectories on the Pareto front that maximize the distributive objectives Kwakkel et al. [2016]. Because not all found policies can be further analysed due to computational constraints, for each applied principle, several example policies will be chosen based on diversity and ability to span up the complete policy space.

Research question 4

What is the influence of deep uncertainty present within climate change on the performance of the tested distributive principles?

Chosen example policies part of the Pareto approximate set are then stress-tested for robustness using Uncertainty Analysis. Strategies will be tested on their performance regarding both to short term (2105) socioeconomic and climate uncertainties as to long term (2305) climate uncertainties. For both analysis, robustness metrics are calculated to assess the robustness of the found set policies McPhail et al. [2018]. The most robust strategies of each principle will form the input for the Scenario Discovery step. The simulation method Scenario Discovery is applied to discover possible futures in which the trajectories of interest perform unexpectedly well or poorly [Hall et al., 2012; Kwakkel et al., 2016].

Research question 5

Which clusters and trade-offs are present within the outcomes of the alternative abatement strategies?

First, the output of the exploratory analysis will be processed using data visualization and data-analysis techniques within Python. The distributive principles' outcomes will be compared with established cost-optimal trajectories such as Nordhaus [2014] in the clustered model outcomes. Outcomes will be clustered based on agglomerative clustering and on tempetature outcomes in the short term. This will show potential vulnerabilities of the analysed policies. Intergenerational trade-offs within the principle specific objectives will be analysed. Lastly, a worst-case discovery analysis will support comparison between vulnerabilities between the applied principles.

Research question 6

How can Integrated Assessment Models benefit from the usage of alternative distributive principles?

In the previous sections, the process of statiscally analyzing the outcomes have been laid down. The next step will be to perform a reflection over the simulation results. The reflection will assess what climate trajectories could be 'fair' and preferable if alternative distributive assumptions are chosen. The focus will lie on how alternative distributive principles can contribute to overcome the problems of inequity arising from the Utilitarian principle. It will state the usefulness of the approaches of deep uncertainty and optimization over multiple objectives for complex IAMs. And what is the linkage of these approaches regarding theories of distributive justice. For example the position of robustness and multiple objective optimization in relation to theories of distributive justice.

Research question 7

What are the policy implications of the usage of alternative distributive principles within IAMs for global climate governance?

Finally, the generated alternative emission reduction pathways are compared with established emission reduction pathways set by the IPCC. du Pont et al. [2017] and Rogelj et al. [2016] have compared the global National Declared Contributions (NDCs) in the Paris agreement which cost-optimal IAM trajectories. Their work will offer practical guidance for this task. Previous literature on alternative distributive principles such as Okereke and Coventry [2016]; Castro [2020]; du Pont et al. [2017] will offer guidance for positioning the tested distributive principles within the current climate regime. Furthermore, the reflection will highlight which steps policy makers can take to achieve more equitable climate strategies. For example which supplementary strategies can reduce inequities arising from climate impact.

II

METHODS

4 SELECTION OF DISTRIBUTIVE PRINCIPLES

This chapter focuses on selecting distributive principles that will be implemented within the RICE model. Section 4.1 gives a brief overview of the fundamental theories that support distributive justice and introduces the chosen welfarist principles. A literature review regarding alternative welfarist principles within Integrated Assessment Models has been executed. Section 4.2 gives an overview of the spatial and temporal application to IAMs of the found welfarist principles. Within section 4.3, the chosen distributive principles are summarized.

4.1 DISTRIBUTIVE JUSTICE AND THE WELFARIST APPROACH

Distributive justice is reflected within economical, political, and social frameworks that shape laws, institutions and rules within society. Each and all of these frameworks are build up by principles of distributive justice [Adler, 2019]. Distributive principles can be seen as tools on moral guidance for political processes that affect distributing benefits and burdens of a policy choice [Lamont and Favor, 2017]. Within the distributive justice theory, many schools exist. The welfarist approach assumes that policies can be valued according to their effect on welfare, which forms the basis of IAM analysis. Strict Egalitarianism neglects that welfare can effectively be measured and prescribes that every person should possess the same level of material goods and services. The Difference Principle by John Rawls holds that inequality is only accepted under certain conditions [Sen, 2018]. The various schools of distributive justice are too extensive to cover here. As the welfarist approach lies at the basis of Integrated Assessment models [Adler, 2019], this approach forms the main focus for the selection of alternative distributive principles.

The welfarist approach assumes that policies can be ranked on their resulting welfare [Sen, 2018]. The welfarist approach is consequentialist as policies are only valued on the basis of their outcomes. In what unit welfare is measured differs between approaches. Often welfare is defined as utility or pleasure, preference satisfaction (e.g. Arrow) or happiness. Welfarist principles make use of a welfare function to allocate welfare across recipients [Lamont and Favor, 2017]. One commonly known welfare function is the Utilitarian social welfare function, which aims at maximizing aggregated utility [Adler, 2019]. Many integrated assessment models adopt this approach for ranking climate trajectories. The climate trajectory with the highest expected utility is chosen as the optimal trajectory [Adler et al., 2017]. Next to the Utilitarian welfarist approach, multiple other welfarist principles exist. Commonly found principles within the literature are the Egalitarian principle aiming for total equality, the Prioritarian principle aiming to prioritize the worst-off and the Sufficitarian principle, which aims to obtain a certain welfare minimum [Adler, 2019; Dietz and Asheim, 2012; Adler et al., 2017; du Pont et al., 2017]. Together, they form the standard principles used to shape the social welfare function within integrated assessment models. The next paragraphs give an overview of each of the principles mentioned.

4.1.1 Utilitarism

The Utilitarian principle is the standard principle within welfare economics, going all the way back to Jeremy Bentham (1747) regarded as one of the founding fathers of utilitarianism. Within the Utilitarian approach, the focus lies on maximizing the total sum of utilities irrespective of the distribution of that total across individuals [Sen, 2018]. The Utilitarian principle does assume declining marginal utility. Thus increasing the consumption level of a person at a low-income level matters more than increasing income at high-income levels. But as utility is aggregated, the

Utilitarian SWF function remains insensitive to the distribution among individuals [Adler, 2019]. The generalized form of the Utilitarian welfare function can be seen below.

$$W = \sum_{t=0}^{T}\sum_{i=1}^{I} U(C_i t)(1+\rho)^{-t} \tag{4.1}$$

Within this function, the amount of well-being at each time *t* is computed by summing monetary well-begin levels across all individuals *i* at time *t*. Then wellbeing at each time *t* is discounted by a factor that reflects the importance of wellbeing at that moment relative to wellbeing at other times. After this, the discounted wellbeings across time are summed [Adler, 2019]. In the regional aggregated RICE model, utility is computed per region based on the average per capita consumption and population of that region (equation 4.2) [Anthoff and Emmerling, 2019].

$$W = \sum_{t=0}^{T}\sum_{r=1}^{R} P_r t U(C_i t)(1+\rho)^{-t} \tag{4.2}$$

4.1.2 Prioritarism

The Prioritarian view differs from the Utilitarian principle in that it accounts for distribution across people. Benefits to people on a low level of wellbeing are valued higher than increasing welfare of well-off individuals [Adler, 2019]. This is different from the idea of declining marginal utility, as in the Utilitarian case, the relative levels do not matter. Suppose two actions A & B: Action A increases utility for a well-off individual while slightly increasing aggregated welfare as a whole, whereas Action B slightly increases welfare for a lower off person while not increasing total welfare. In the Utilitarian case, action A is chosen over action B. Whereas the Prioritarian case would favour action B over action A as benefits for the worse-off are prioritized [Lamont and Favor, 2017]. To achieve this, prioritarianism approaches make use of a strictly increasing and strictly concave transformation function *G(x)* within the social welfare function, see figure 4.1. Another Prioritarian approach is the Leximin social welfare function which ranks outcomes relative to how they perform on the outcome of the worst-off [Adler, 2019; Sen, 2018].

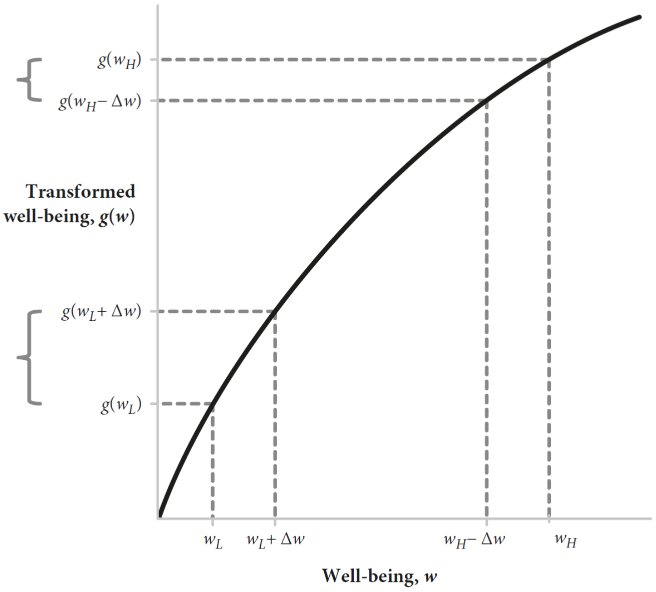


Figure 4.1: Concave Prioritarian transformation function, derived from Adler [2019]

Equation 4.3 shows the Prioritarian social welfare function, including the transformation function. The transformation function can be specified as a power function see equation 4.4. The parameter γ resembles the priority for the worse-off with $\gamma = 0$ being strictly Utilitarian and increasing γ for more priority for the worse off. When γ is bigger than 0, the resulting function has resembles a positive slope which decreases at higher wellbeing levels W. The result is that actions that add wellbeing at lower levels are favored over increasing wellbeing at higher levels [Adler, 2019]. The Utilitarian function is one specific function for the ordering of welfare. In contrast, the Prioritarian social welfare function represents a family of functions as various shapes for *g(x)* can be chosen.

$$W = \sum_{t=0}^{T} \sum_{r=1}^{R} P_{rt} G\Big(F(U(C_i t))\Big)(1+\rho)^{-t} \tag{4.3}$$

with:

$$G(u*) = (1-\gamma)^{-1}(u*)^{1\gamma} \tag{4.4}$$

Regarding discounting, the Prioritarian principle does not offer strict guidance. Within Prioritarian analysis, often no discounting is applied based on the ethical axiom of impartiality. Harms to future generations should be weighed equally high as to present generations [Adler, 2019]. Nevertheless, there is no absolute reason that discounting can not be applied within the Prioritarian view. Therefore other approaches adopt discounting schemes that protect for the position of the worst-off. Within Prioritarian conditional discounting, discounting is only applied when the worst-off experiences a certain welfare improvement relative to previous generations.

4.1.3 Sufficitarianism

The Sufficitarian principle aims that benefits and burdens should be distributed so that as many persons as possible can enjoy a decent welfare level [Page, 2007]. According to sufficitarians, problems of inequality occur when some individuals are so deprived of wellbeing to a level that is seen as morally unacceptable [Adler, 2008]. Sufficitarian norms can be found throughout public governance, for example within country-specific poverty lines and minimal living standards. One example of this is the $ 2.10 poverty line defined by the World Bank. The level after which sufficitarians accept inequality is defined as the Sufficitarian threshold [Adler, 2019]. The Sufficitarian approach prescribes that policymakers are morally obliged to put absolute focus on improving the position of people below the Sufficitarian threshold. Applying the Sufficitarian approach to integrated assessment models results in conditions such as welfare per head may never decline [Beckerman, 1999]. Or each generation is entitled to inherit a planet at least as good as that of previous generations [Arrow et al., 1996]. Another intertemporal application is the condition that every generation is entitled to experience a certain level of growth, for example 25 % per generation [Llavador et al., 2015].

4.1.4 Egalitarianism

Within the Egalitarian principle, both a non-consequentialist and welfarist approach exist. The non-welfarist approach rejects that there exists a social welfare function that can effectively measure and compare interpersonal well being. By doing so, this virtually rejects the use of any kind of social welfare function as a tool to reach a fair distribution [Lamont and Favor, 2017]. Contrary to this, the welfarist Egalitarian approach can offer an alternative principle to integrated assessment models. In this approach, as opposed to prioritarianism which deals with absolute inequality, the focus lies on relative inequality between individuals. The moral weight of individual wellbeing depends on the wellbeing of everyone else in the population, hereby rejecting the ethical axiom of separability [Adler, 2019].

One way to apply the Egalitarian principle within a social welfare function is to penalize distributions that have a high inequality among the distributed welfare. This can be done by penalizing inequality by using an inequality measure such as the GINI-index, see formula 4.6 [Ciullo et al., 2020]. Other approaches include the usage of a rank-weighted welfare function, which ranks distributions on how equal welfare is distributed amongst individuals [Adler, 2019].

$$W = \sum_{t=0}^{T} \sum_{r=1}^{R} P_r t U(C_i t)(1+\rho)^{-t} + E \tag{4.5}$$

with:

$$E = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |x_i - x_j|}{2n^2} \tag{4.6}$$

4.2 SPATIAL AND TEMPORAL APPLICATION TO IAMS

In the preceding sections, the four main welfarist principles have been introduced. This section will discuss their implication for how to treat spatial and temporal distribution of climate change's burden and benefits in IAMs.

4.2.1 Utilitarian principle

Within the Utilitarian perspective, it is simple how to deal with intragenerational justice. The optimal spatial distribution is found by maximizing aggregated utility within the Utilitarian social welfare function (equation 4.1) [Sen, 2018].

The Utilitarian perspective deals with justice between generations by applying discounting to the utility level of future generations. To what extent the importance of the future is weighted is set by Ramsey's social discount formula (section 2.3.1). Most Utilitarian scholars agree that some level of discounting must be applied due to the capital accumulation of positive payouts of investments. However, there are also scholars that argue for a non-discounted approach and the usage of negative discount rates [Fleurbaey and Zuber, 2012; Greaves, 2017]. The precise setting of the parameter values within this formula is the center of a heated debate among economists, most notably between Nordhaus [2014]; Tol [2013] who support the descriptive view on the one hand and Stern [2007] which supports the prescriptive view on the other.

According to the descriptive (positivist) view, the discount rate should be set based on observed market rates of return [Arrow et al., 2013]. Following this view, it is wise to invest in profitable portfolios now and use the profits of these investments in the future for climate mitigation action [Storm, 2017]. According to the prescriptive view, the discount rate should be set following ethical considerations. For example, future generations should be valued equally by setting a low pure rate of time preference of ρ = 0.01 and low elasticity of marginal utility [Stern, 2007]. Nordhaus [2014] is one of the most commonly known defenders of the descriptive argument, which is why the DICE/RICE model adopts a social discount rate of 5.5 %. This implies that future generations are better off richer, but with the possible adverse effects of climate change [Kowarsch, 2016; Storm, 2017].

Overview of used discounting parameters in literature				
	elasticity of utility (η)	growth rate (g)	pure rate of time (δ)	social discount rate (R)
descriptive (Nordhaus, 2007)	1.4 %	1.5 %	2 %	5.5 %
descriptive (Weitzman, 2008)	2 %	2 %	2 %	6 %
prescriptive (Stern Review, 2007)	0.1 %	1.5 %	0.01 %	1.4 %
French Lebegue report	0 %	2 %	2 %	4 %
UK greenbook	1.5 %	2 %	1 %	4.5 %

Figure 4.2: Parameter values for Ramsey formula in literature

Important climate studies, such as the Fifth Assessment report on the Climate by the IPCC adhere to the descriptive view by applying 'high' discount rates [Golosov et al., 2014; Masson-Delmotte et al., 2018]. Also, within national policies, more value is given to the present generation over future generations. For example, both the UK and French government recommends applying a positive pure rate of time preference. But within the scientific literature, debates persist on how to treat discounting in the presence of uncertainty. Fleurbaey and Zuber [2012] argues that because of these uncertainties, the discounting rate should be set negative. Others suggest that when discounting is done over longer time frames, discounting rates should decline over time to account for the uncertainty in future rate of return [Arrow et al., 2014].

The inability to set the objective discount rate is essentially an ethical debate over what is the right moral principle to apply to intergenerational justice. This opposes some economists' standpoint that discounting is an objective and defensible economic practice [Beck and Krueger, 2016]. The idea that discounting is normative is the most critical reason no definite answer on discounting can be found. Therefore, Taebi et al. [2020] have argued that the discounting factor can be defined as an epistemic normative uncertainty.

4.2.2 Prioritarian principle

Within the Prioritarian principle, extra priority should be given to the worst-off individuals when selecting a fair distribution of welfare. One way of doing this is by applying a concave transformation function (section 4.1.4), which shapes the spatial distribution of welfare across its recipients [Adler et al., 2017]. Thus the Prioritarian principle entails a continuous transformation of the worst-off. Because it is not possible to select individuals in models, more practical approaches make use of disaggregated income groups to optimize for the lowest income groups across regions as done by Dennig et al. [2015]. Another approach is to favour climate impact reductions for regions where climate impact is highest, which is comparable to the approach of Ciullo et al. [2020] on risk reduction for flood risk. These approaches entail the prioritization for the group with the highest impact of climate change. When expressed impact is computed relative to consumption, this can overcome the accounting problem of the differences in relative welfare levels present within IAMs.

Regarding intergenerational justice, the prioritairan principle does not prescribe one absolute way of valuing the importance of future generations compared with current contemporaries. Adler [2008] has argued that when applying a Prioritarian distribution, no discounting should be applied. Because discounting assigns less weight on individuals just because they live further into time, discounting violates the axiom of impartially. The reason behind this is that future worst-off should be valued equally, also if they live in the future. Other approaches make use of standard Utilitarian discounting when applying a spatial prioritairan distribution [Greaves, 2017]. Some approaches adopt discounting schemes that protect for position of the worst-off. Within Prioritarian conditional discounting, discounting is only applied when the worst-off experiences a certain welfare improvement relative to previous generations. The welfare improvement can be related to a certain growth level [Adler, 2019; Greaves, 2017].

4.2.3 Sufficitarian principle

Within the Sufficitarian case, welfare should be distributed in such a way that as many individuals are above the Sufficitarian threshold W_{tresh} [Adler, 2019]. Inequality above the Sufficitarian threshold is accepted, and as a distributional rule, often the Utilitarian social welfare function is adopted. Below the Sufficitarian threshold, the sufficiency approach applies a Prioritarian approach to distributing welfare [Adler and Holtug, 2019]. Thus, the Sufficitarian view differs from the Prioritarian approach in that the Sufficitarian view is a discrete transformation of the distribution of utility while the Prioritarian approach aims at a continuous transformation.

When applying the sufficiency approach to intergenerational justice, this is often linked to conditional discounting. Future wellbeing is only discounted when future generations find themselves above a given threshold. Examples are that every generation should experience a 25 % increase in wellbeing compared to the preceding generations (growth discounting) or that every generation should experience at least the same wellbeing as current generations (inheritance discounting) [Beckerman, 1999]. Discounting is only applied when these threshold conditions are met. Here the sufficiency approach regarding temporal justice follows the same line of reasoning as the spatial justice variant. Below the threshold, the Sufficitarian approach does not apply discounting, whereas above the threshold the distribution of welfare follows the Utilitarian principle [Dietz and Asheim, 2012; Page, 2007].

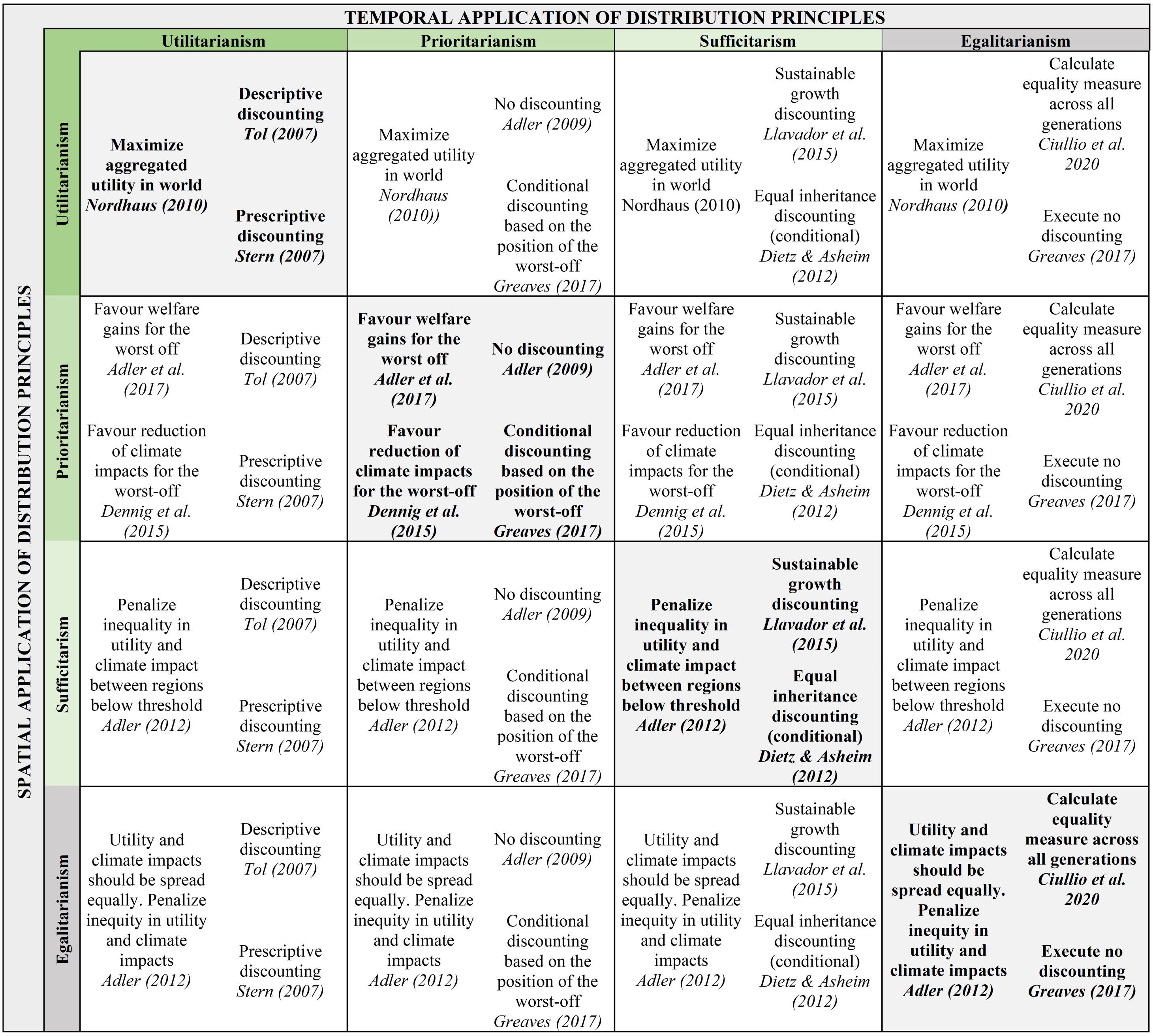
4.2.4 Egalitarian principle

Regarding spatial justice, the Egalitarian case focuses on dividing the distribution of welfare as equal as possible. This can be done by penalizing relative inequality in the distribution of welfare [Ciullo et al., 2020]. The amount of penalization determines the level of aimed equality within the distribution of utility. Extensions to this approach entail to equalize relative damages between regions. In the literature review, no research has been found that applies one of these approaches to IAMs.

When assessing intergenerational justice within the Egalitarian case, no discounting should be applied. This originates from the primary Egalitarian idea that every individual is equal and show be treated equally [Adler, 2019]. The temporal case can be extended by calculating the inequality measure over time across all periods. In this way, the Egalitarian SWF strives for equal welfare divisions across generations. This intertemporal inequality measure should account for differences in populations across times, making it more complicated to implement practically. [Adler et al., 2017] adopted a zero discounted SWF within the RICE model as part of a Prioritarian SWF. The use of zero discounting as part of an Egalitarian distribution within IAMs has been underused in the assessed literature.

4.3 OVERVIEW AND SELECTION OF PRINCIPLES

Figure 4.3 below gives an overview of the discussed welfarist principles and their applications within IAM analysis. The table shows that combinations can be made between temporal and spatial applications regarding a different welfarist principle. For example, by applying a Prioritarian spatial approach while applying no discounting which can be based both on Egalitarian and Prioritarian grounds.



SPATIAL APPLICATION OF DISTRIBUTION PRINCIPLES	TEMPORAL APPLICATION OF DISTRIBUTION PRINCIPLES							
	Utilitarianism		**Prioritarianism**		**Sufficitarism**		**Egalitarianism**	
Utilitarianism	**Maximize aggregated utility in world** ***Nordhaus (2010)***	**Descriptive discounting** ***Tol (2007)*** **Prescriptive discounting** ***Stern (2007)***	Maximize aggregated utility in world *Nordhaus (2010))*	No discounting *Adler (2009)* Conditional discounting based on the position of the worst-off *Greaves (2017)*	Maximize aggregated utility in world Nordhaus (2010)	Sustainable growth discounting *Llavador et al. (2015)* Equal inheritance discounting (conditional) *Dietz & Asheim (2012)*	Maximize aggregated utility in world *Nordhaus (2010)*	Calculate equality measure across all generations *Ciullio et al. 2020* Execute no discounting *Greaves (2017)*
Prioritarianism	Favour welfare gains for the worst off *Adler et al. (2017)* Favour reduction of climate impacts for the worst-off *Dennig et al. (2015)*	Descriptive discounting *Tol (2007)* Prescriptive discounting *Stern (2007)*	**Favour welfare gains for the worst off** ***Adler et al. (2017)*** **Favour reduction of climate impacts for the worst-off** ***Dennig et al. (2015)***	**No discounting** ***Adler (2009)*** **Conditional discounting based on the position of the worst-off** ***Greaves (2017)***	Favour welfare gains for the worst off *Adler et al. (2017)* Favour reduction of climate impacts for the worst-off *Dennig et al. (2015)*	Sustainable growth discounting *Llavador et al. (2015)* Equal inheritance discounting (conditional) *Dietz & Asheim (2012)*	Favour welfare gains for the worst off *Adler et al. (2017)* Favour reduction of climate impacts for the worst-off *Dennig et al. (2015)*	Calculate equality measure across all generations *Ciullio et al. 2020* Execute no discounting *Greaves (2017)*
Sufficitarism	Penalize inequality in utility and climate impact between regions below threshold *Adler (2012)*	Descriptive discounting *Tol (2007)* Prescriptive discounting *Stern (2007)*	Penalize inequality in utility and climate impact between regions below threshold *Adler (2012)*	No discounting *Adler (2009)* Conditional discounting based on the position of the worst-off *Greaves (2017)*	**Penalize inequality in utility and climate impact between regions below threshold** ***Adler (2012)***	**Sustainable growth discounting** ***Llavador et al. (2015)*** **Equal inheritance discounting (conditional)** ***Dietz & Asheim (2012)***	Penalize inequality in utility and climate impact between regions below threshold *Adler (2012)*	Calculate equality measure across all generations *Ciullio et al. 2020* Execute no discounting *Greaves (2017)*
Egalitarianism	Utility and climate impacts should be spread equally. Penalize inequity in utility and climate impacts *Adler (2012)*	Descriptive discounting *Tol (2007)* Prescriptive discounting *Stern (2007)*	Utility and climate impacts should be spread equally. Penalize inequity in utility and climate impacts *Adler (2012)*	No discounting *Adler (2009)* Conditional discounting based on the position of the worst-off *Greaves (2017)*	Utility and climate impacts should be spread equally. Penalize inequity in utility and climate impacts *Adler (2012)*	Sustainable growth discounting *Llavador et al. (2015)* Equal inheritance discounting (conditional) *Dietz & Asheim (2012)*	**Utility and climate impacts should be spread equally. Penalize inequity in utility and climate impacts** ***Adler (2012)***	**Calculate equality measure across all generations** ***Ciullio et al. 2020*** **Execute no discounting** ***Greaves (2017)***

Figure 4.3: Overview of literature review of distributive principles for IAMs

To limit the scope of this research. This research focuses on homogeneous combinations of principles, meaning that only the diagonal combinations will be tested within the RICE model. In this way, the outcomes generated within the RICE model will only depend on one distinct application of a welfarist principle. This enables easier comparison between principles. Thus, a total of eight combinations will be tested within the RICE model.

5 THE RICE MODEL

William Nordhaus was one of the first scholars to link the effects of climate change with the global economy. The Dynamic Integrated model of Climate and the Economy (DICE) 1992 model was the first released version. In 2010, the Regional Integrated model of Climate and the Economy (RICE) was released as a way to study the effects of the Copenhagen Climate Accord. The RICE/DICE models are simplified analytical models that integrate emission reductions pathways to a dynamic Ramsey-Koopman growth model. The RICE/DICE models are non-linear, intertemporal optimization models. There are many versions of the DICE/RICE models as damage functions and other parameters are updated when new climate research comes available [Nordhaus, 2017]. For this research, the RICE2010 model is chosen. It is the most updated version of the RICE model, well used in other disaggregated impact studies and consists of 12 regions which enables better spatial comparisons over other versions of RICE [Dennig, 2014]. Section 5.1 addresses the main assumption of the DICE/RICE models. Section 5.2 states the relations in the RICE2010 model with more detail.

5.1 MAIN ASSUMPTIONS

The economic backbone of the RICE model is set-up by applying the framework of economic growth theory. The model follows the logic of the neoclassical optimal growth model known as the Ramsey-Cass-Koopman model (RCK). In this growth model, society invests in capital goods by reducing today's consumption to increase future consumption [Koopmans, 1965]. The representative agent within the model is infinitely lived. Thus, for each region in RICE, there is one social planner or representative agent. As the RCK-model only represents households and firms, the household can be seen as a dynasty which is infinitely lived with an unending chain of generations connected through family relationships. This assumption forms the basis for why the representative agent besides the present also values the (far) future (although to a lesser extent than the present). To the general structure of the RCK model, the DICE/RICE models add a climate impact and climate investment component. CO_2 concentrations can be seen as negative natural capital. Emissions reductions reflect investments to lower the quantity of negative capital by reducing today's consumption but increase consumption in the future [Nordhaus, 2011].

The main structure of the RICE model consists of three sub-models representing the climate, the economy and the carbon cycle. Within the economy sub-model, the main output forms the world economy over time. The economic activity results in an increase of atmospheric CO_2 calculated in the carbon cycle model [Fiddaman, 1997]. This forms the input for the climate model, which is calibrated against more complex climate models [Frisch, 2013]. Via the damage function, atmospheric warming is linked to a certain level of climate impact relative to the size of the economy. Finally, the utility sub-model aggregates consumption and damages over time per region to calculate a net economic consumption which is discounted over time using a discount rate [Weyant, 2017]. Within RICE, the economic sub-model is disaggregated over 12 regions such as large countries like the United States, China or multi-country regions such as the European Union or Africa. Each region has a well-defined assumed set of preferences represented by the social welfare function to optimize its consumption, emission reduction and investments. The importance of future generations is modeled by applying a pure rate of time preference. Increases in consumption will lead to relative lower increases of utility because of the declining marginal utility of consumption. Parameters within the model should reflect real market behaviour and are therefore calibrated by Nordhaus [2011].

5.2 RELATIONSHIPS IN THE RICE MODEL

The following paragraphs address the relationships within the RICE2010 model by [Nordhaus, 2011] in more detail.

5.2.1 Economic sub-model

The economic sub-model in RICE is based on the neoclassical economic growth theory model by Ramsey-Cass-Koopmans. In the RCK model two separate agents, households and firms maximize the present and the future flow of discounted utilities. Within RICE for every region the present and future utility is maximized [Nordhaus, 2011]. In the RCK model, households supply labour to the firms and are also shareholders of these firms. Thus, the representative household receives all value-added from both labour and capital income. Utility is maximised by consuming a share of the world output, Y_{gross}, while investing the remaining share in firms to increase future consumption. The world gross output, Y_{gross}, is set by the Cobb-Douglas production function (5.1).

$$Y_{gross,t,r} = A_{t,r} L_{t,r}^{1-\gamma} K_{t,r}^{\gamma} \tag{5.1}$$

where:

$A_{t,r}$:	Total factor productivity per region per period
$L_{t,r}$:	Population and labour force per region per period
$K_{t,r}$:	Capital stock per region per period
γ:	Output elasticity of capital

The output elasticity of capital resembles the response of the gross output to changes in capital. The accumulation of capital is driven by investment in every region, $I_{t,r}$. Depreciation reduces the stock of capital by the depreciation rate of capital, δ.

$$K_{t+1,r} = I_{t,r} T_{step} + (1-\delta)^{T_{step}} K_{t,r} \tag{5.2}$$

where:
T_{step}: time step

Because climate change is incorporated in the RICE model, some fraction of Y_{gross} is lost to damages and to the cost of abatement. Therefore, the RCK model is extended with 5.3 to derive the total income $Y_{t,r}$ per region at time step t.

$$Y_{t,r} = Y_{gross,t,r} * (1 - \Delta_{t,r} - \Omega_{t,r}) \tag{5.3}$$

Investment, $I_{t,r}$ is the difference between total income per region and the total consumption within that region, $C_{t,r}$. The amount of investment is determined by the savings rate which is optimized for every region in RICE.

$$I_{t,r} = Y_{t,r} - C_{t,r} \tag{5.4}$$

The damages caused by climate change over time in every region, $\Omega_{t,r}$, are determined by the damage function. The damage function is crucial as it links induced warming with damages to the economy. Therefore the specification of the damage function is one of the most fundamental debates within IAMs [Beck and Krueger, 2016]. In chapter 6, this uncertain parameter and others are covered more extensively. Within the RICE2010 model, the damage function is dependent on temperature and on induced Sea Level Rise (SLR). Recent versions of DICE only make use of a temperature dependent damage function. The sea-level rise component adds extra complexity to climate abatement strategies. Research has shown that sea-level-rise can be irreversible once triggered, even when negative emissions are deployed on a large scale [Masson-Delmotte et al., 2018; Hallegatte and Rozenberg, 2017]. This is why the SLR component is maintained within the RICE model.

$$\Omega_{t,r} = \lambda_{1,r} T_{ATM,t} + \lambda_{2,r} (T_{ATM,t})^{\lambda 3,r} \tag{5.5}$$

The abatement costs are calculated via the cost of the backstop technology which price is assumed to decline over time [Nordhaus, 2010]. Technology advancement will lead to an increase in efficiency of the backstop technology until the price of this technology reaches zero. The backstop technology is defined by Nordhaus [2011] as the technology that can remove carbon from the atmosphere or as a zero carbon-emitting energy technology.

$$\Delta_{t,r} = \beta_{1,r}\mu_{t,r}^{\beta_2} \tag{5.6}$$

Given the ensemble of model outputs, the social planner tries to maximise the social welfare function by setting the emission control rate, $\mu_{t,r}$, and the savings rate, $S_{t,r}$. In chapter 4, multiple social welfare functions have been introduced. The standard RICE welfare function is the Utilitarian welfare function (5.7).

$$W = \sum_{t=1}^{T_{max}} \sum_{r=1}^{R} U(C_{t,r})L_{t,r}R_t \tag{5.7}$$

where:

$C_{t,r}$:	Consumption per Capita per region
$L_{t,r}$:	Population and labour force per region per period
R_t:	Social discount factor

The social discount factor is set by the social rate of time preference, ρ, which applies welfare weights on the welfare experienced by future generations.

$$R_t = \frac{1}{(1+\rho)^t} \tag{5.8}$$

The period utility function, $U(c_{t,r}$, is set by a Constant Relative Risk Aversion (CRRA) utility function (5.9)

$$U(c_{t,r}) = \frac{C_{t,r}^{1-\alpha} - 1}{1-\alpha} - 1, \alpha < 1 \tag{5.9}$$

5.2.2 Carbon sub-model

Within the carbon sub-model, the total global emissions E_t, that are the result of economic activity, give rise to an increase of the CO_2 concentration in the atmosphere, MAT_t. The total emissions are determined by the sum of the industrial emissions per region, $E_{ind,t,r}$, and the resulting emissions from changes in land usage such as deforestation, $E_{land,t}$.

$$E_t = \sum_{r=1}^{R} (E_{ind,t,r}) + E_{land,t} \tag{5.10}$$

The industrial emissions are set by the total economic output per region using the emissions control rate, $\mu_{t,r}$ and the emissions output ratio, $\sigma_{t,r}$. In the original RICE model, the emission control rate is one of the optimized control variables. The emission output ratio, $\sigma_{t,r}$, is determined exogenously and is set to decline over time due to assumed efficiency improvements.

$$E_{Ind,t,r} = \sigma_{t,r}Y_{t,r}(1-\mu_{t,r}) \tag{5.11}$$

The carbon model within the RICE model consists of three equations that resemble the release of CO_2 into the atmosphere and absorption of in the upper oceans, MU_t and lower oceans, ML_t. The parameters ϕ are derived from fitting on more detailed climate models by Nordhaus [2010].

$$\begin{pmatrix} MAT_{t+1} \\ MU_{t+1} \\ ML_{t+1} \end{pmatrix} = \begin{pmatrix} 1.36 \\ 0 \\ 0 \end{pmatrix} E_t + \begin{pmatrix} \phi_{11} & \phi_{12} & 0 \\ \phi_{21} & \phi_{22} & \phi_{32} \\ 0 & \phi_{23} & \phi_{33} \end{pmatrix} \begin{pmatrix} MAT_t \\ MUt \\ MLt \end{pmatrix} \tag{5.12}$$

The CO_2 emissions that are not absorbed by the oceans lead to increases in the atmospheric CO_2 concentration. This leads to an increase in radiative forcing, $FORC_t$ when atmospheric concentration, MAT_t exceeds the pre-industrial equilibrium concentration MAT_{eq}, see equation 5.13. Furthermore, radiative forcing is influenced by external radiative forcing, $FORC_{ex,t}$, which corresponds to other greenhouse gasses from changes in land usage.

$$FORC_t = \eta[\log_2(\frac{MAT_t}{MAT_{eq}})] + FORC_{ex,t} \tag{5.13}$$

5.2.3 Climate sub-model

The climate model determines the atmospheric temperature increases, $T_{ATM,t}$ due to the increases in radiative forcing calculated within the carbon sub-model. Once again, the oceans work as a buffer that absorbs some of the induced warming in the atmospheric layer by increasing the temperature of the ocean, $T_{OCEAN,t}$.

$$\begin{pmatrix} T_{ATM,t+1} \\ T_{OCEAN,t+1} \end{pmatrix} = \begin{pmatrix} \chi 1 \\ 0 \end{pmatrix} FORC_t + \begin{pmatrix} 1 - \chi 1 \chi 2 - \chi 1 \chi 3 & \chi 1 \chi 3 \\ \chi 4 & 1 - \chi 4 \end{pmatrix} \begin{pmatrix} T_{ATM,t} \\ T_{OCEAN,t} \end{pmatrix} \tag{5.14}$$

where:

$\chi 1$: Climate equation coefficient for upper stratum
$\chi 2$: Climate sensitivity parameter
$\chi 3$: Heat transfer coefficient between upper and lower stratum
$\chi 4$: Climate equation coefficient for lower stratum

An important model parameter is the climate sensitivity parameter, χ_2, which represent the temperature response of the earth by a doubling of atmospheric CO_2 concentrations. The climate sensitivity is set by the following equation:

$$\chi 2 = \frac{fco22x}{t2xCO2} \tag{5.15}$$

Estimates of the climate sensitivity vary widely [Beck and Krueger, 2016] which is why this parameter is treated as a deep uncertainty (see chapter 6.4: climate uncertainties). Within the RICE2010 model, Nordhaus estimates the equilibrium climate sensitivity at 3.2°C, but in the DICE2016 model, it is set at 2.9°C.

6 THE PYRICE MODEL

To explore the implications of applying distributive principles in RICE, the original RICE model has been reformulated as the Python PyRICE model. The PyRICE model is no longer an optimization model but has been transformed into a stochastic simulation model. Section 6.1 shows how the original RICE model is set-up within Python and how objective parameters in PyRICE are conceptualized. In section 6.2 and 6.3, the PyRICE model is verified by comparing the original RICE output with the output of PyRICE. In section 6.4, the uncertainties within the original RICE model are introduced consisting of the climate and socioeconomic uncertainties. This includes the adaptation of the SSP scenario-framework in PyRICE.

6.1 MODEL IMPLEMENTATION

The RICE model has been reformulated in Python, largely following the structure of the original model. The work of Lingeswaran [2019] were the DICE model was formulated as the PyDICE model served as an example work for formulating PyRICE as a stochastic simulation model. All original data used in the RICE model has been loaded in the PyRICE model. The most significant revisions are that of the original control variables in RICE, namely the emission control rate $\mu_{t,r}$ and the savings rate $\sigma_{t,r}$. And the implementation of a disaggregated income and damage component within each region. In the original RICE model, the optimal savings rate and emission target year are determined at the end of the optimization run. In this way, the representative agent sets the savings rate and emission control rate such that utility is maximised. The DICE/RICE models are non-linear, intertemporal optimization models that optimize the savings and emission control rate towards the end of this century. Within the PyRICE model, through the usage of a Many-Objective-Evolutionary-Algorithm (MOEA), Pareto optimal policies are identified that satisfy multiple objectives. In contrast to the RICE model, strategies are optimized for different snapshots in time over a 300 year period up to 2305.

6.1.1 Savings rate

The savings rate is exogenously set to converge to the steady-state savings rate for the world determined by the formula below. Similar approaches have been adopted by Dennig et al. [2015]; Smith [2010]; Fankhauser and Tol [2005] This corresponds to the savings rate where economies will tend to converge to as developing countries catch up with developed economies. This is consistent with the original output of RICE2010 where all regions convert to a similar savings rate. Dietz and Stern [2015] have looked at the influence of the savings rate on the optimal abatement trajectory. Their findings show that when the savings rate is set exogenously, the effect of the endogenously set savings rate is non-significant. This supports the adoption of this research by setting the savings rate exogenously to the steady state savings rate.

$$S*_{longrun} = \frac{\gamma}{(1+\delta)} \tag{6.1}$$

where:

γ: The capital share in the Kopp-Douglas capital production function
δ: The annual pure rate of time preference

With a pure rate of time preference of δ = 1.5 and capital share γ = 0.3 the resulting long term savings rate is S = 25,8 %. Within the model, the savings rate is assumed to decrease/increase linearly to the calculated savings rate.

$$S_{t,r} = (S *_{longrun} - S_{t=1,r}) * \frac{t}{S_{time}} + S_{t=1,r} \tag{6.2}$$

where:

$S*_{longrun}$:	The long run savings rate
S_{time}:	Time to converge for the savings rate to the long run savings
$S_{t=1,r}$:	The savings rate in 2015 in region r

6.1.2 Emission control rate

The emission control rate will increase linearly towards the maximum emission control rate set by the regional planner from the observed historical emission control rates in 2015. An extra feature within the PyRICE model is that the maximum control rate can become higher than one. In the DICE2016 model, Nordhaus has assumed that negative emissions will be possible in the future [Nordhaus, 2017]. The possibility of negative emissions is also adopted within the pathways set by the IPCC [Masson-Delmotte et al., 2018].

$$\mu_{t,r} = \mu_{t=0,r} + \frac{(\mu_{max} - \mu_{t,r})}{\mu_{period,r}} \tag{6.3}$$

where:

$\mu_{t,r}$:	The control rate per region at time step *t*
$\mu_{max,r}$:	The maximum control rate per region set by the global planner
$\mu_{period,r}$:	The period where the emissions control rate reaches the maximum control rate

6.1.3 Disaggregated regional consumption

The original RICE model only computes the average consumption per region. But especially in the lower income region, the income distribution is heavily skewed to the right. Although the average CPC output, keeps the model output simple, it neglects significant differences in per capita consumption within regions. Dennig et al. [2015] have found that optimizing for the lowest income groups can result in significant changes in the optimal CO_2 emission pathway. Furthermore, when applying worst-off distribution principles, an extra income resolution enables for a better comparison of worst-off cases. For example, in the Sufficitarian case, average consumption could be around 1500 $ per capita, but the lowest 20 % could only have a per capita consumption of 500 $, which is well below the absolute poverty line defined by the World Bank.

Therefore, within the PyRICE model, a disaggregated consumption function has been implemented which splits average regional consumption into five income quintiles within a region [Dennig et al., 2015]. The pre-damage consumption is computed by calculating the aggregate consumption in every income group by dividing it by the size of the income group. The regional distribution of income across the five quintiles, $D_{r,q}$, has been derived from the World Bank. It is assumed that the distribution of income across groups remains constant over time.

$$C_{pre-damage,t,r,q} = \frac{Y_{gross,t,r} * D_{r,q}}{0.2 * L_{t,r}} \tag{6.4}$$

where:

$Y_{gross,t,r}$:	Gross economic output before damages and abatement
$L_{t,r}$:	The total labour population in a region

The damages per quintile within every region, $\Omega_{t,r,q}$, is primarily determined by setting the damage share distribution. This is set by the elasticity of climate impact, ϕ. An elasticity of 1 assumes a perfect distribution of climate impact across economic consumption. While an elasticity value of -1 results in a damage distribution which predominantly affects the lower-income shares. Dennig et al. [2015] have argued that values for the damage elasticity are justified towards more elastic values as the rich have more means to prepare and mitigate climate damage. Historical examples also show that economic inequalities are a good indicator for exposure to climate impacts [Chancel, 2020; Masson-Delmotte et al., 2018]. For example in Nigeria, the bottom 20 % of the income hierarchy is 50 % more likely to be affected by a flood, 80% more likely to be affected by droughts and 130 % more likely to be exposed to heatwaves than other income groups [Hallegatte and Rozenberg, 2017].

$$\Omega_{t,r,q} = \frac{D^{\phi}_{r,q} * \Omega_{t,r}}{1/5 * L_{t,r}} \tag{6.5}$$

The post damage consumption, $C_{postdamage,t,r,q}$, is calculated by subtracting the damage experienced by every quintile in a region, $Omega_{t,r,q}$, from the pre-damage consumption, $C_{predamage,t,r,q}$

$$C_{post-damage,t,r,q} = C_{pre-damage,t,r,q} - \Omega_{t,r,q} \tag{6.6}$$

The figure below shows the trajectory of the consumption per head in every income quintile for the US and Africa and the average consumption per capita originally calculated in RICE (the brown line). From figure 6.1, it becomes clear that both income distributions are skewed. At first sight, the average consumption in both regions lies at an 'acceptable' level well above most extreme poverty thresholds set by the World Bank. But in 2005, in Africa, the average consumption for bottom 20% was only 380 dollars per year, which is well below the extreme poverty line. Furthermore, also the second income quintile found itself below the poverty line resulting that 40 % of the whole population lived in extreme poverty in Africa around 2005. This shows the importance of disaggregated consumption indicators for determining the worst-off position in both the Prioritarian as the Sufficitarian case.

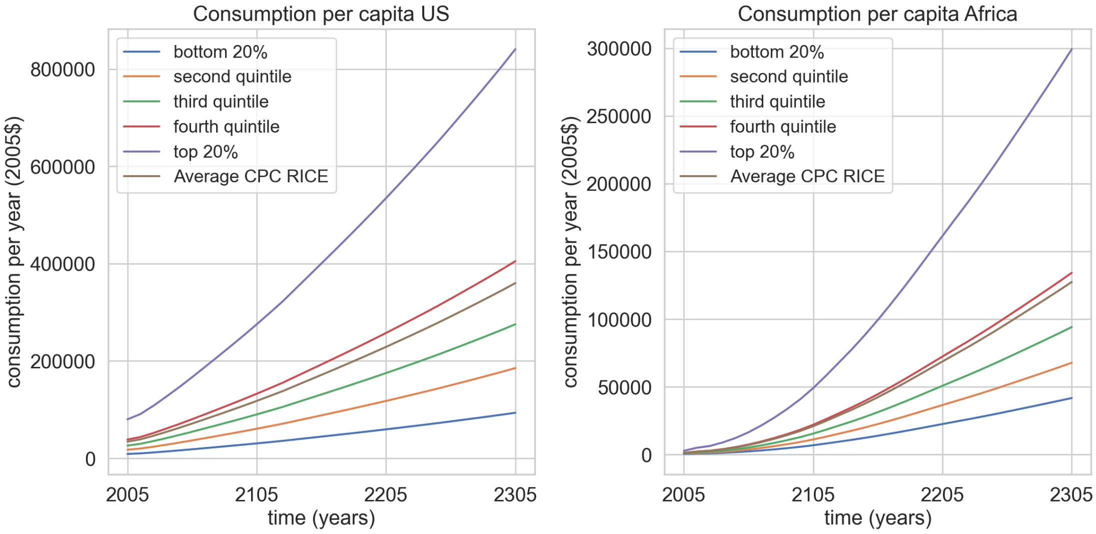


Figure 6.1: Consumption per capita lowest highest income quintile US & Africa

6.2 VERIFICATION OF INPUTS

In the previous section, it was explained how the deterministically set control variables have been adopted in PyRICE. To verify the PyRICE model implementation, the PyRICE control variables are compared with that of the original RICE model in figure 6.2. The figure below compares the savings rates from the original RICE2010 model with the input of PyRICE. The savings rate in RICE follows the observed savings rate in 2005 and 2015. Then, the model converges linearly to the long-run savings rate. Although the behaviour is less dynamic then the original RICE model it follows the same steady state behaviour as the original RICE model.

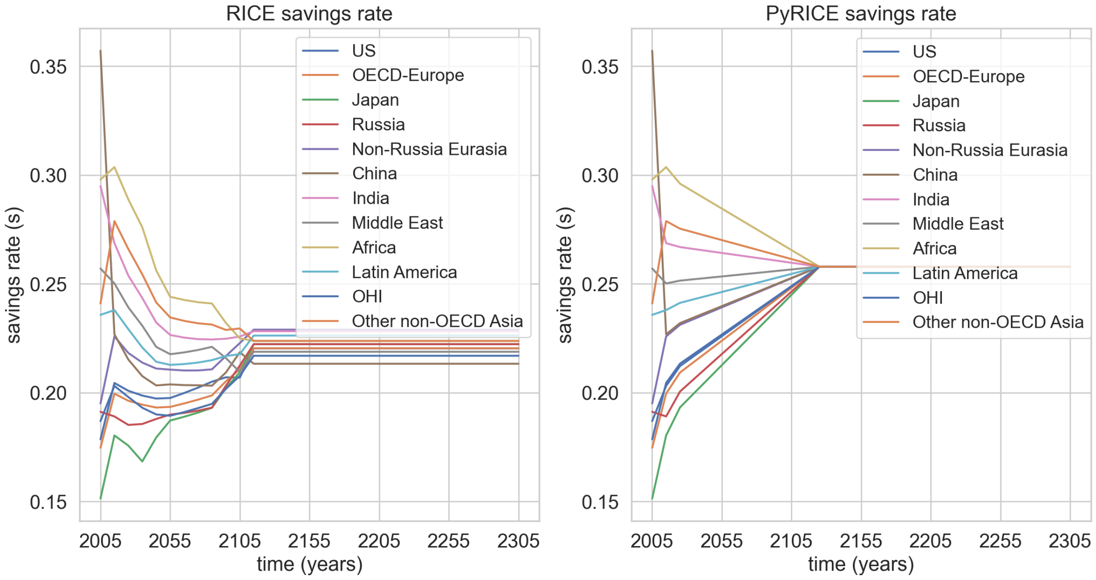


Figure 6.2: Comparison of the savings rate in RICE2010 & PyRICE

Figure 6.3 compares the emission control rate (μ) from the original RICE2010 model with the input of PyRICE. The original RICE input forms a little different trajectory than the straight linear relation in RICE2010.

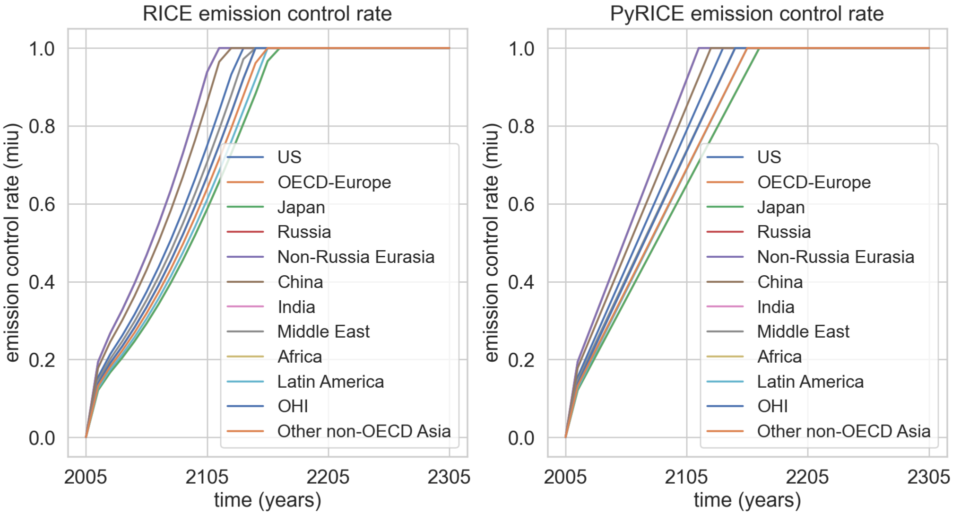


Figure 6.3: Comparison of emission control rate in RICE2010 & PyRICE

6.3 VERIFICATION OF OUTPUTS

To verify if the RICE model has been properly translated into PyRICE, the output of PyRICE has been compared with that of the original RICE model. This has been done in two ways. Firstly, the PyRICE model has been run with the same control variables as RICE2010 optimal run.

Original RICE optimal levers

When the PyRICE model is ran using the RICE optimal levers. The following results are obtained (figure 6.4). From this can be concluded that all output variables follow the original RICE model very well.

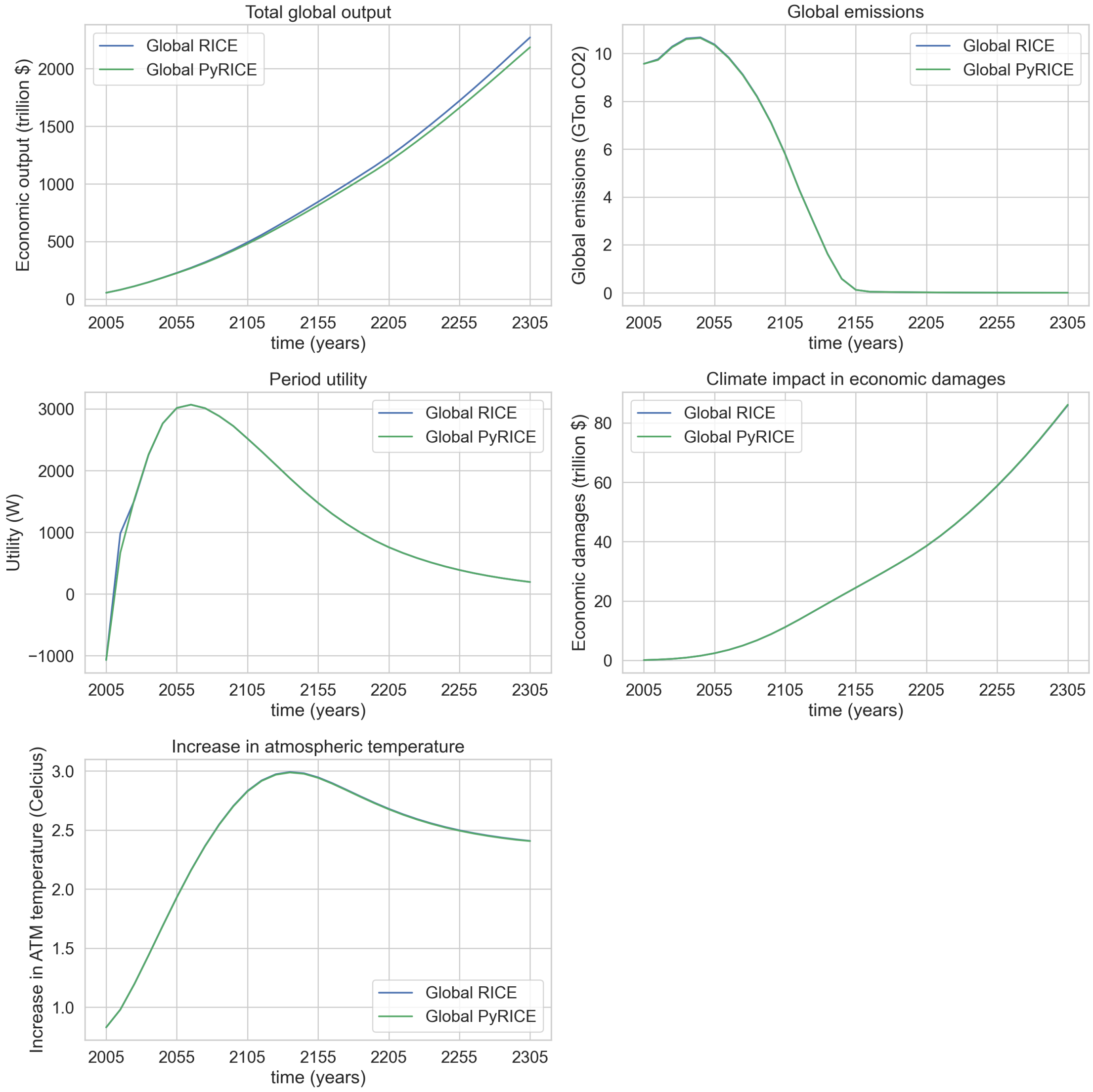


Figure 6.4: Comparison of output of PyRICE deterministic and RICE2010

PyRICE deterministic levers

When we compare the output of PyRICE using the in model calculated values for the levers, we see that global emissions deviate slightly at the beginning of the simulation results. This is because the deviation of the in model-set emission control rate with that of RICE2010. This results in a slightly higher increase in atmospheric temperature. Overall, period utility generally follows the original output quite well. Thus, it can be concluded that the PyRICE model is successfully implemented and can produce similar results as the original RICE model.

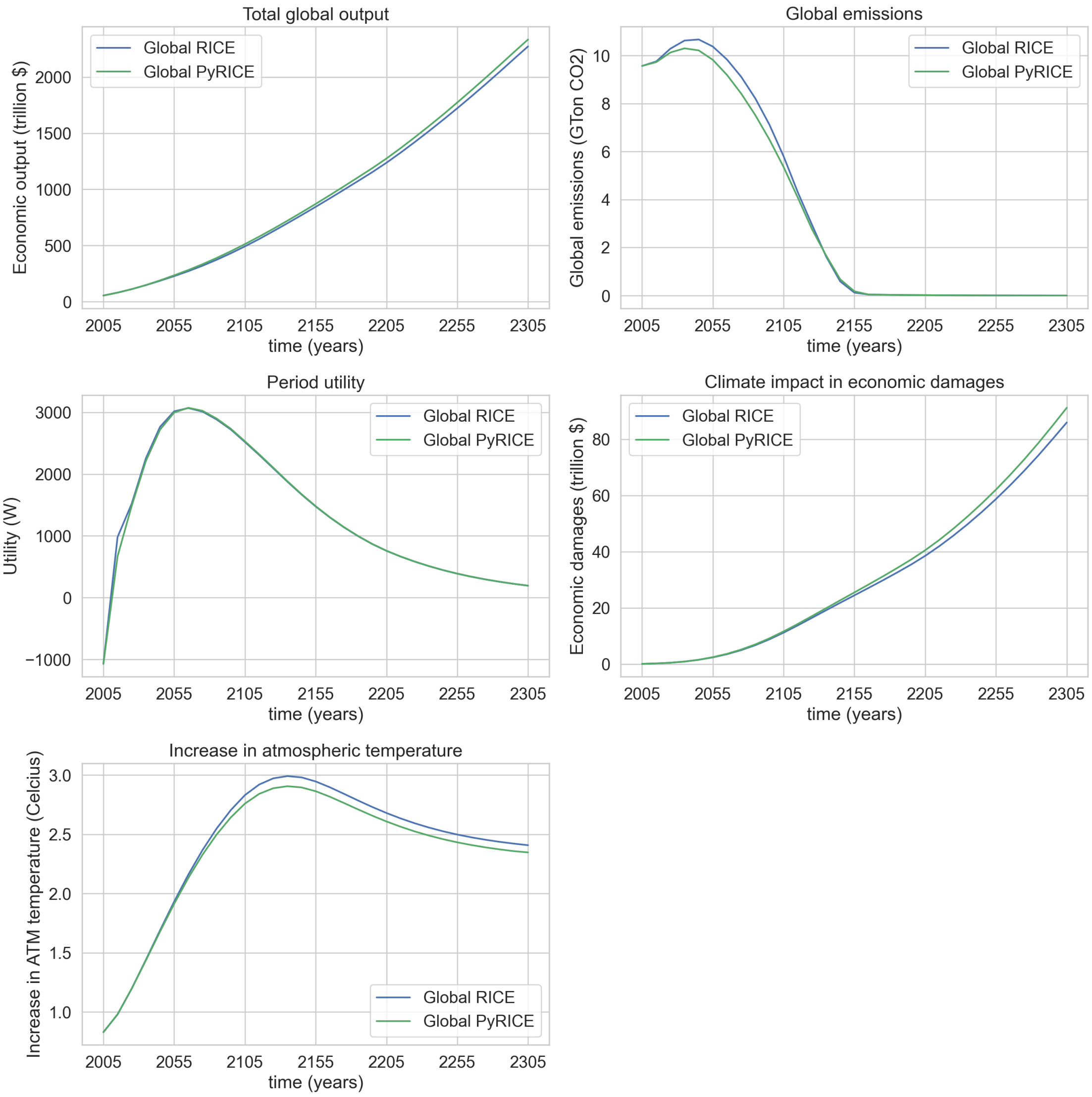


Figure 6.5: Comparison of output PyRICE simulation model and RICE2010

6.4 RICE UNCERTAINTIES

Within the RICE model, there are two main groups of uncertainties, namely uncertainties regarding the earth's climate system and socioeconomic uncertainties in respect to population growth, development of the economy, and that of energy-neutral technologies [Lamontagne et al., 2018]. The following sections introduce the origin and setup of these uncertainties in the PyRICE model.

6.4.1 Climate uncertainties

In climate change modeling, uncertainties play an essential role. Two key uncertainties of global climate change are the world's climate sensitivity and the relation between atmospheric heating and climate damage. The climate sensitivity is defined as the temperature increase resulting from a doubling of the CO2 concentration in the atmosphere [Sherwood et al., 2020]. The damage function is defined as the relation between the impact on the socioeconomic systems as a result of the induced warming [Weitzman, 2009]. The climate sensitivity parameter is uncertain because of the complex feedback loops present within the earth's heating system [Wagner and Weitzman, 2018]. Therefore, the climate sensitivity parameter can not be calculated objectively. For the relation between atmospheric warming and the resulting damage, there is currently a problem of induction for estimating the shape of the damage function. Climate change has just started to occur with current damages being relatively low. This means that historical data can not be used to appropriately estimate the right damage function for much higher levels of atmospheric heating in the future [Pindyck, 2017; Wagner and Weitzman, 2018; Weitzman, 2009]. In many IAMs, quadratic damage functions are fitted on historical data as a way to establish an 'objective' damage function. But there is no objective argument for why high-order damage functions should not be chosen for the same purpose. Higher order distributions can fit the sparse historical data on climate impacts evenly well [Frisch, 2013]. Changing the quadratic damage functions to higher-order damages functions has a big impact for all Integrated Assessment Models as much more serious damages are then associated with higher levels of atmospheric warming.

Regarding the climate sensitivity parameter, Nordhaus sets this at a value of $txCO_2 = 2.9$. This is roughly in the middle of the IPCC estimates. But the range specified by the IPCC ranges from 1.5 to 4.5. Despite the efforts of climate scientist, the likelihood estimate of this range has not been improved in the last 30 years [Weitzman, 2009]. By choosing a single value for this parameter, Nordhaus internalizes a big risk of choosing the wrong parameter value for this influential model component of the DICE/RICE model. To improve the model elements reflecting the earth heating and damage relations, [Lingeswaran, 2019] implemented a way to sample multiple probability density functions for the climate sensitivity parameter to draw from within the DICE2013 model. In this way, the climate sensitivity parameter is treated as a deep uncertainty and sampled across a range of values. Furthermore, [Lingeswaran, 2019] introduced two additional damage functions, namely the Weitzman curve [Weitzman, 2009] and the Newbold & Martin damage function. An additional used damage function will be the original damage function of RICE2010, which consists of a sea-level-rise (SLR) component. Especially the Weitzman damage function can be seen as a hedge against extreme climate impact due to its inclusion of fat-tailed climate impact.

6.4.2 Socio-economic uncertainties

The socioeconomic uncertainties in the original RICE model consist of the population growth, the total factor productivity growth, the efficiency of production factors growth, the availability of fossil fuels and the backstop uncertainties reflecting renewable energy technologies. Future economic development is a key uncertainty regarding future CO_2 emissions. In RICE, economic development is exogenously driven by the total factor productivity (the level of economic efficiency in a region) and population growth. Other key uncertainties are the ratio of the emission to GDP and the cost of the backstop technology, which determines CO_2 abatement costs.

[Lingeswaran, 2019] varied these key uncertainties by changing the original input parameters over +/- 20 % range. There are two disadvantages with this approach: 1) population growth and economic development are not independent of each other 2) the chosen range assumes positive economic growth for all scenarios, which neglects possible negative growth scenarios for the global economy due to population and economic decline.

These disadvantages can be overcome by applying the well-established Shared Socio-Economic Pathways by the IPCC for spanning up the uncertainty space until 2105. The IPCC community has developed the SSPs to enhance inter-study comparison and translation of research findings across disciplines within climate change research [Lamontagne et al., 2018]. Using the SSPs to span the input space enhances not only comparability with other research but also results in a more coherent and diverse scenario set. Because the SSP's projection only project towards 2100, using the SPPs has the implication that two uncertainty analysis will be conducted: 1) a short term uncertainty analysis to assess the exposure to short term uncertainties towards 2105 and 2) a long term uncertainty analysis to test for robustness on longer time frames. The main reason for executing the long term uncertainty analysis is that the earth heating system has a slow response to changes in the earth's atmosphere. The full range of consequences of emission policies, such as the level of sea level rise, will be felt well beyond the twenty-first century. Because the IPCC projections only extend towards 2100 and no other detailed projections exist until 2300, the ranges set by [Lingeswaran, 2019] will be used as input for the long term uncertainty analysis.

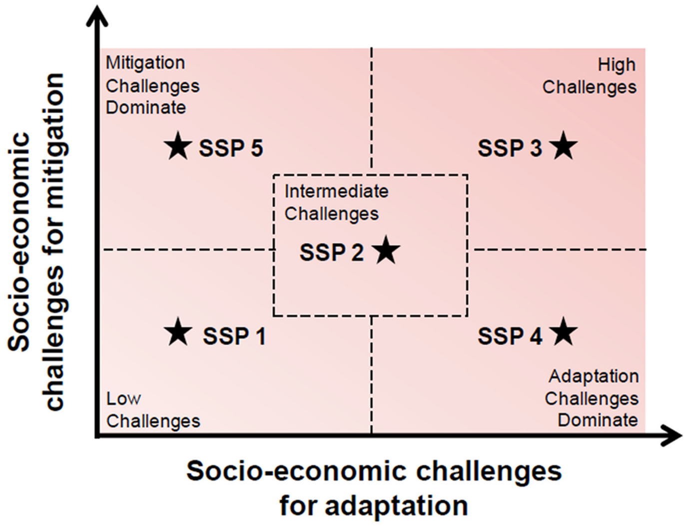


Figure 6.6: Shared Socioeconomic Pathway matrix, derived from Riahi et al. [2017]

SSPS naratives

In the following section, a quick overview will be given on the narratives of the SSPs. The following summary is based on the IPCC narratives published in Riahi et al. [2017], see figure 6.6. It is important to note that, by far, not all narrative points in the SSPs can be adopted in the RICE model. The RICE model structure is not detailed enough to be able to adopt all of these factors. Figure 6.7 show how the narrative elements of the SSPs have been adopted in RICE.

SSP1 Sustainability – Taking the Green Road (Low challenges to mitigation and adaptation) In SSP1, the world shifts gradually towards a more sustainable path. Inclusive development, respecting the world's environmental boundaries becomes important. Educational and health investment accelerate the demographic transition towards lower population growth and more focus is placed on human well-being instead of economic growth. Inequality is reduced within and between countries.

SSP2 Middle of the Road (Medium challenges to mitigation and adaptation) The global community follows similar social, economic, and technological trends in respect to historical patterns. Economic growth proceeds unevenly. The world makes a slow process in achieving sustainable development goals. Population growth is moderate and slows down at the end of the century. Income inequality persists and the vulnerability of societal and environmental shocks remain unchanged.

SSP3 Regional Rivalry – A Rocky Road (High challenges to mitigation and adaptation) Out of resurgent nationalism, countries focus increasingly on domestic and regional issues. As a result of this the goal of energy and food policies shift towards their own regions at the expense of global mitigation efforts. Investments in education and technology decline. There is slow economic growth, and population growth is high in developing countries and slow in the established economies. Inequality is widened over time.

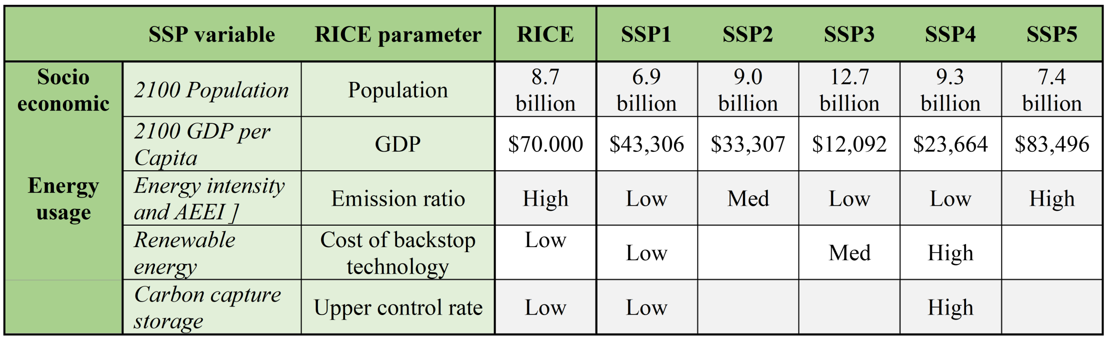
SSP4 Inequality – A Road Divided (Low challenges to mitigation, high challenges to adaptation) There are high unequal investments in human capital between regions leading to increasing disparities in economic opportunities and political power between regions. There emerges a gap between internationally connected societies that contribute to the high-tech sectors in the global economy and the collection of lower-income, less-educated societies that mainly produce goods in a labor-intensive low-tech economy. The global connected high-tech sector diversifies with both investments in fossil fuels and low carbon energy sources. Environmental policies focus mostly on local issues in high and middle-income areas.

SSP5 Fossil-fueled Development – Taking the Highway (High challenges to mitigation, low challenges to adaptation) In this scenario, faith in competitive market innovation and participatory societies remains to produce rapid technological progress as a way to sustainable development remains high. Also, investments in health and education are vast. The urge for strong development is accompanied by wide-scale use of fossil fuels. Resource and energy-intensive lifestyles are adopted globally. Combined, all of these factors produce rapid economic and population growth—the global population peaks in the 21st century. Nevertheless, the faith to effectively manage environmental problems remains high, including the wide-scale adoption of geo-engineering.

SSP specification in RICE

Population development and economic development are dependent on each other. Therefore for the short term uncertainty analysis, the GDP and Population parameters will be set in conjunction with each other. To be able to use the IPCC projections in the RICE model, the regions used in the RICE model have been mapped with the country projections within the SSP data. Because the IPCC does not provide total factor productivity statistics, as a workaround, SSP GDP level forms the input for the economic development in the PyRICE model. The corresponding total factor productivity is then calculated in the RICE based on the SSP GDP input data.

The figure below summarizes the SSP scenarios in relation to the corresponding variables in RICE. The quantitative values for the discrete values for CCS and the emission ratios are derived from Calvin et al. [2017]. The option of BECCS to be able to obtain negative emissions is added to the RICE model which makes it compatible with the IPCC scenarios. Negative emissions have been adopted equally to the implementation of negative emissions in the DICE2013 model by [Nordhaus, 2014]. Although the SPPs build a coherent and highly detailed set of future scenarios, they only reflect a limited view of five distinct scenarios of how the future might look like. The SSPs are build up out of discrete levels reflecting unique time series. Lamontagne et al. [2018] has used this to span up a factorial set of scenarios. This research takes a similar approach by using a partial factorial sampling of the combined socioeconomic and climate uncertainty space. By spanning up a factorial set of scenarios, a total of 35000 scenarios have been generated for the short term uncertainty analysis.



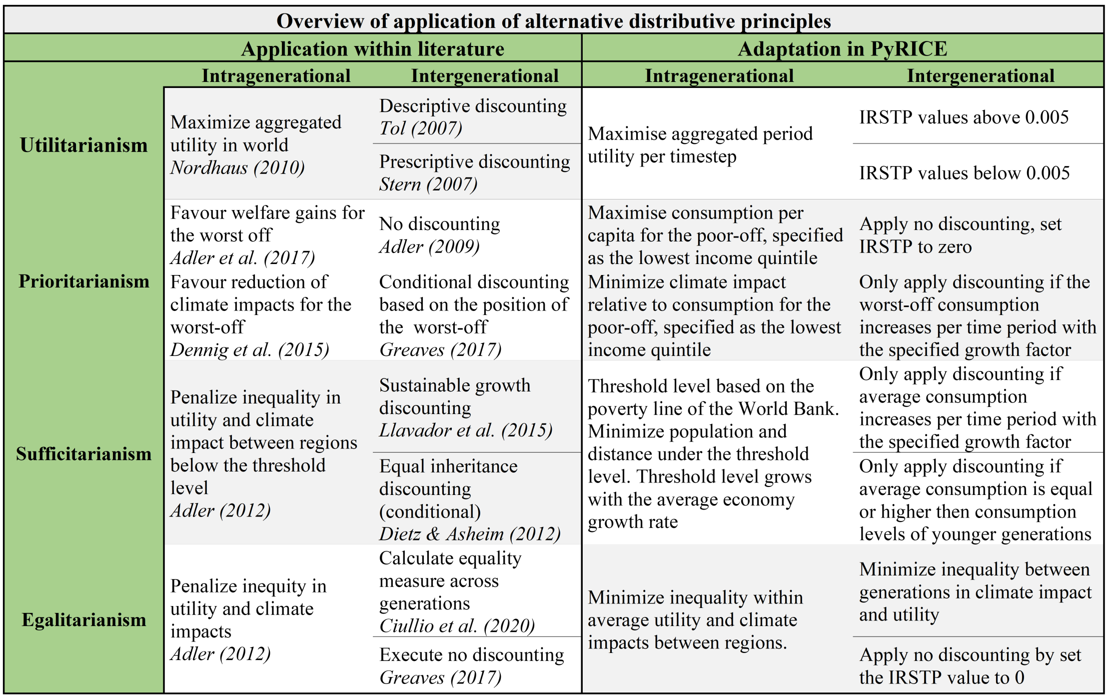
	SSP variable	**RICE parameter**	**RICE**	**SSP1**	**SSP2**	**SSP3**	**SSP4**	**SSP5**
Socio economic	*2100 Population*	Population	8.7 billion	6.9 billion	9.0 billion	12.7 billion	9.3 billion	7.4 billion
	2100 GDP per Capita	GDP	$70.000	$43,306	$33,307	$12,092	$23,664	$83,496
Energy usage	*Energy intensity and AEEI]*	Emission ratio	High	Low	Med	Low	Low	High
	Renewable energy	Cost of backstop technology	Low	Low		Med	High	
	Carbon capture storage	Upper control rate	Low	Low			High	

Figure 6.7: Implementation of the SPPs as uncertainties in PyRICE

7 PYRICE SIMULATION MODEL

When applying the MORDM-method, the first step is to generate new candidate policies. This is done by using the alternative distributive principles within the PyRICE model for altering the objective function. Then a Many Objective Evolutionary Search Algorithm (MOEA) is used to discover Pareto optimal policies [Kasprzyk et al., 2013]. The objectives are the outcomes of interest within the XLRM Framework. The XLRM framework further consists of the uncertainties (X), the policy levers (L), the outcomes of interest (M) and relationships within the model (R) Kwakkel et al. [2016]. Section 7.1 introduces how the eight combinations of distributive principles from chapter 4 are implemented as objectives for the search algorithm in PyRICE. Section 7.2 summarizes the implemented XLRM framework including the levers, model outcomes and external factors.

7.1 IMPLEMENTATION OF DISTRIBUTIVE PRINCIPLES



Overview of application of alternative distributive principles				
	Application within literature		**Adaptation in PyRICE**	
	Intragenerational	**Intergenerational**	**Intragenerational**	**Intergenerational**
Utilitarianism	Maximize aggregated utility in world *Nordhaus (2010)*	Descriptive discounting *Tol (2007)*	Maximise aggregated period utility per timestep	IRSTP values above 0.005
		Prescriptive discounting *Stern (2007)*		IRSTP values below 0.005
Prioritarianism	Favour welfare gains for the worst off *Adler et al. (2017)*	No discounting *Adler (2009)*	Maximise consumption per capita for the poor-off, specified as the lowest income quintile	Apply no discounting, set IRSTP to zero
	Favour reduction of climate impacts for the worst-off *Dennig et al. (2015)*	Conditional discounting based on the position of the worst-off *Greaves (2017)*	Minimize climate impact relative to consumption for the poor-off, specified as the lowest income quintile	Only apply discounting if the worst-off consumption increases per time period with the specified growth factor
Sufficitarianism	Penalize inequality in utility and climate impact between regions below the threshold level *Adler (2012)*	Sustainable growth discounting *Llavador et al. (2015)*	Threshold level based on the poverty line of the World Bank. Minimize population and distance under the threshold level. Threshold level grows with the average economy growth rate	Only apply discounting if average consumption increases per time period with the specified growth factor
		Equal inheritance discounting (conditional) *Dietz & Asheim (2012)*		Only apply discounting if average consumption is equal or higher then consumption levels of younger generations
Egalitarianism	Penalize inequity in utility and climate impacts *Adler (2012)*	Calculate equality measure across generations *Ciullio et al. (2020)*	Minimize inequality within average utility and climate impacts between regions.	Minimize inequality between generations in climate impact and utility
		Execute no discounting *Greaves (2017)*		Apply no discounting by set the IRSTP value to 0

Figure 7.1: Implementation of chosen distributive principles

Within chapter 4, eight combinations of spatial and temporal distributive principles have been chosen to be applied within PyRICE. The principles have been selected as a result of the literature review. Within the literature, alternative principles are often implemented within social welfare functions. For example, by applying a concave welfare function to operationalize the Prioritarian distribution of welfare. The reason for doing this is that by implementing the principle within the social welfare function, a single optimal solution can be found, e.g., the highest aggregated utility policy. The concave welfare function thus acts as a form of aggregating of the Prioritarian principle into one objective variable. Following Arrows impossibility theorem, the decision problem is then transformed into a priori biased decision objective without knowing in advance which element is biased [Franssen, 2005]. To overcome this, the alternative distributive principles are implemented as a many objective decision problem. A summary of how the principles are operationalized is shown in figure 7.1. The following paragraphs highlight the specification of the objectives of each principle.

7.1.1 Prioritarian objectives

Prioritarian SWFs make use of a concave welfare function to favour utility gains of the worst-off relative to utility gains of well-off individuals. Thus, the Prioritarian welfare function tries to accomplish a continuous upward transformation of the position of the worst-off. To imitate this transformation in the PyRICE model, the primary objective is to continuously improve the position of the worst-off income class. The worst-off income class is defined as the lowest income quintile over all regions of the world in the RICE model.

Prioritarian objective 1: maximize: $C_{worst-off}$

where: $C_{worst-off}$ = min$\left[C_{r,q}\right.$ for region r in quintile $\left.q\right]$

Optimizing for only the lowest income class is insensitive to the distribution of climate damages. Therefore an additional objective has been added to the Prioritarian objective function; the relative to consumption climate impact. An argument in favor of splitting the utility and damages as separate objectives has been made by Kulkarni [2020]. The argument is that besides the consumption lowering effect of damages resulting from climate impact, damages in itself have a disutility effect which needs be taken into account separately.

$$C_{relative,t,r,q} = \frac{D_{r,q} * D^{\phi}_{r,q}}{1/5 * L_{t,r}} * \frac{1}{C_{post-damage,t,r,q}} \tag{7.1}$$

Prioritarian objective 2: minimize: $C_{worst-off-relative-consumption}$

where: $C_{worst-off-relative-consumption}$ = min$\left[C_{relative,t,r,q}\right.$ for region r in quintile $\left.q\right]$

7.1.2 Sufficitarian objectives

The Sufficitarian principle aims to minimize the number of individuals living below the threshold level. Therefore the Sufficitarian welfare function can be seen as a discontinuous transformation of the consumption level of worst-off individuals under the threshold. This is different from the Prioritarian principle which will always put more emphasis on the position of the worst-off no matter his absolute position. The Sufficitarian principle only favors welfare gains for individuals below the Sufficitarian threshold. Therefore, the Sufficitarian principle is indifferent to the shape of the distribution above the threshold. As a practical solution for this, often the Utilitarian threshold is applied for shaping the distribution of utility above the threshold [Adler, 2019]. This means that in scenarios where positive economic growth brings all income groups above the threshold, policies are still optimized for utility maximization. In total, three main objectives have been identified for the Sufficitarian principle:

$L_{below-tresh,t}$:	Population living below the Sufficitarian utility threshold
$U_{tresh,t}$:	Maximum utility distance of consumption quintile q over regions r
U_{aggr}:	Aggregated utility W over all regions r and periods t

which makes the Sufficitarian model objectives:

Sufficitarian objective 1 minimize:	$L_{below-thresh,t}$
Sufficitarian objective 2 minimize:	$U_{thresh,t}$
Sufficitarian objective 3 maximize:	U_{aggr}

7.1.3 Egalitarian objectives

In section 4.1, the Egalitarian welfare function has been introduced, which has the form of the normal Utilitarian welfare function with a penalty factor that penalizes inequality within the distribution of utility. This research takes a more strict Egalitarian approach by only specifying objectives that steer the generated policies towards equality. This makes this principle rather extreme, which eases the comparison because a broader distinction between principles can be made. A total of four measures of inequality will be used. The first two objectives act as measure for intergenerational inequality, namely intergenerational consumption inequality and impact inequality. The intergenerational consumption inequality is expressed by the following formula:

$$GINI_{inter-consumption} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} |C_{world,t=i} - C_{world,t=j}|}{2n^2} \tag{7.2}$$

with: $C_{world,t}$: the average global consumption of time period t

The intergenerational impact inequality is expressed by the following formula:

$$GINI_{inter-impact} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} |D_{world,t=i} - D_{world,t=j}|}{2n^2} \tag{7.3}$$

with: $D_{world,t}$: the average global climate impact per time period per time period t

The spatial inequality objectives are the spatial consumption inequality and the spatial climate impact inequality relative to consumption. High-income countries have consumption levels that are a magnitude greater than lower-income countries. Thus the equal amount of climate damage in dollars has a more significant effect in lower-income countries than in higher-income countries. The intragenerational climate impact has therefore been defined relative to the region consumption to overcome the problem of unequal comparison. The intragenerational consumption inequality is expressed by the following formula:

$$GINI_{intra-consumption,t} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} |C_{region,t,r=i} - C_{region,t,r=j}|}{2n^2} \tag{7.4}$$

where: $C_{region,t,r}$: the average regional consumption at time period t in region r

The intragenerational impact inequality is expressed by the following formula:

$$GINI_{intra-impact,t} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n} |D_{relative,t,r=i} - D_{relative,t,r=j}|}{2n^2} \tag{7.5}$$

where: $D_{relative,t,r=j}$ given by:

$$D_{relative,t,r=j} = \frac{D_{average,r,t}}{C_{average,r,t}} \tag{7.6}$$

7.1.4 Utilitarian objectives

In comparison with Nordhaus's application of the Utilitarian principle, additional model objectives have been added that aim to maximize period utility at various points in time (Utilitarian objective 1). This is done to steer the Utilitarian principle in maximizing utility across the whole run. The Utilitarian problem formulation has been set up using utility outputs already specified in the original RICE model (see section 5.1). The two main Utilitarian objectives are:

Utilitarian objective 1: maximize: $U(c_{t,r})$
Utilitarian objective 2: maximize: $W = \sum_{t=1}^{T_{max}} \sum_{r=1}^{R} U(C_{t,r}) L_{t,r} R_t$

7.2 EXPLORATORY MODELING SETUP

This research follows an exploratory modeling approach to evaluate alternative distributive principles. Within chapter 3, the single scenario MORDM has been chosen as the primary method for the exploratory modeling approach. Within this setup, the XLRM framework is used to define the simulation model. The XLRM framework consists of the external factors (X), the policy levers (L), the outcomes of interest (M) and relationships within the model (R) [Kwakkel et al., 2016]. Depending on the simulation method's goal, these parameters are used to search over interesting outcomes, search for new policies or to test policies on robustness.

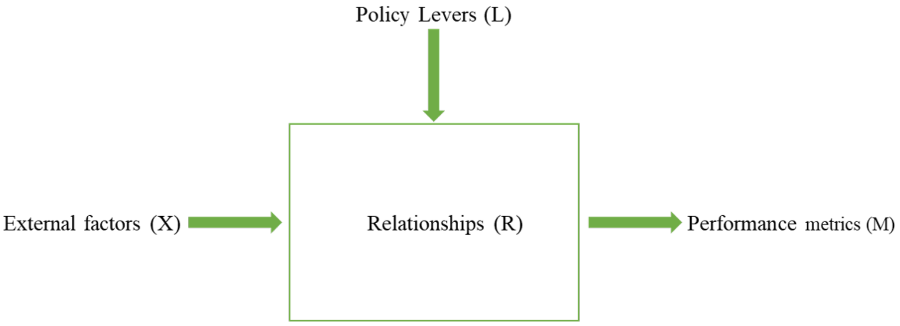
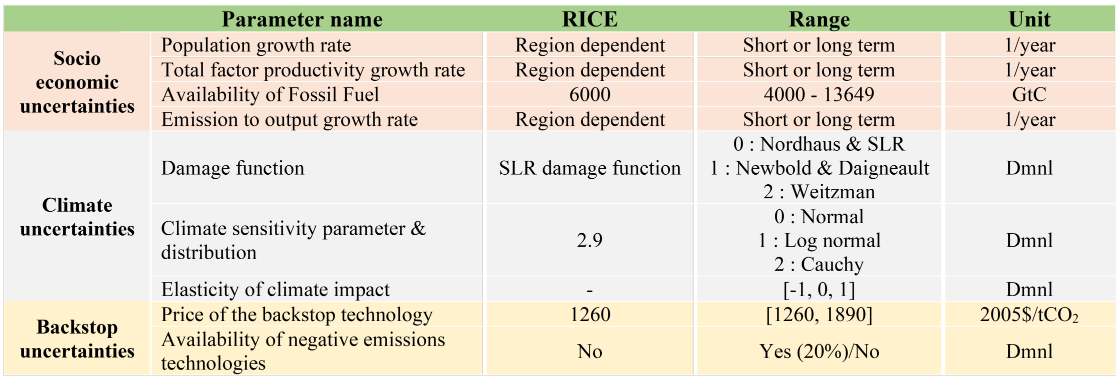


Figure 7.2: Overview of the XLRM framework

7.2.1 External factors

The external factors form all input parameters that lay outside the control of the decision-maker. Deep uncertainty exists in some of the external parameters. Deep uncertain factors are the parameters that have a large impact on the outcomes, do not have known probabilities of outcomes and historical data is insufficient for estimating future values and/or experts disagree on the consequences [Kwakkel et al., 2016]. Within RICE, an example of a deep uncertainty is the earth's climate sensitivity. All uncertain parameters within the PyRICE model are shown below. The origin and setup of these uncertainties have been covered in section 6.4.

The socioeconomic and backstop uncertainties are set up using the shared socioeconomic pathways. The climate uncertainties are drawn from Lingeswaran [2019], which include multiple damage functions and distributions for the climate sensitivity parameter for DICE. As RICE uses an aggregated global climate model, these climate uncertainties can directly be used within RICE. Regarding the backstop uncertainties, an extra deep uncertainty has been introduced, namely the availability of negative emission technologies. RICE2010 does not consider the possibility of negative emissions, whereas DICE2013 heavily depends on negative emissions within its optimal climate trajectory. Negative emissions are also used within many of the Shared Socioeconomic Pathways. But the social and technical feasibility of large scale negative emissions has been questioned [Hallegatte and Rozenberg, 2017; Masson-Delmotte et al., 2018]. Because many pathways that limit warming to 1.5 °C at the end of this century rely on negative emissions, it resembles an important uncertain factor in the PyRICE model.

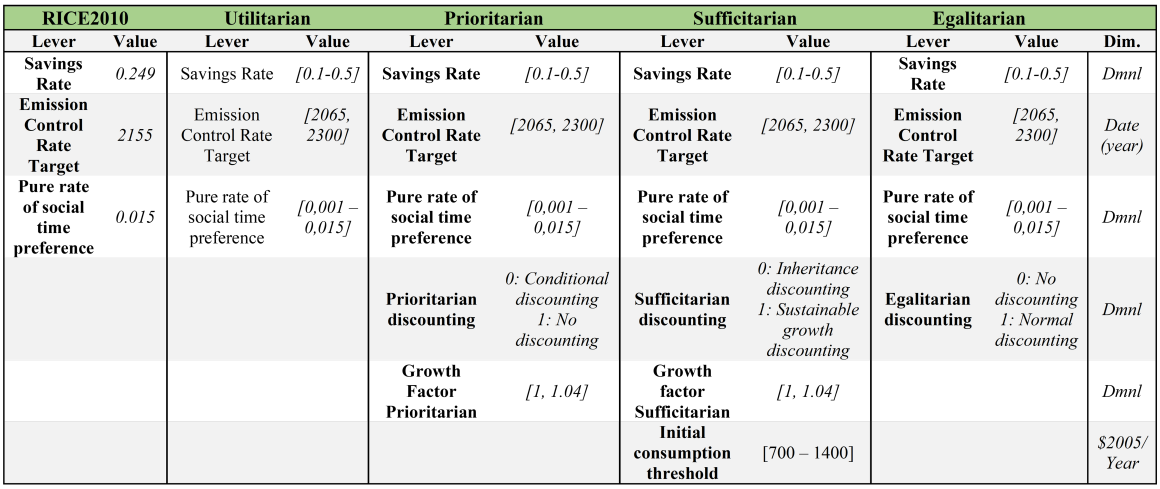


Parameter name		RICE	Range	Unit
Socio economic uncertainties	Population growth rate	Region dependent	Short or long term	1/year
	Total factor productivity growth rate	Region dependent	Short or long term	1/year
	Availability of Fossil Fuel	6000	4000 - 13649	GtC
	Emission to output growth rate	Region dependent	Short or long term	1/year
Climate uncertainties	Damage function	SLR damage function	0 : Nordhaus & SLR 1 : Newbold & Daigneault 2 : Weitzman	Dmnl
	Climate sensitivity parameter & distribution	2.9	0 : Normal 1 : Log normal 2 : Cauchy	Dmnl
	Elasticity of climate impact	-	[-1, 0, 1]	Dmnl
Backstop uncertainties	Price of the backstop technology	1260	[1260, 1890]	2005\$/tCO$_2$
	Availability of negative emissions technologies	No	Yes (20%)/No	Dmnl

Figure 7.3: Deep uncertainties in PyRICE

7.2.2 Policy levers

Within the RICE model, the levers are the control parameters that the social planner of each region can control to reach desirable outcomes. The original levers of RICE2010 have been extended with the additional levers originating from the implemented principles. For example conditional discounting has been added to partly obtain the Prioritarian principle, see figure 7.4. This implicates that in total, there are four separate planning problems.



RICE2010		Utilitarian		Prioritarian		Sufficitarian		Egalitarian		
Lever	**Value**	**Lever**	**Value**	**Lever**	**Value**	**Lever**	**Value**	**Lever**	**Value**	**Dim.**
Savings Rate	*0.249*	Savings Rate	*[0.1-0.5]*	**Savings Rate**	*[0.1-0.5]*	**Savings Rate**	*[0.1-0.5]*	**Savings Rate**	*[0.1-0.5]*	*Dmnl*
Emission Control Rate Target	*2155*	Emission Control Rate Target	*[2065, 2300]*	**Emission Control Rate Target**	*[2065, 2300]*	**Emission Control Rate Target**	*[2065, 2300]*	**Emission Control Rate Target**	*[2065, 2300]*	*Date (year)*
Pure rate of social time preference	*0.015*	Pure rate of social time preference	*[0,001 – 0,015]*	**Pure rate of social time preference**	*[0,001 – 0,015]*	**Pure rate of social time preference**	*[0,001 – 0,015]*	**Pure rate of social time preference**	*[0,001 – 0,015]*	*Dmnl*
				Prioritarian discounting	*0: Conditional discounting* *1: No discounting*	**Sufficitarian discounting**	*0: Inheritance discounting* *1: Sustainable growth discounting*	**Egalitarian discounting**	*0: No discounting* *1: Normal discounting*	*Dmnl*
				Growth Factor Prioritarian	*[1, 1.04]*	**Growth factor Sufficitarian**	*[1, 1.04]*			*Dmnl*
						Initial consumption threshold	[700 – 1400]			*\$2005/ Year*

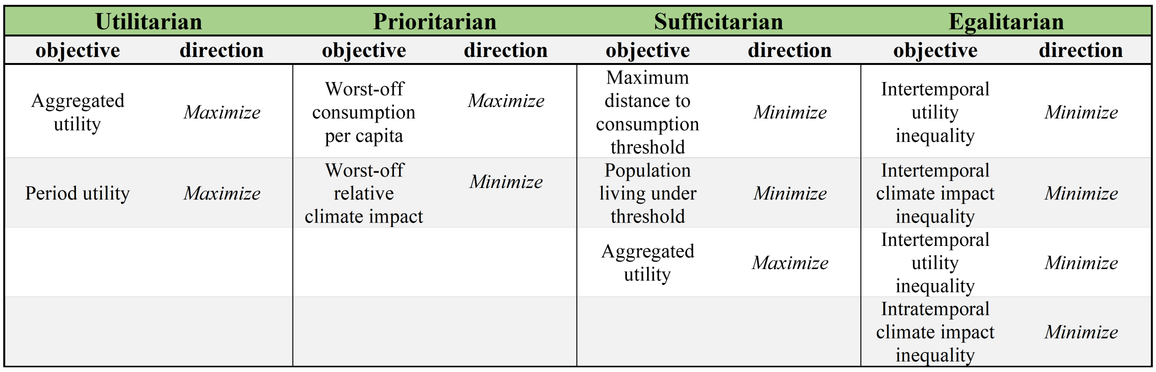
Figure 7.4: Overview of policy space in PyRICE

The original RICE model only optimizes the savings rate and emission control rate to obtain utility maximizing abatement pathways. In the reformulated version of PyDICE Lingeswaran [2019] has argued that the pure rate of social time preference can be seen as an additional lever as it determines how much we value future generations. This approach is also adopted in this research. The savings rate and emission control rate are adopted as described in section 6.1. The emission control rate has been set to a minimum of 2055 to constrain the generated abatement strategies towards policies with a realistic abatement target. In the policy generation step, the savings rate is determined that maximize the objectives of one the planning problems. This means that the savings rate can be set much higher of lower then the end of horizon optimal savings rate.

7.2.3 Model outcomes

The model outcomes form the objectives within the PyRICE model. For example, when searching for new candidate global abatement strategies (a combination of the model levers), these levers are ranked on the performance on the model outcomes. Comparable as for the model levers, the original RICE model objectives have been replaced with objectives that correspond to the selected distributive view on the world by the social planner as introduced in section 7.1. This results in four distinct planning problems corresponding to a Utilitarian, Prioritarian, Sufficitarian and Egalitarian view on the world.

The objectives have been specified for various points in time in order to achieve maximization of the principle specific objectives across the whole run and to be able to identify intergenerational trade-offs. During the policy generation step, all objectives, except the aggregated utility and intertemporal equality objectives, have been optimized for 2055, 2105, 2205 and 2305. Thus in the Utilitarian perspective, the social planner seeks to maximize aggregated utility at the end of run and maximize period utility at 2055, 2105, 2205 and 2305 respectively. Regarding the Prioritarian case, the social planner seeks to optimize the position of the worst-off both in terms of consumption and relative climate impact. For the Sufficitarian case, the social planner seeks to minimize the number of people and the distance of welfare to the threshold. When the global population is above the specified threshold, the social planner seeks to maximize utility following the less strict specification of the Sufficitarian principle by Adler [2019]. Lastly, within the Egalitarian case, the social planner seeks to minimize inequality experienced in consumption and climate impact between regions and between generations.



Utilitarian		**Prioritarian**		**Sufficitarian**		**Egalitarian**	
objective	**direction**	**objective**	**direction**	**objective**	**direction**	**objective**	**direction**
Aggregated utility	*Maximize*	Worst-off consumption per capita	*Maximize*	Maximum distance to consumption threshold	*Minimize*	Intertemporal utility inequality	*Minimize*
Period utility	*Maximize*	Worst-off relative climate impact	*Minimize*	Population living under threshold	*Minimize*	Intertemporal climate impact inequality	*Minimize*
				Aggregated utility	*Maximize*	Intertemporal utility inequality	*Minimize*
						Intratemporal climate impact inequality	*Minimize*

Figure 7.5: Overview of objective function per principle PyRICE

7.2.4 Model relationships

The model relationships (R) are derived from the original RICE model. These relationships connect the external factors, levers and outcomes. Some extra model components have been added, which are described and have been verified in chapter 6. The resulting model is connected with the EMA-workbench, which is an open-source Python package for exploratory modelling and analysis. The EMA-workbench consists of the tools that will be used to analyse the different distributive principles, such as many-objective optimization, uncertainty analysis and scenario discovery. These techniques will be introduced in the coming chapter.

8 EXPLORATORY METHODS

This chapter focuses on the introduction of the simulation methods that will be used to execute the MORDM method. This research applies the single reference scenario MORDM to the PyRICE model. Figure 8.1 shows the steps of the MORDM method. First, the model is specified by drawing from the operationalized distributive principles introduced in the preceding chapter. Then a Many Objective Evolutionary Algorithm (MOEA) is deployed to search over the possible ensemble of all combinations of input levers. This will result in a Pareto approximate set of strategies per alternative principle. The Pareto-set of non-dominated policies is then stress-tested by sampling over the uncertainty input space. By using robustness metrics, policies are ranked on how well they perform over multiple futures. Scenario discovery is applied to identify which system conditions strongly influence the objectives and to identify interesting outcome clusters [Kasprzyk et al., 2013]. The last step is comparing all results from the alternative distribution principles with each other.

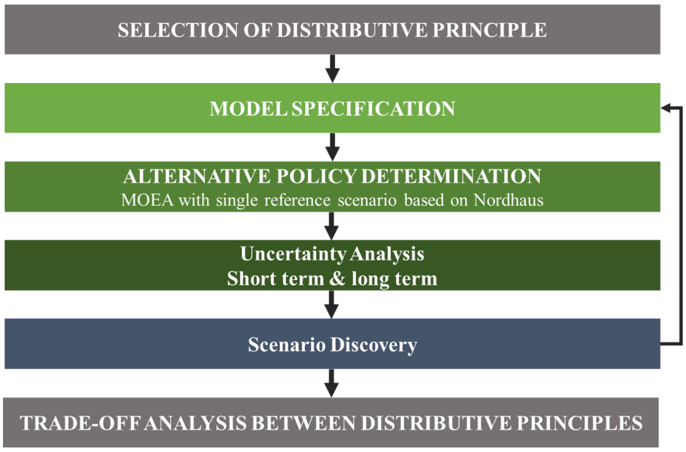


Figure 8.1: Single reference scenario MORDM method

In section 8.1, the choice of the search algorithm to find candidate policies has been highlighted. Section 8.2 states the Uncertainty Analysis approach which includes the sampling method, the choice of robustness metrics and the feature scoring algorithm. Section 8.3 argues which scenario discovery method has been chosen to cluster the outcomes of the uncertainty analysis.

8.1 DIRECTED SEARCH: NSGAII & ϵ-NSGAII

The first step of the MORDM method is to identify candidate policies satisfy the principle specific objectives. Thus, it is the goal to find Pareto optimal policy combinations of the input lever space. This requires a search algorithm capable of finding the Pareto front even when dealing with conflicting objectives. Many objective evolutionary algorithms have been developed for this purpose. The general form of a search algorithm is indicated below, based on Bartholomew and Kwakkel [2020].

1. A set of candidate policies is randomly generated and compared with the objective target
2. The best fitting options are used to generate new candidate policies

3. Relevance of the new options is determined using the objective target in step 1
4. Candidate policies with the lowest relevance in the original set are replaced with items found in the discovered set at step 2.
5. iterate from 2 until a stop condition is met

One of the earliest and breakthrough algorithm is the NSGAII search algorithm. NSGAII makes use of a constant population size for each generation of tracked solutions. NSGAII was one of the first algorithms to deploy Pareto dominance as a way to search and rank alternative solutions to a decision problem [Reed et al., 2013]. Each search iteration, the algorithm employs a Pareto sorting algorithm to find a new non-dominated set of solutions by combining the existing set of possible solutions and the newly found population of potential alternatives. This results in a new set of non-dominated policy alternatives which forms the input for the next iteration. In complex systems, due to the presence of uncertainty and conflicting objectives, it is often not possible to reach the exact Pareto optimal front. Therefore the goal of the NSGAII, and many other search algorithms, is to arrive at the approximate Pareto front [Kasprzyk et al., 2013].

The NSGAII algorithm was extended into the ϵ-NSGAII algorithm by building in ϵ dominance in the sorting process, adaptive population sizing, and time continuation. Time continuation is the injection of new policy solutions to improve the search step. Other MOEAs often used fixed population sizes throughout the whole run. Whereas in ϵ-NSGAII, adaptive sizing and time-continuation is done through a series of smaller runs. The search can start with a relatively low population size to reduce computational cost. Then when a more stable set of alternatives have been generated, more emphasis can be put on the selection of the Pareto approximate set. Therefore the ϵ-NSGAII algorithm can find high-quality Pareto approximate sets efficiently [Reed et al., 2013]. The desired level of precision is specified by the decision-maker through the epsilon value. Solutions are only considered dominant if they fall outside the box determined by the epsilon precision value.

Epsilon progress is used to assess the accuracy level of the found policy in the Pareto approximate set. Epsilon progress is a measure for new policies that are being added to the set of non-dominated policy alternatives. Thus when assessing epsilon progress, you are looking for a curve that has flattened, which indicates convergence [Reed et al., 2013]. Another convergence metric for MOEAs is Hypervolume. Hypervolume is a measure of the possible policy space that is being covered by the set of non-dominated policy alternatives found within the MOEA. When the slope of the Hypervolume is flat, no new diversifying policy alternatives are added to the Pareto front. Therefore these new policies are of lesser importance as they do not reveal any new information about successful combinations of the policy levers. In this research, due to the complexity of the decision problems and computational constraints, the focus has been laid on the stabilization of the epsilon-progress. This is because Hypervolume adds considerable extra computational burden for complex decision problems [Reed et al., 2013].

8.2 UNCERTAINTY ANALYSIS

Uncertainty analysis makes use of a large number of possible scenarios as input for the model. To sample across the uncertainty space, Latin hyper-cube sampling is used. Latin Hyper-Cube sampling is chosen over Monte Carlo simulation. This is because Monte Carlo is a rather inefficient way of sampling as generated scenarios rely on pure randomness. This can lead to clusters at specific intervals. In contrast to this, Latin Hyper-cube sampling ensures equal spread over the input space by partitioning up the input space and selecting one sample per interval. Furthermore, Latin Hyper-cube shuffles each input parameter to create an unbiased set [Kwakkel, 2017].

8.2.1 Features scoring algorithm

To assess the relative importance of the uncertainty analysis inputs, a feature score method will be applied to the uncertainty outcomes. There are three main techniques for determining feature importance: 1) Regression based methods 2) Decision tree based global sensitivity analysis (GSA) and 3) Variance-based GSA. Variance based global sensitivity analysis has the advantage that it can estimate not only relative importance but also the direct effect of an input parameter on one of the output parameters. Because of these advantages, Variance-based GSA has become the defacto standard of assessing parameter importance in complex environmental models Jaxa-Rozen and Kwakkel [2018]. But Variance GSA is computational expensive as the run time increases linearly with the number of input parameters. Because the uncertainty analysis consists of over a million scenarios, the Variance-based GSA has not been chosen to be applied in this research.

Classical regression-based techniques are less suited for non-linear models such as the PyRICE model. For that matter, decision-tree based method offer better and more accurate performance for non-linear models. Furthermore, Decision-trees methods perform well with heterogeneous input data such as continuous or categorical parameters. Decision-trees based methods are well-known within machine learning. Ensemble techniques such as Random Forest and Extra Trees improve performance over single decision tree methods, such as CART, by fitting multiple trees [Hapfelmeier and Ulm, 2013]. Both Random Forest and Extra Trees reduce the variance resulting from the usage of only one single tree by taking into account the predictions of multiple trees. Extra-trees is faster than Random Forest because the cutting points at each node in the tree are determined randomly instead through optimization in Random Forest. But at the final step in Extra-Trees, optimal cut-off points are still selected over all trees. Therefore Extra-Trees introduces randomization but also includes optimization in the building process of the trees. Jaxa-Rozen and Kwakkel [2018] showed that Extra-Trees therefore outperforms Random forest on establishing feature importance within the CDICE model. This is why Extra-Trees is chosen as the feature scoring method within this thesis.

8.2.2 Choice of robustness metrics

During the uncertainty analysis, the candidate policies will be stress-tested over many different scenarios. Robustness metrics are calculated as a way to aggregate the performance of a candidate strategy over all scenarios. Two categories of robustness metrics can be distinguished. Statistical regret metrics consider the distribution of outcomes of interest over the tested scenarios. Regret based metrics are calculated for every strategy in relation to each scenario. When robustness metrics are calculated for each model objective, this enables robustness trade-off comparison between objectives [Eker and Kwakkel, 2018]. This is of particular usages in climate models as a decision-maker is interested in conservative and robust pathways regarding atmospheric warming but could be more willing to accept a lower robustness level on other parameters.

Numerous robustness metrics can be chosen as a proxy for robustness. Examples are the Maximin, Minimax, Maximin regret, Hurwicz optimism-pessimism rule, Laplace's principle ofinsufficient reason and the mean/standard deviation [McPhail et al., 2018]. Often different robustness metrics measure different 'kinds' of robustness. For example, the Minimax (strict robustness) metric is a worst-case approach that looks for the best performance under the worst-case analyzed. These are often rare combinations of the uncertainty parameters with a significant impact on the outcomes. However, because these combinations are rare, this robustness metric does not provide a good proxy for actual robustness across all scenarios [Bartholomew and Kwakkel, 2020].

For assessing robustness in the uncertainty analysis, the minimax regret metric has been chosen due to its high risk-adversity. Minimax regret, better known as the Savage criterion, tries to minimize regret to the worst-case scenario [Eker and Kwakkel, 2018]. The Minimax compares the situation of what the decision-maker did and what he could have done if he could perfectly predict the future. The Minimax then minimizes this regret [Bartholomew and Kwakkel, 2020]. Because the Minimax regret is so risk-averse, the mean/standard deviation metric has been selected as an average indicator for robustness across the full range of scenarios. The Mean/Standard deviation metric is adopted from the signal to noise ratio in control theory. It determines the mean and standard deviation of the performance of candidate policies over all scenarios. The mean/standard deviation seeks a strategy that has a good average performance with little variation around the average performance [Eker and Kwakkel, 2018].

8.3 SCENARIO DISCOVERY METHODS

Scenario discovery is the process of finding vulnerabilities of candidate policies. The goal is to find clusters of model runs that can be labeled into understandable combinations of model parameters where robust policies perform well or poorly [Bryant and Lempert, 2010]. This can be challenging as the outcomes of 35000 individual scenarios will be computed across many strategies. Therefore only candidate policies that have performed well during the policy search and have high robustness will be subjected to clustering.

8.3.1 Clustering methods

To cluster the outcome space, many clustering techniques can be used. PRIM and CART are commonly used clustering methods to cluster outcomes during the Scenario Discovery step within the MORDM method. PRIM is a bump hunting algorithm that refers to the process of mapping out local regions where the target function of interest has lower or higher values than its average across the entire space. CART is a binary tree-based classification algorithm that can be used for the classification of binary outcome regions.

Another commonly used algorithm within scenario discovery is Time Series based Clustering techniques. The aim of Time Series Clustering algorithms is to cluster a group of times series into two or more subset with high similarity within each subset while having a low similarity between the subsets [Liao, 2005]. Therefore, time series clustering has the potential to better account for dynamics over time within Scenario Discovery. For example, when climate impacts suddenly drop near the horizon, a time series clustering algorithm should be able to distinguish this dynamic from suddenly rising climate impact to that some point. Clustering based on single points would miss these kinds of dynamics. A second benefit to scenario clustering is that the whole outcome space is partitioned in clustered instead of a small subset within other techniques [Steinmann et al., 2020].

Overall, time series clustering has numerous advantages over PRIM or CART, especially in the RICE model, which focuses on abatement pathways over time. Furthermore, the whole outcome space will be partitioned into clusters that will help to form coherent conclusions of the effects of the different principles. Therefore time series clustering will serve as the primary clustering technique within the scenario discovery step.

8.3.2 Time series clustering

There are three main approaches for time series clustering, namely feature based, data-based and model based. The feature-based try to identify time series properties such as the number of peaks and amplitude [Lingeswaran, 2019]. Time series are then compared in terms of similarity across these properties. Data-based approaches compare data points between time series and determine similarity using a distance function. Model-based approaches try to fit a mathematical model on each time series, for example, using linear regression. Then similarity is based on the parameters that are fitted on the time series [Steinmann et al., 2020].

Steinmann [2018] have found that data-based approaches such as the complexity-invariant distant (CID) method perform well to identify tipping points in non-linear systems. Within this approach, the Euclidean distance is determined between each time series. This distance is then corrected by the estimated complexity of the distance, which is calculated as the root of the sum of the squares of every distance difference between two observations. This correction is done because complex time series are often estimated too far apart than they truly are within clustering methods [Batista et al., 2011]. The CID measure is implemented within the EMA-workbench and can therefore relatively easily be used. Due to its good performance on non-linear systems and its availability in the EMA-workbench. The data based CID similarity approach has been chosen as time series clustering method.

After calculating the distance matrix containing all distances between all time series, a hierarchical agglomerative clustering algorithm is used to build the clusters of time series. This bottom-up clustering algorithm lets each observation start into its own cluster. Then pairs of clusters are merged or split based on a certain linkage criterion, which is a measure of dissimilarity or a cluster [Yim and Ramdeen, 2015]. Clusters are determined based on the complete linkage criterion which measures similarity of two clusters based on the similarity of its most dissimilar members in the cluster. A drawback of the complete linkage criterion is that it pays to much attention to outliers that do not fit well within the cluster [Schütze et al., 2008]. An important advantage of the complete-linkage approach is that it overcomes the chaining phenomenon drawback present within single-linkage clustering where clusters are formed because single items lie close to each other and are merged together. Instead, complete linkage tends to result in more compact clusters with equal diameters [Liao, 2005].

III

SIMULATION RESULTS

9 GENERATION OF ALTERNATIVE TRAJECTORIES

Within this chapter, the alternative distributive principles in the PyRICE model will be used to generate new abatement pathways. Their performance will be compared with the Nordhaus policy under the reference scenario. Firstly, in section 9.1, a Many Objective Evolutionary Algorithm (MOEA) is applied to each problem formulation to search for Pareto optimal strategies. Section 9.1.1-9.1.4 introduce the generated policies for the Utilitarian, Prioritarian, Sufficitarian, and Egalitarian principle. Section 9.2 summarizes the chosen example policies for each principle and evaluates the outcomes of the Nordhaus strategy (9.2.1) and the alternative strategies under the reference scenario (9.2.2).

9.1 DIRECTED POLICY SEARCH

For each problem formulation, representing one of the four distributive principles, the MOEA has searched for candidate policies that score higher on the reference scenario on principle specific objectives. Due to the complexity of some of the optimization problems, the Pareto approximate front of some principles was large. For example, for the Utilitarian principle, more than 800 Pareto approximate optimal candidate strategies have been identified. It is not possible to test all of these strategies for robustness due to the computational burden. Therefore, after policies were generated, example policies have been chosen. Example policies have been selected based on diversity and ability to span up the whole lever space to test all principle components.

To what extent the search algorithms look for new candidate solutions is controlled by the amount of NFE. When the NFE is set too small, convergence is not reached, and potential optimal solutions are missed. When NFE is set to high, an unnecessary long computation is executed to obtain the Pareto set. To increase the likelihood that the full policy space has been covered during the search phase, each of the optimization problems was sampled across NFE = 200000. During the first iteration of the strategy search, full spread across the whole policy space was not obtained. Because optimal policies concentrated on specific principle combinations. Therefore, the Utilitarian and Sufficitarian optimization problems have been constrained to search for candidate policies across the full lever space. For example, to ensure that found Utilitarian policies have elements of prescriptive and descriptive discounting. The constraints have limited the complexity of the optimization problem. Based on the higher complexity of the Utilitarian search problem, NFE was set to 75000 and 10000 for the Sufficitarian problem. From figure 9.2, it becomes apparent that convergence has been reached for each of the optimization problems as the curve has flattened for all optimization problems.

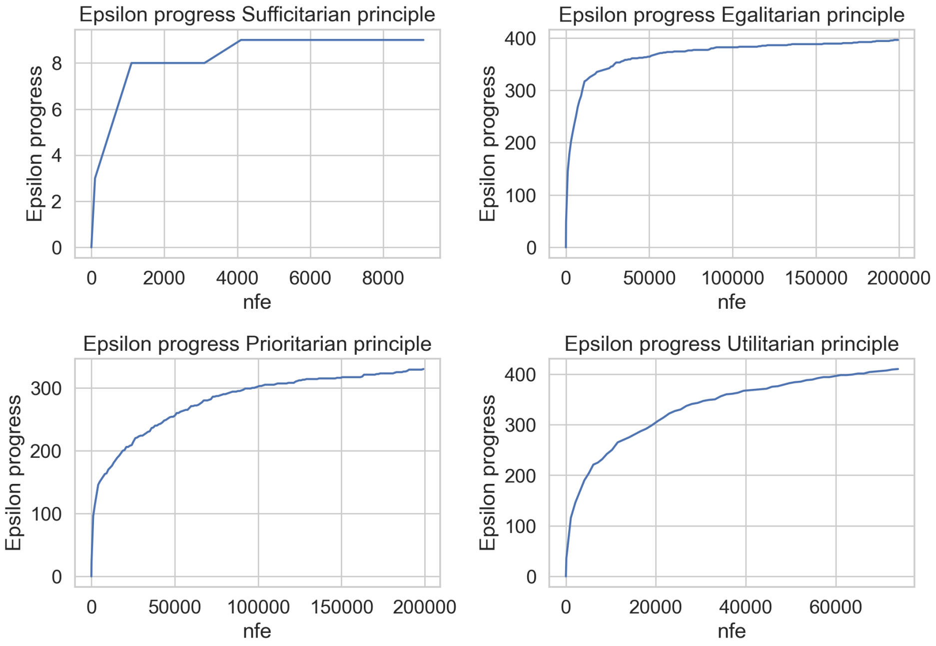


Figure 9.1: Epsilon progress four optimization problems

9.1.1 Alternative Utilitarian policies

In total, 882 alternative Utilitarian policies have been generated during the directed search. The policy space of the Utilitarian policies has been reduced by selecting the 50 top policies based on aggregate welfare. An overview of these top 50 policies can be seen below in the parallel coordinates plot. Each line represents a policy combination that is part of the Pareto approximate set of generated policies. This means that each of these policies scores at least better on one of the objectives than the Nordhaus optimal policy.

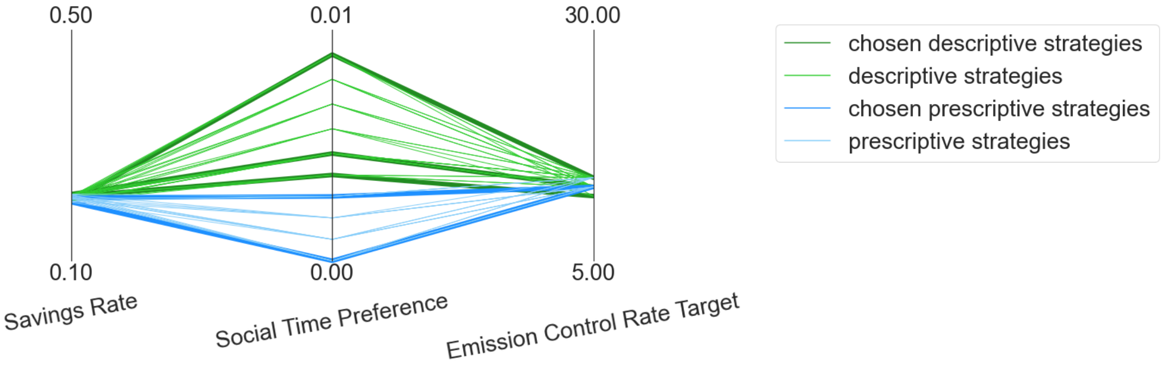


Figure 9.2: Generated Utilitarian strategies

Figure 9.2 shows that Utilitarian policies have homogeneous emission control rates and savings rates that match the Nordhaus optimal policy. The savings rates are all near 0.248, and the emission control rates in the range of 13. From the 50 policies, a total of five, of whom three descriptive and two prescriptive policies have been selected with an equal spread across the lever space.

9.1.2 Alternative Prioritarian policies

For the Prioritarian case, a total of 64 alternative Prioritarian policies have been generated (figure 9.3). These policies form the Pareto approximate front for the Prioritarian problem formulation. Prioritarian policies tend to have a stringent emission control target as most policies reach zero emissions within the 2065 to 2105 period.

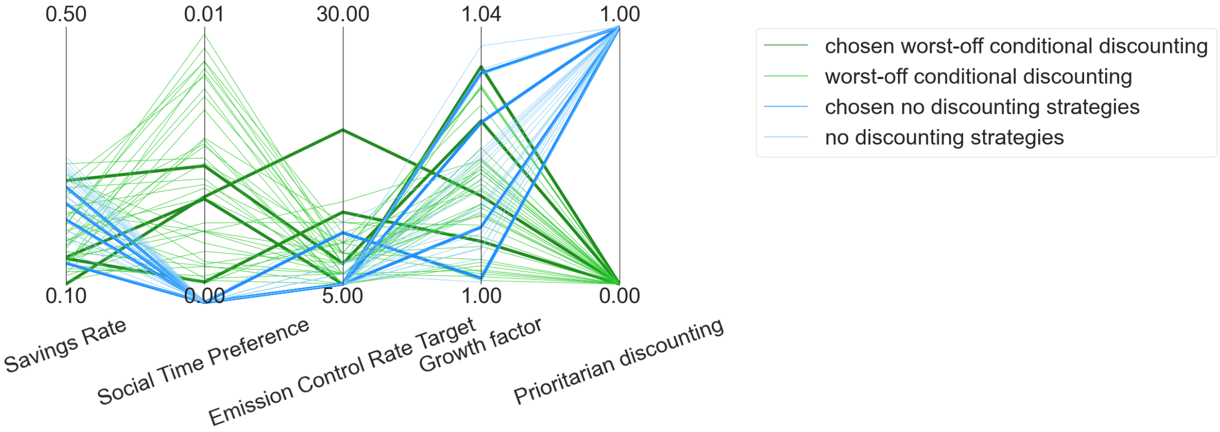


Figure 9.3: Generated Prioritarian strategies

9.1.3 Alternative Sufficitarian policies

The generated 34 alternative policies (see figure 9.4) possess very similar savings rate and social rate of time preference. Because of the usage of the optimistic Nordhaus reference scenario, the Sufficitarian objectives (e.g., threshold distance & population under threshold) are minimized over time. In combinations of policy inputs where this is the case, the optimization problem is reduced to maximizing aggregated welfare. This favors lower IRSTP values and an optimized savings rate regarding total economic output over time. The emission control rate is more stringent than the Utilitarian case. Because faster abatement minimizes the number of people under the threshold.

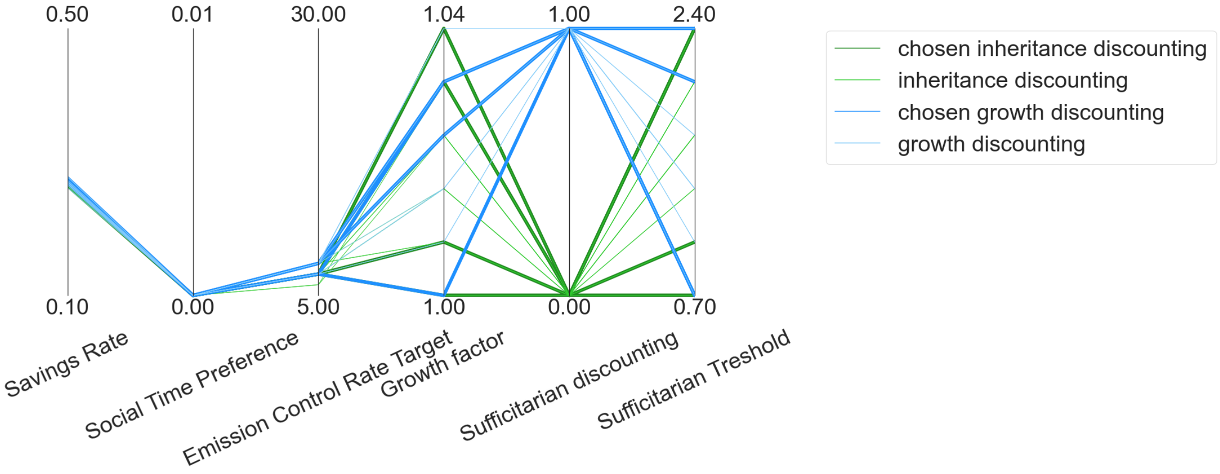


Figure 9.4: Generated Sufficitarian strategies

9.1.4 Alternative Egalitarian policies

Applying the directed search to the Egalitarian principle resulted in 52 Egalitarian Pareto optimal policies. In comparison with the other principles, Egalitarian strategies are more spread across the lever space. Egalitarian objectives can be optimized by slow and high climate action and by a low and high savings behaviour of households. The explanation is that by saving less, current inequality is reduced due to increased consumption. Saving more in the short results in higher equality in the long term. The same holds for higher emission control rate targets. Slow targets of net-zero well beyond 2150 result in lower inequality in the short term. While stringent emission control rate targets have the potential to reduce inequality in the future. For both Egalitarian temporal principles, four example policies have been selected.

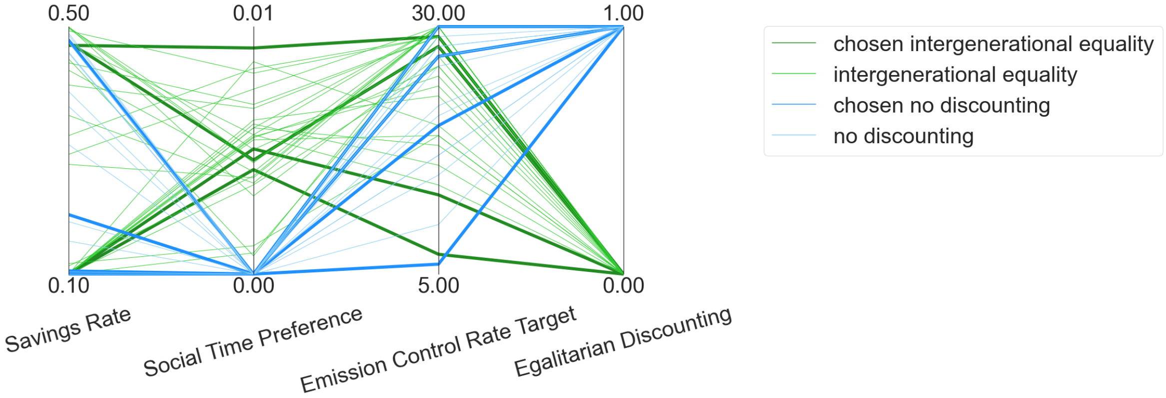


Figure 9.5: Generated Egalitarian strategies

9.2 SUMMARY GENERATED STRATEGIES

The figure below shows the abatement pathways for each principle. Most Egalitarian strategies require a slow abatement pathway. Only one Egalitarian policy demands rapid abatement reaching net-zero emissions in 2070. As expected, Utilitarian pathways possess similar pathways as the Nordhaus (Utilitarian) pathway. The Sufficitarian and the Prioritarian pathways have faster abatement pathways than the Nordhaus policy, with Sufficitarian pathways being the most stringent relative over all individual policies.

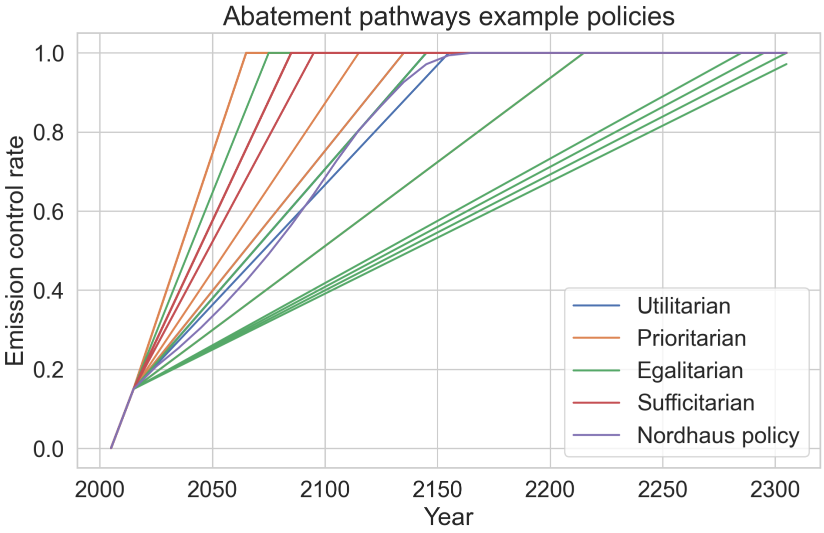


Figure 9.6: Abatement rate development of each example strategy

Appendix D summarizes the characteristics of all example policies regarding the emission control rate, the savings rate, IRSTP, and the setting of the principle specific intergenerational levers.

9.2.1 Reference scenario outcomes of Nordhaus policy

Within the assumed Nordhaus optimal policy, economic growth will substantially reduce inequality in consumption within generations. In the long run, climate impact on the worst-off will rise to 5% in 2100, and 12.5 % in 2305 of economic consumption. Because climate impact is still low in the short run, spatial climate impact inequality remains low initially. But rising damages, in the long run, increase inequality in climate impact. Furthermore, climate damages do not peak when emissions peak due to the slow response of the earth heating to the damage system due to the impact of sea-level rise on the socioeconomic system. This magnifies impact inequality between generations. For a full evaluation of the base case, see Appendix C.

9.2.2 Reference scenario outcomes alternative policies

In general, the Prioritarian strategies achieve the highest protection for the lowest income groups. But also, the Sufficitarian strategies result in high-income levels for the worst-off. Although the difference in absolute economic consumption with the Utilitarian and Egalitarian strategies is small. This is because the worst-off performance is partially locked in the economically optimistic Nordhaus reference scenario. Nevertheless, under the Nordhaus policy, the relative climate impact endured by the worst-off is almost two times higher than in the best performing Prioritarian policy at 2305. There is a clear negative relationship between higher atmospheric warming and a weaker performance on the Prioritarian objectives (Appendix E: fig E.1)

The high levels of economic growth lead to rapid consumption growth in the lower-income countries. This quickly reduces the number of people under the Sufficitarian threshold while reducing inequality in consumption between regions. This shows the importance of the economic scenario in determining inequality and the economic position of the worst-off. Relative climate impact for the worst-off is severe within some Egalitarian strategies; up to 40 % of income is lost due to climate impact caused by almost no emission reduction. Across all strategies, inequality in climate impact between generations rises even when atmospheric warming decreases after peaking.

10 VULNERABILITY ANALYSIS

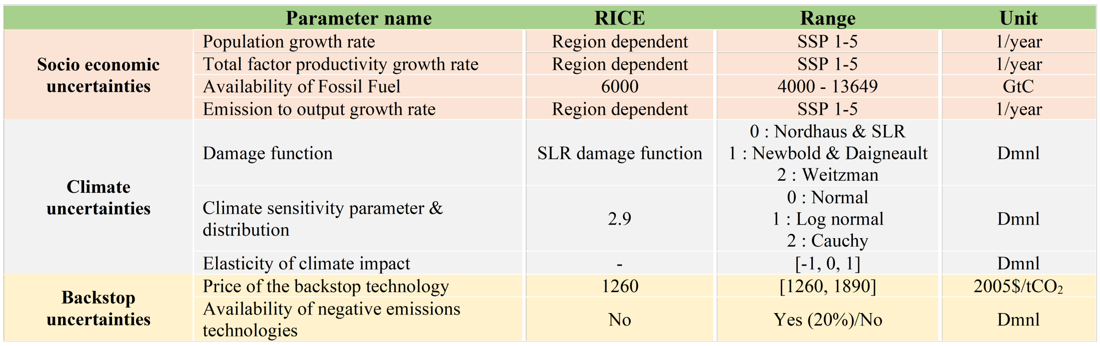
In the previous chapter, alternative strategies have been discussed that were generated by applying distributive principles to the PyRICE model. Strategies were optimized over the reference scenario of Nordhaus 2010. In this chapter, the strategies' performance is stress-tested over multiple possible futures to assess the robustness of each strategy. Section 10.1 states the taken approach of the uncertainty analysis. Section 10.2 gives an overview of the most important short-term uncertainty analysis outcomes until 2105 including the robustness scores. Section 10.3 states the relative importance of the short term uncertainty inputs. The strategies are also tested on their long term vulnerability to climate uncertainties (section 10.4). Section 10.5 states the summary of the uncertainty analysis.

10.1 UNCERTAINTY ANALYSIS APPROACH

Within the uncertainty analysis, two questions regarding uncertainties have been investigated. 1) How do the distributive principles perform under the Shared Socioeconomic Pathways set by the IPCC community. And 2) What is the exposure to long term climate vulnerabilities for each principle? To answer both questions, two separate uncertainty analyses have been conducted.

10.1.1 Short term uncertainty analysis

The first part of the uncertainty analysis makes use of the SSPs to span up the uncertainty space. The socioeconomic and climate uncertainties are sampled across their corresponding ranges, hereby obtaining 35000 unique scenarios. Compared with the original SSPs scenarios, which only apply five distinct scenarios to IAMs, the principles are tested across a much richer set of scenarios. The 35000 scenarios are applied for all generated policies and the Nordhaus policy, resulting in a total of 1.05 million individual simulation runs.

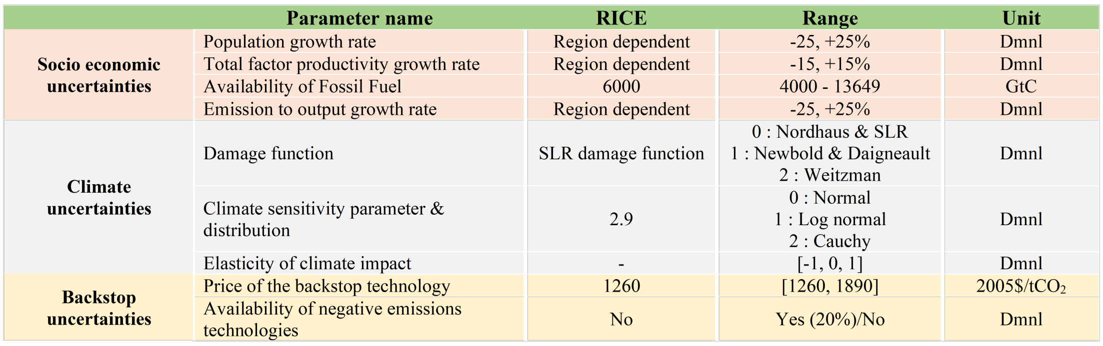


	Parameter name	RICE	Range	Unit
Socio economic uncertainties	Population growth rate	Region dependent	SSP 1-5	1/year
	Total factor productivity growth rate	Region dependent	SSP 1-5	1/year
	Availability of Fossil Fuel	6000	4000 - 13649	GtC
	Emission to output growth rate	Region dependent	SSP 1-5	1/year
Climate uncertainties	Damage function	SLR damage function	0 : Nordhaus & SLR 1 : Newbold & Daigneault 2 : Weitzman	Dmnl
	Climate sensitivity parameter & distribution	2.9	0 : Normal 1 : Log normal 2 : Cauchy	Dmnl
	Elasticity of climate impact	-	[-1, 0, 1]	Dmnl
Backstop uncertainties	Price of the backstop technology	1260	[1260, 1890]	2005$/t$CO_2$
	Availability of negative emissions technologies	No	Yes (20%)/No	Dmnl

Figure 10.1: Overview of short term uncertainty space, based on Riahi et al. [2017]

10.1.2 Long term uncertainty analysis

The second uncertainty analysis focuses on long term uncertainties until 2305. The long term uncertainty analysis has been set up using the ranges from Lingeswaran [2019], see figure 10.2. The input space is largely based on Nordhaus estimates. This forms the advantage of utilizing a coherent set of inputs. However, the disadvantage is that the reference scenario of Nordhaus is somewhat optimistic as projected economic and population growth are high, and efficiency gains are positive. Although the variety of the long term scenario space is limited, the analysis is still useful to evaluate exposure towards long term vulnerabilities. Furthermore, it can be evaluated if the short term performance is consistent with the long term performance. To limit the computational burden of this analysis, the long-term uncertainties have been sampled across 25000 unique scenarios. In combination with the 30 individual policies, this resulted in a total of 750,000 simulation runs.



	Parameter name	RICE	Range	Unit
Socio economic uncertainties	Population growth rate	Region dependent	-25, +25%	Dmnl
	Total factor productivity growth rate	Region dependent	-15, +15%	Dmnl
	Availability of Fossil Fuel	6000	4000 - 13649	GtC
	Emission to output growth rate	Region dependent	-25, +25%	Dmnl
Climate uncertainties	Damage function	SLR damage function	0 : Nordhaus & SLR 1 : Newbold & Daigneault 2 : Weitzman	Dmnl
	Climate sensitivity parameter & distribution	2.9	0 : Normal 1 : Log normal 2 : Cauchy	Dmnl
	Elasticity of climate impact	-	[-1, 0, 1]	Dmnl
Backstop uncertainties	Price of the backstop technology	1260	[1260, 1890]	2005$/tCO$_2$
	Availability of negative emissions technologies	No	Yes (20%)/No	Dmnl

Figure 10.2: Overview of the long term uncertainty space, based on Lingeswaran [2019]

10.2 SHORT TERM VULNERABILITIES

The following paragraphs highlight the most important outcomes from the short term uncertainty analysis. The full overview of figures displaying the distribution of the outcomes can be found within Appendix F. The short term uncertainty analysis consists of three parts:

1. Identification most important relations (section 10.2.1 to section 10.2.3)
2. identification most influential uncertain factors (section 10.3)
3. Robustness comparison of each strategy (section 10.4)

10.2.1 Influence of the economic scenario

The reference scenario's performance showed that the economic scenario co-determines the maximum height of economic objectives such as the worst-off income, inequality in consumption, and total GDP. This relation is confirmed by figure 10.3, which shows distinct clusters in the uncertainty outcomes for the total world GDP in 2105. For example, high growth scenarios such as the Nordhaus reference scenario and SSP5 lead to distinct clusters with high levels of global GDP. But, these clusters are not reflected in the utility levels due to differences in the used discount rates. Lastly, extremely low cases for economic output occur relatively more within the Egalitarian case than within the other principles.

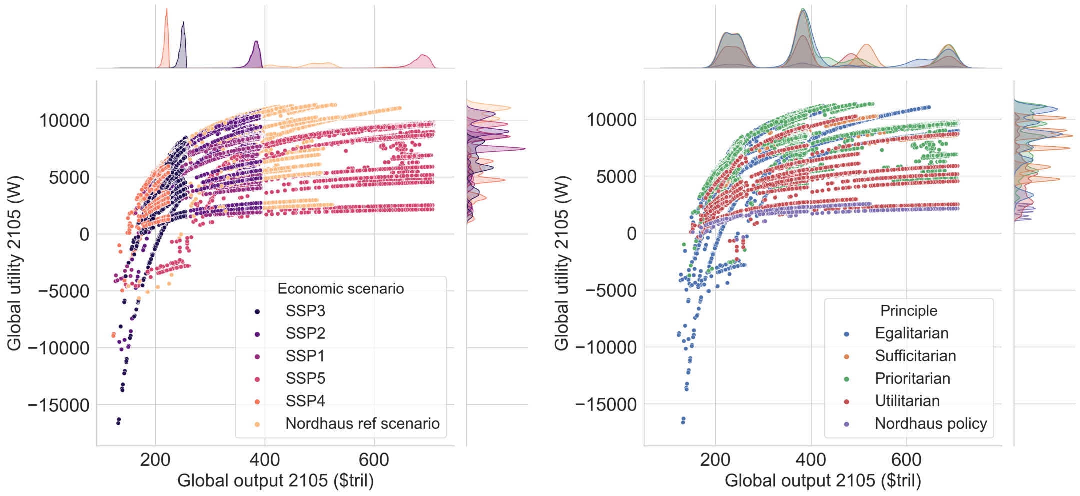


Figure 10.3: Distribution of period Utility economic scenario & principle

The economic scenario is also influential in determining levels of inequality both between generations and within regions. High growth scenarios such as SSP5 and medium growth scenarios (SSP1) can lead to low inequality between regions in 2105. There is a trade-off between economic growth in regions and between generations. In outcomes with less inequality between regions, there is higher inequality between generations. Within many scenarios, Egalitarian strategies result in the highest level of equality. Surprisingly some Utilitarian strategies result in higher equality than Sufficitarian and Prioritarian objectives. The absolute differences in principles in intertemporal utility equality are small. This indicates that all outcomes have some level of inequality between generations due to economic growth.

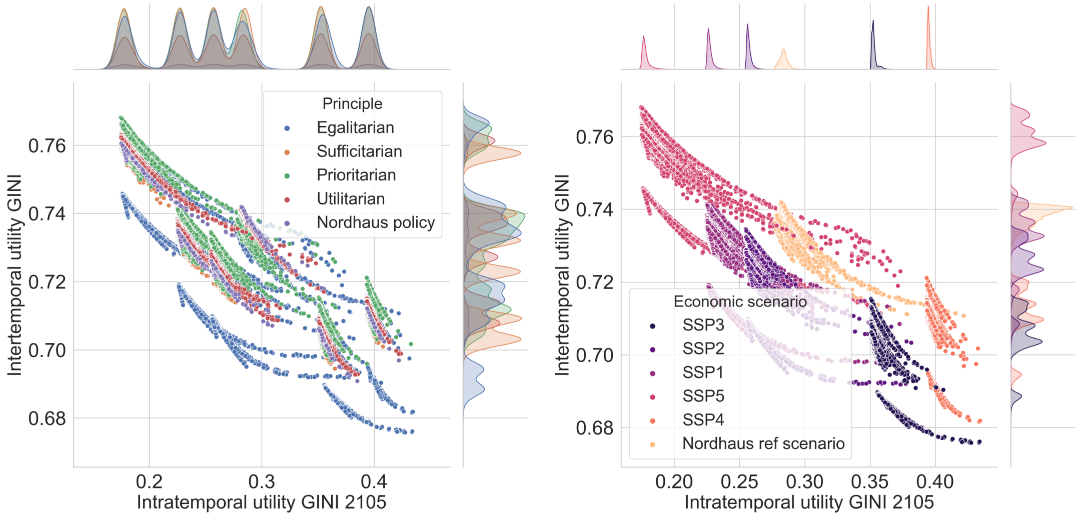


Figure 10.4: Distribution of spatial Egalitarian utility objectives

The economic scenario is also influential in determining the number of people living under the minimum acceptable welfare level. Figure 10.5 shows the population's distribution under the Sufficitarian threshold across principles and the economic scenario. For every principle, the same relation holds that in less economically optimistic scenarios (SSP1 & SSP4), a larger share of the population lives below the Sufficitarian threshold. The variance is smaller for the Prioritarian and Sufficitarian strategies. This indicates that these strategies minimize the number of people under the threshold locked-in by the economic scenario.

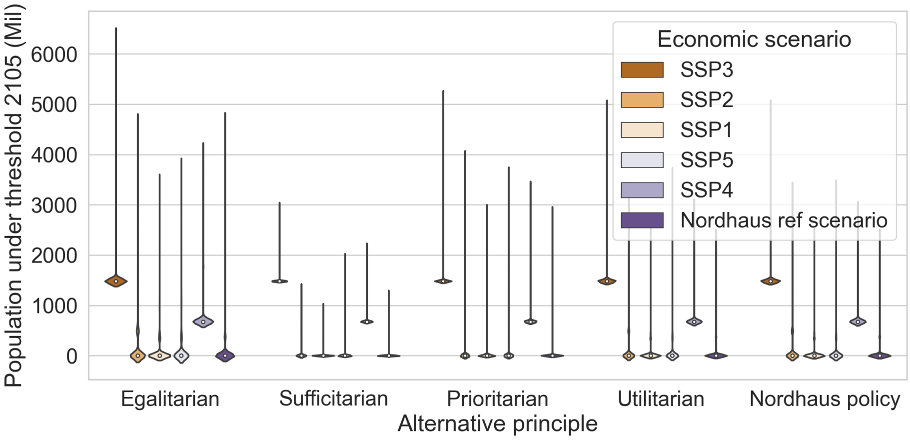


Figure 10.5: Distribution of population under threshold

10.2.2 Influence of the distributive principles

The impact inequality between generations (figure 10.6) shows that the Egalitarian and Utilitarian principles result in more extreme cases. The high amount of severe cases suggests that these principles have lower robustness to extreme climate impact cases. The Prioritarian and Sufficitarian principle outcomes are more concentrated at the lower range of impact inequality. This is surprising as you would expect that the Egalitarian principle would perform best at equalizing impact. Regarding impact inequality within generations, all principles show that regional impact inequality will be significant in most scenarios. This means that lower-income regions are hit relatively harder compared to high-income regions. There is no direct relation between the applied principles and resulting impact inequality within generations. This indicates that other parameters play a critical role, such as the economic scenario and the elasticity of damages.

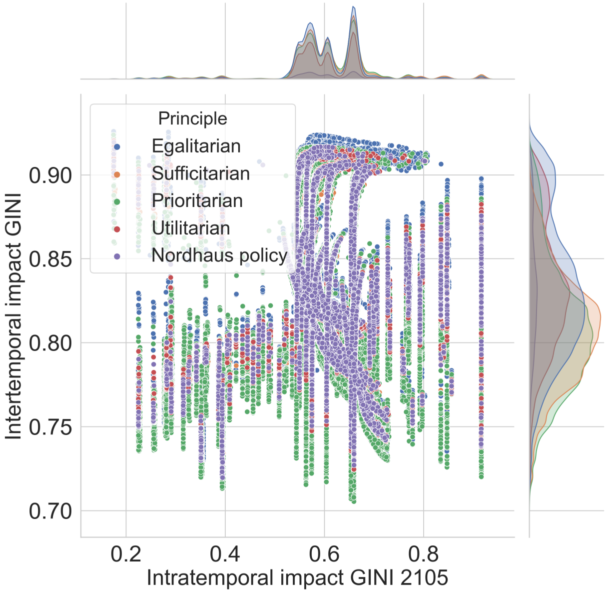


Figure 10.6: Distribution of spatial impact inequality in 2105

The importance of the applied distributive principle is visible in the distribution of the outcomes of the Prioritarian objectives. Figure 10.7 shows the economic consumption of the worst-off income class and the relative climate impact on their pre-damage consumption. It is clear that in the bulk of the scenario outcomes, the temperature increase in 2105 is in the

2 to 4 degrees range. This results to up to 30 % loss of consumption due to climate impact consistent for every economic scenario. Positive outcomes (low relative climate impact) are more prevalent for the Prioritarian and Sufficitarian strategies. Whereas the Egalitarian and Utilitarian principles show fat-tailed risk behaviour with a concentration of cases where 100% of income is lost due to climate impact for the lowest 20% income group. From the right figure in 10.7, it becomes clear that the Prioritarian and Sufficitarian strategies result in less atmospheric warming over all scenarios due too the more stringent emission abatement targets.

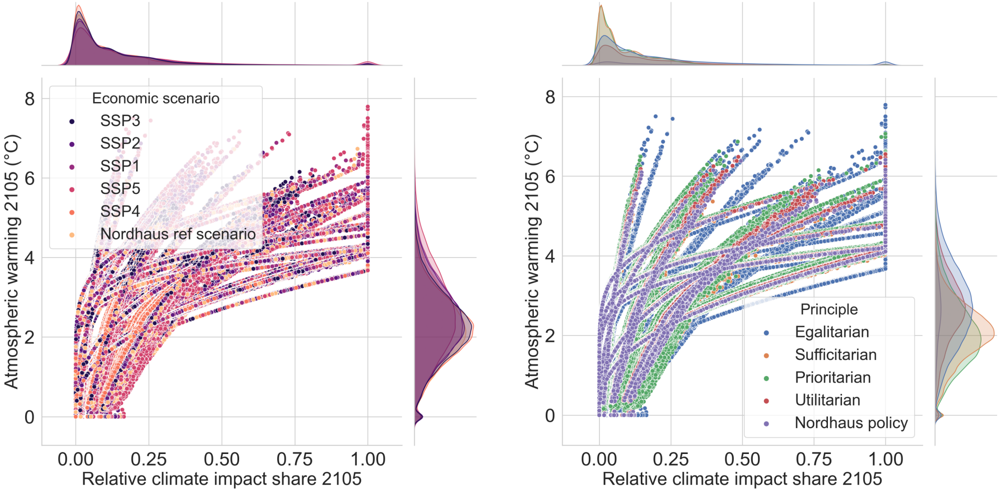


Figure 10.7: Principle and scenario distribution of relative climate impact

10.2.3 Relation to the elasticity of damages

Figure 10.8 shows the relationship between the SSP-economic scenario and the economic consumption for the worst-off. As indicated earlier, the economic scenario determines the maximum height of the lowest income group. Even in very optimistic economic scenarios, such as SSP5 and Nordhaus scenario, with enough climate impact, the economic consumption of the lowest 20 % can be severely reduced. This is indicated by the dots going to the left in figure 10.8.

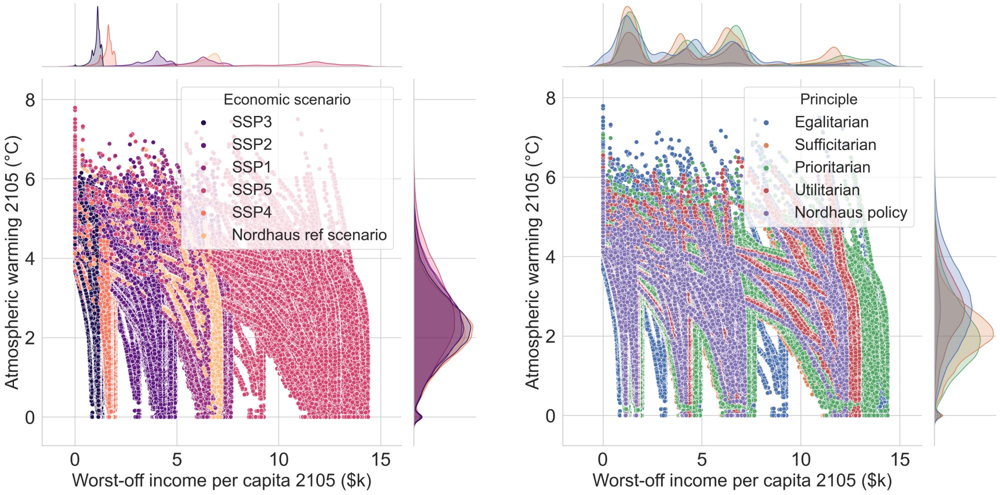


Figure 10.8: Distribution of relative climate impact for the lowest 20%

Because of the economic scenario's importance to determine economic outcomes, the influence of the applied distributive principle is less apparent. Earlier results have indicated that the Sufficitarian and Prioritarian have better protection against climate extremes, which should protect against extreme low outcomes of economic consumption for the worst-off. This relation is not directly visible here but shall be assessed within the scenario discovery, chapter 11. The occurrence of low consumption levels for the worst-off in high-temperature scenarios can be explained by figure 10.9. This shows the relation between the elasticity of damages and the applied economic scenario. The elasticity of damages expresses the assumed distribution of climate impact across income groups. What is apparent for every economic scenario is that when the poor are relatively more affected by climate change, this can push the lowest income group back into poverty. This holds for the more extreme variant of elasticity of -1 but also in the case of the more conservative e = 0.

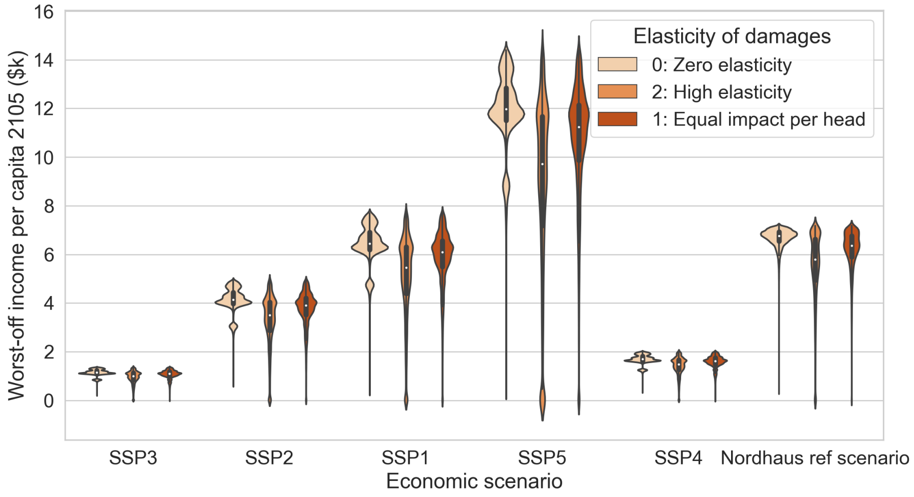


Figure 10.9: Distribution of economic position of the worst-off

10.2.4 Short term strategy robustness

For each of the 30 strategies, the SNR and Max-regret robustness metric have been calculated over the outcomes of all 35000 scenarios. The SNR metric is an indication for average performance across all objectives, whereas the Max-regret metric indicates robustness against worst-off cases. Figure 10.11 shows the relation between the SNR score and the Maximin regret criterion for each strategy.

Many Utilitarian policies, including the Nordhaus policy, have high exposure to max-regret scenarios. The same is true for 5 of the 8 Egalitarian strategies. The Prioritarian and Sufficitarian strategies have significantly less exposure to regret cases. At the same time, average robustness is equal or higher compared to the Egalitarian and Utilitarian principles. The difference in performance regarding Max-regret is explained by that Prioritarian and Sufficitarian policies have earlier net-zero targets. This protects against extreme climate impact, negatively affecting multiple model outcomes such as relative climate impact, total global damages, and the Sufficitarian threshold objectives.

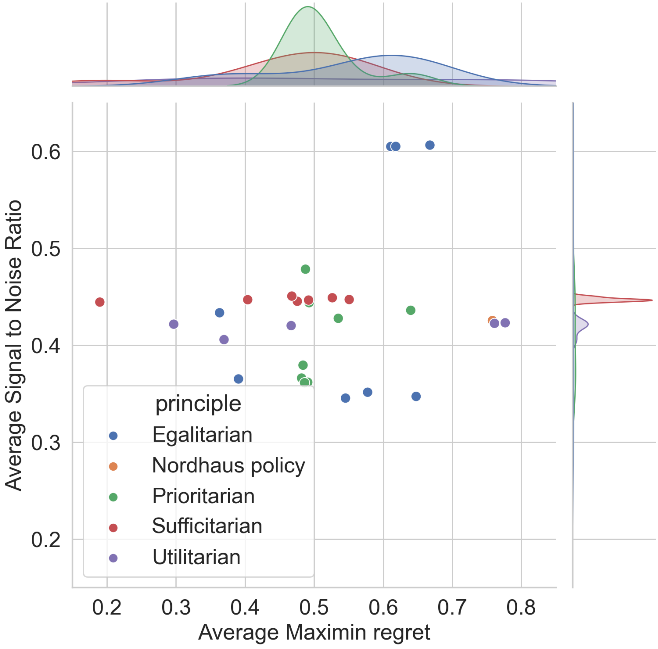


Figure 10.10: Robustness score short terms uncertainty comparison

10.3 INFLUENCE OF SHORT TERM UNCERTAINTY INPUTS

Feature scoring is used as a way to identify the relative importance of input parameters over a set of outputs. Figure 10.10 shows the feature score heat map based on an extra-trees regression over all 1.05 million outcomes of the total short term uncertainty. In general, the feature scoring results confirm the results found in the initial vulnerability analysis. The high feature score of the economic scenario for many outcomes, such as the Prioritarian and Egalitarian objectives, is clearly visible in the heat-map. The economic scenario mainly determines the height of the relative climate impact, the consumption of the lowest 20 %, the population living under the threshold, and the total output in 2105.

The efficiency scenario is more influential than the economic scenario in determining industrial emissions. This means that efficiency gains can contribute significantly to determine the outcomes of climate policies. What is surprising is the relatively low influence of the climate uncertainty parameters, such as the climate sensitivity parameter, in determining the model's outcomes. Although the damage function and the elasticity of damages are influential for determining the relative climate impact and population under the threshold.

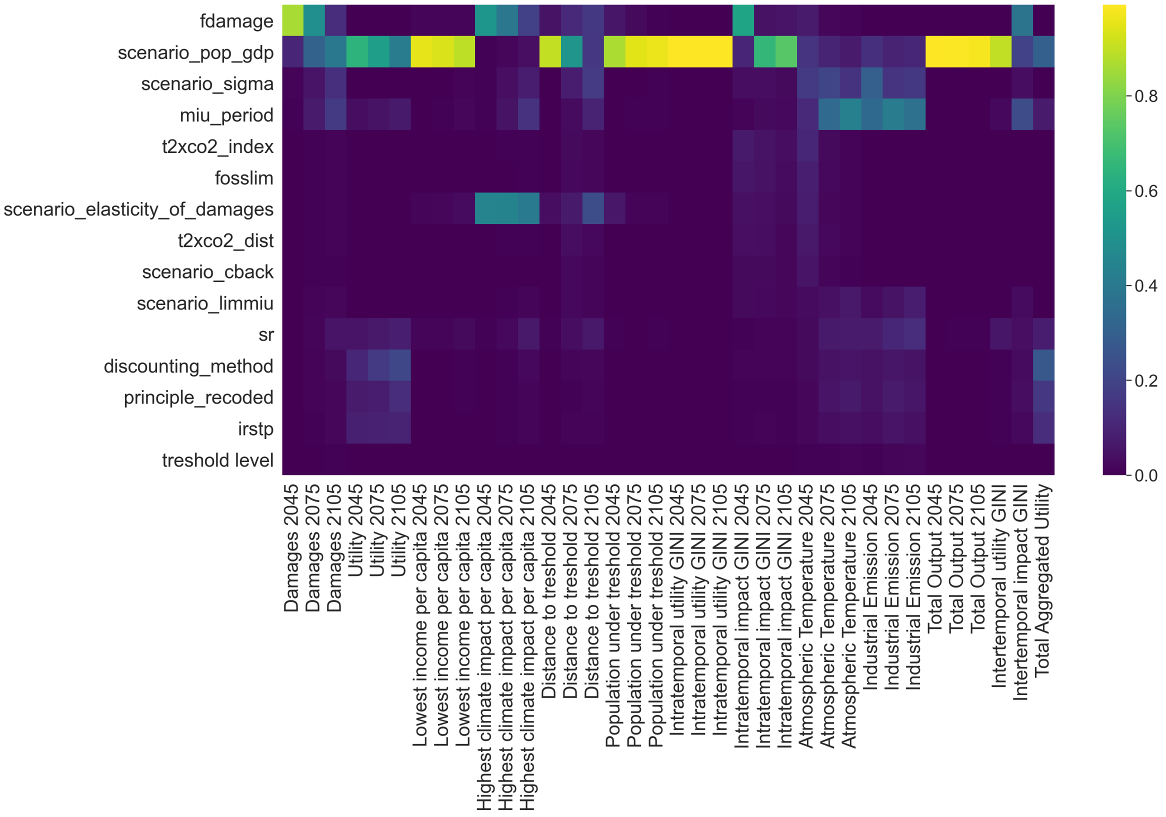


Figure 10.11: Feature score of input parameters short term uncertainty outcomes

10.4 LONG TERM VULNERABILITY ANALYSIS

The socioeconomic drivers of the long term uncertainty input space are less diverse. Therefore, the focus lies on the influence of climate-related uncertainties on the strategies' long-term robustness.

10.4.1 Vulnerability of long term outcomes

The long-term uncertainty analysis outcomes show that the bulk of the runs has low damages (Appendix H: fig H.1). Consistent with the short term uncertainty analysis, the Utilitarian and Egalitarian strategies are over-represented in extreme cases of damages and lower economic output both in 2205 and 2305. The Weitzman Newbold damage functions contribute to extreme cases of low utility under high-temperature outcomes. But generally, the distribution of the damage function over Utilitarian objectives is similar.

Surprisingly, all principles outperform the Egalitarian principle in equalizing climate impact inequality across generations in the long term (Appendix H: fig H.3). The explanation for this is twofold; the other principles tend to have better-optimized savings rates, which lead to more sustained economic growth in the long run. Furthermore, faster abatement simply leads to less climate impact in the long run. This increases equality in climate impact as the difference in climate impact experienced by current generations and generations in the next centuries is reduced.

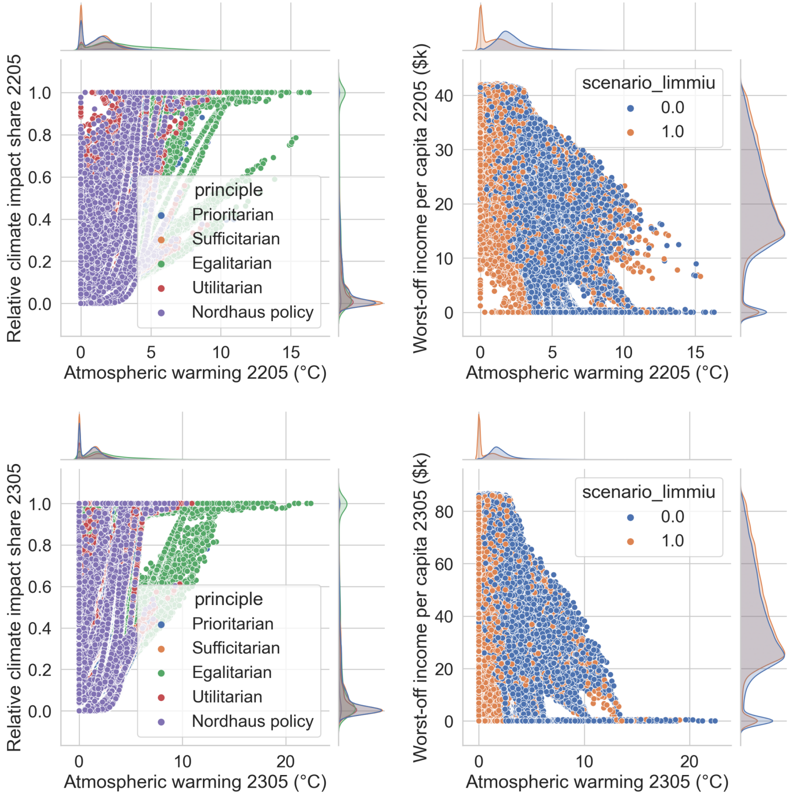


Figure 10.12: Long term uncertainty outcomes Prioritarian objectives

A clear distinction in principle performance can be found regarding the Prioritarian objectives (figure 10.12). This shows that the Prioritarian and Sufficitarian strategies are more robust regarding the Prioritarian objectives. In the long run, the bulk of the Utilitarian outcomes are in the range of the 2 - 5 Celsius range. Even extremer temperature increases are observed for the Egalitarian strategies. This leads to higher climate impact in the long run for both the Egalitarian and Utilitarian strategies. The same behavior is observed for the optimal Nordhaus policy. The relative climate impact distribution in 2205 and 2305 shows fat-tailed risk characteristics with extreme cases with complete loss of consumption. These severe cases are more prevalent for the Utilitarian and Egalitarian principle.

There is a clear distinction in scenarios where negative emissions are feasible and where these negative emissions are not possible (right figures of fig. 10.12). Negative emissions are vital for obtaining low atmospheric increases (0-1.5 degrees) in 2205 and 2305. Although this effect only has a limited impact on the resulting economic position of the worst-off. This is due to the optimistic economic growth assumptions in the long term economic uncertainty space.

10.4.2 Long term strategy robustness

The same robustness metrics have been calculated over the long term uncertainty outcomes as done in the short term analysis. The general image is that the results in the long term are consistent with the short-term. Furthermore, the results show that, compared with the short term robustness, more distinct behavior in performance between principles can be distinguished (figure 10.13). The Egalitarian and Utilitarian strategies form a group of low average and high regret robustness. Prioritarian objectives have high average performance and medium to high regret. Whereas the Sufficitarian strategies form a separate group of high average and low regret performance. This shows that the Prioritarian and especially the Sufficitarian focused policies tend to pay-out in the long run compared to Utilitarian and Egalitarian strategies. The difference between the Prioritarian and Sufficitarian strategies can be explained by that Sufficitarian tend to possess faster abatement pathways, which offers better protection from the more extreme cases. However, this cannot explain all differences because there are also Prioritarian policies with fast abatement targets. The difference could arise because the savings rate of Sufficitarian policies is better optimized for the overall economy due to Utilitarian objectives present in the Sufficitarian problem formulation.

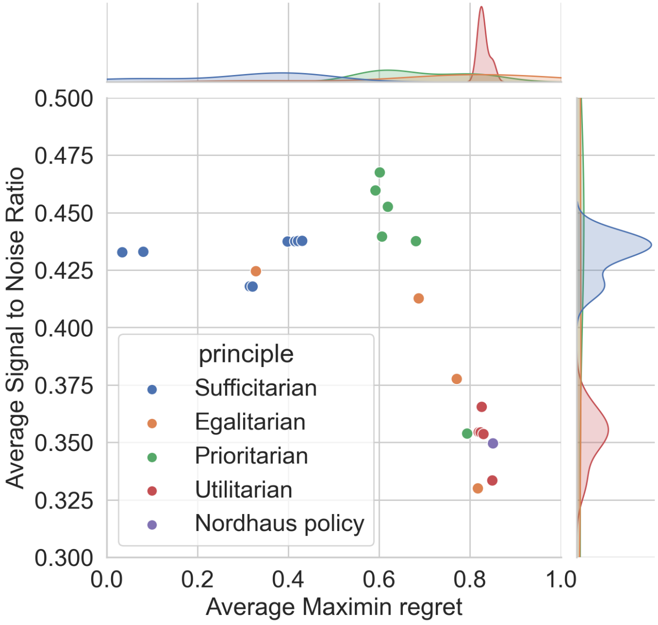


Figure 10.13: Robustness score short terms uncertainty comparison

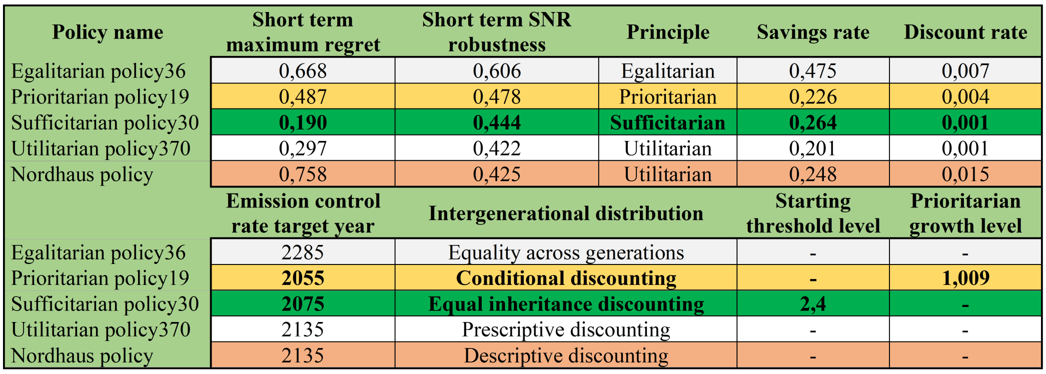
10.5 SUMMARY SHORT & LONG TERM UNCERTAINTY ANALYSIS

In the previous paragraphs, the generated principles have been stress-tested via an extensive uncertainty analysis. The 30 policies have been sampled across thirty-five thousand scenarios that tested the policies' performance over the SSP uncertainty space. Twenty-five thousand scenarios have been sampled across the long term uncertainty space. Robustness metrics have been computed to have an overview of each policy's performance across all scenarios. With these combined results, the fifth research question can be answered:

Research question 4

What is the influence of deep uncertainty present within climate change on the performance of the tested distributive principles?

Prioritarian and Sufficitarian strategies show consistently higher robustness against climate extremes in both the short and long term, with Sufficitarian principles also having higher average robustness. Prioritarian policies perform well under more positive economic scenarios, especially in the long term. Sufficitarian policies seem to protect more against climate extremes and therefore have low regret robustness across all cases. Egalitarian and Utilitarian strategies suffer from exposure to extreme climate events due to slow climate action. When focusing on the Utilitarian principle, the best performing strategy applies prescriptive discounting instead of descriptive discounting, which has a comparable average performance compared to the Nordhaus policy but considerably lower exposure to climate extremes. Egalitarian policies put too much emphasis on achieving equality, hereby foregoing by the economic optimality of strategies, leaving everybody worse off.



Policy name	Short term maximum regret	Short term SNR robustness	Principle	Savings rate	Discount rate
Egalitarian policy36	0,668	0,606	Egalitarian	0,475	0,007
Prioritarian policy19	0,487	0,478	Prioritarian	0,226	0,004
Sufficitarian policy30	**0,190**	**0,444**	**Sufficitarian**	**0,264**	**0,001**
Utilitarian policy370	0,297	0,422	Utilitarian	0,201	0,001
Nordhaus policy	0,758	0,425	Utilitarian	0,248	0,015

Policy name	Emission control rate target year	Intergenerational distribution	Starting threshold level	Prioritarian growth level
Egalitarian policy36	2285	Equality across generations	-	-
Prioritarian policy19	**2055**	**Conditional discounting**	**-**	**1,009**
Sufficitarian policy30	**2075**	**Equal inheritance discounting**	**2,4**	**-**
Utilitarian policy370	2135	Prescriptive discounting	-	-
Nordhaus policy	2135	Descriptive discounting	-	-

Figure 10.14: Characteristics most robust strategy per principle

The next step in the analysis is the scenario discovery step in chapter 11. To limit the computational burden, the best performing strategies, in terms of robustness, have been selected for each principle (figure 10.14). Strategies have been selected mainly on the short-term robustness score as the short-term economic scenarios are more diverse. Therefore, the ensemble of scenarios in the short term also emphasizes negative economic growth futures compared to the long term uncertainty analysis. Only if best-performing short term strategies performed extremely bad in the long term, they have been replaced with strategies that have a better long-term performance. This is how Utilitarian policy 370 has been selected.

11

SCENARIO DISCOVERY

In the previous chapter, the robustness of the principle specific strategies has been assessed. This chapter will identify the most critical outcome spaces that will lead to undesirable and desirable outcomes. Firstly, the worst-case discovery will show which combinations of scenario inputs lead to worst-case outcomes (section 11.1). These form the perfect storm conditions for each principle. In the time series clustering step, outcome regions of interest will be identified (section 11.2) by using the agglomerative clustering results. Furthermore, the outcomes have been clustered on their temperature outcomes in 2105 to compare the alternative principles with the Nordhaus policy. Section 11.3 shows intergenerational trade-offs within the Egalitarian and Prioritarian principle. Lastly, section 11.4 summarizes the findings of the executed scenario discovery.

11.1 WORST CASE DISCOVERY

A worst-case scenario discovery has been run over the uncertainty space. The results have been split up into the composition of worst-case scenarios over the socio-economic uncertainties and the worst-cases regarding climate uncertainties. The directed search for the worst combinations of uncertainty inputs has been executed principle objective specific. For example, one of the Egalitarian case's search objectives was to find the combinations of uncertainty inputs that lead to high inequality between regions.

11.1.1 Composition of worst-case climate uncertainties

Figure 11.1 Appendix J.1 shows that the Weitzman damage function is over-represented in worst-cases for the Utilitarian and Egalitarian principle. This is because the Weitzman curve is sensitive towards more extreme heating outcomes. Especially the Egalitarian principle show high sensitivity towards Weitzman, with around 80% of Egalitarian worst-off outcomes. This is because Egalitarian strategies involve higher temperature increases due to slow climate abatement.

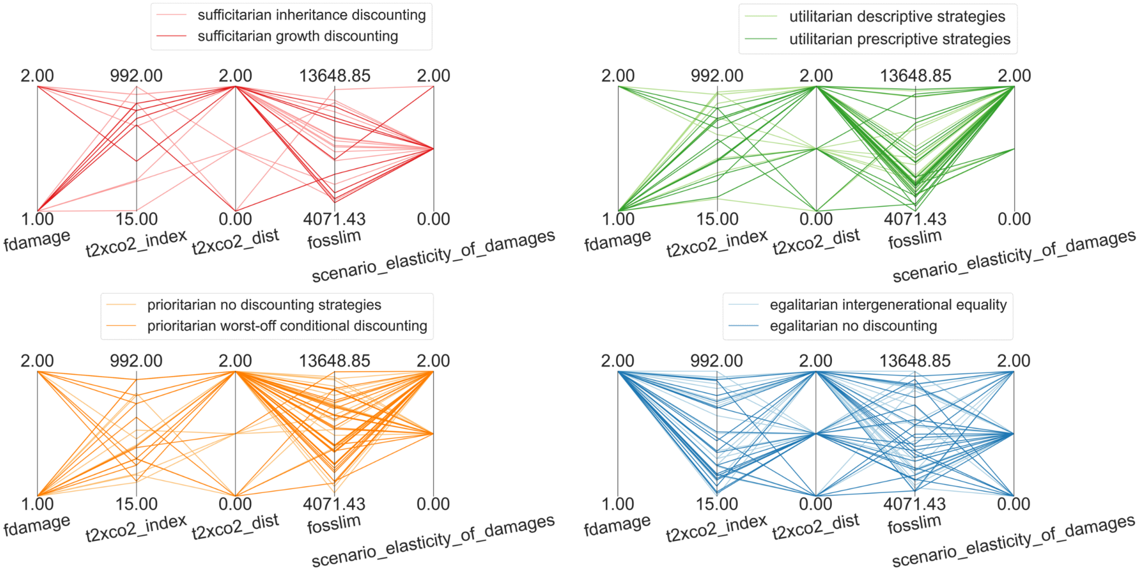


Figure 11.1: Composition of climate input uncertainties for worst-cases

Lower fossil fuel availability limits lead more often to worst-case outcomes for the Prioritarian principle. For the Sufficitarian principle, higher fossil fuel limits are over-represented (Appendix J.1). The availability of fossil fuel works as a limit on the maximum height of industrial emissions. When higher emissions are possible, this harms Sufficitarian goals leading towards worst-case outcomes. Whereas lower emission possibilities in the Prioritarian case result in fewer possibilities for the required catch-up process to improve the worst-off's economic position.

11.1.2 Composition of worst-case socioeconomic uncertainties

All principles are sensitive to low-efficiency scenarios of the economic production factors. Relatively more worst-off cases have been found that do not consider the possibility of negative emissions. But the difference is not very significant (60 to 40 % split). Both the Prioritairan and Sufficitarian strategies have an over-representation of high elasticity of damages scenarios within their worst cases (Appendix J.2).

The feature scoring analysis has shown that the economic scenario is the most influential uncertainty. Prioritarian worst-case outcomes tend to concentrate around SSP1 'Taking the green road' and SSP2 'Middle of the road', which is surprising. These SSP narratives should possess favorable conditions for equitable growth. One explanation is that lower GDP growth scenarios in combination with the Weitzman damage curve, high elasticity of damages, low-efficiency growth, and no negative emissions result in perfect-storm conditions that minimize the Prioritarian objectives because no economic catch-up process can take place.

The Utilitarian and Sufficitarian strategies tend to have more worst-case outcomes in higher growth scenarios. An explanation is that these higher growth scenarios, combined with less stringent emissions targets, more often lead to high climate impact, negatively affecting overall utility for the Utilitarian case. For the Sufficitarian strategies, the perfect storm consists of high growth, the Weitzman damage function, fat-tailed Cauchy climate sensitivity, high prices for renewable, no negative emissions, and slow efficiency growth. This forms the ideal conditions to push income groups below the Sufficitarian threshold in extreme climate impact situations.

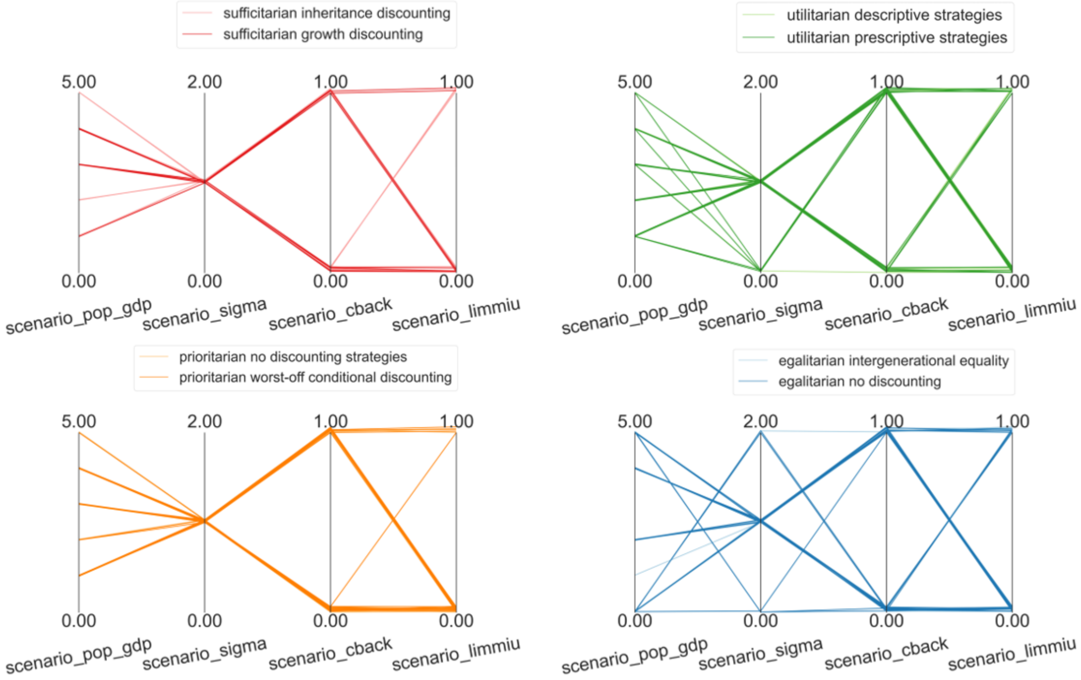


Figure 11.2: Composition of socio-economic uncertainties for worst-cases

11.1.3 Worst-case outcomes

The worst-cases' Prioritarian and Sufficitarian outcomes (figure 11.3) are significantly lower than the base case outcomes under the Nordhaus reference scenario (figure 11.3). The worst-off income class's consumption level in the worst cases ranges from 0 - 2.000 $. While in the base case, the worst-off income class rises towards 40 thousand $. Low worst-off consumption levels are not limited to more extreme values for elasticity of damages but are also possible for the more conservative *elasticity damage* = 0. Similar differences in outcomes are observed for the Sufficitarian case. In the base case, the population below the threshold swiftly drops towards zero as the world economy grows. In the worst cases, the number of people living under the Sufficitarian threshold can expand from 500 million in 2005 to 2 or 3 billion in 2105, depending on the combinations of scenario inputs.

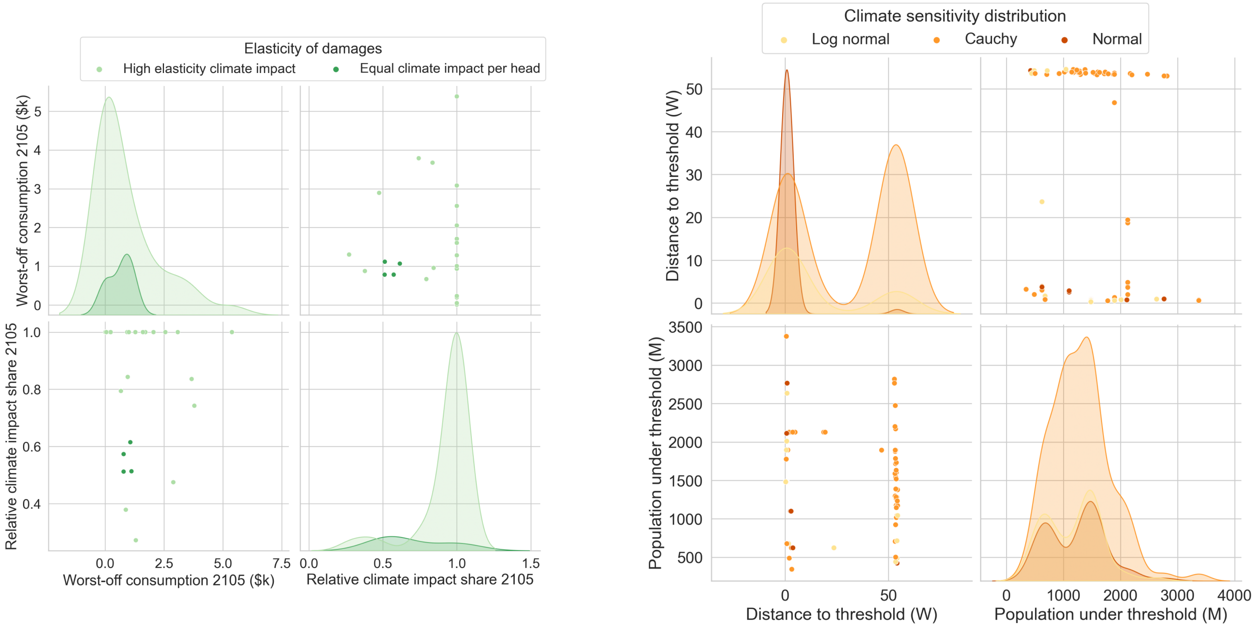


Figure 11.3: Composition of Prioritarian and Sufficitarian worst-case outcomes

The worst-case outcomes also show that the quick removal of inequality in the reference scenario can be opposed in many worst-case scenarios. Inequality levels in consumption between regions can become higher in 2105 than in 2005 (Appendix J: fig J.4. Consumption inequality between generations is expanding in worst-case scenarios leaving future generations considerably worse-off than the current generation compared to the base case. Extreme levels of inequality regarding climate impact can be observed under the influence of the Weizmann damage function with GINI-indicators surpassing 0.9. In comparison, this is a greater level of inequality than the most unequally divided nation income distribution on earth. Furthermore, perfect storm conditions for high climate impact (see above) can lead to situations with very low levels of utility for the Utilitarian case in the long term.

11.2 TIME SERIES CLUSTERING

In the previous chapter, based on the combined robustness score of the short- and long-term uncertainty analysis, for each principle, one strategy has been chosen as input for the scenario discovery. Scenario Discovery is aimed at structuring the uncertainty output to find interesting clusters of behaviours. This research has utilized time series clustering based on the complexity-invariant-distance, which has been introduced in 8.3.

The chosen time series clustering method in chapter 8 has an O(n2) relation, making it not easy scalable towards bigger data sets as run time increases exponentially. It is therefore not feasible to cluster the full outcome space of the uncertainty space at once. As a practical solution to this problem, a sub-set of 15000 runs of each policy have been clustered. Appendix K, figure K.1 gives an overview of how the silhouette width score has been used to assess the appropriate number of clusters.

The uncertainty analysis has shown overall principle differences in performance. This chapter will focus on strategy specific performance. Several questions remain unanswered. For example, how does the Nordhaus policy performance compare to the most robust policies found in chapter 10, such as the Prioritarian policy 19 and Sufficitarian policy 30?

11.2.1 Alternative emission pathways under the SSP scenarios

Firstly, the emission pathways have been clustered regarding their resulting warming in 2105 and SSP economic scenario (Figure 11.4). The analysis is supported by the agglomerative clustering results in appendix K. It is apparent that the Egalitarian and Nordhaus policy are over-represented in higher temperature outcomes. Both 80 % of the Egalitarian and Nordhaus runs result in a temperature increase above 2 degrees at the end of this century (see Appendix K: fig K.2). Thus, in many scenarios, the Nordhaus policy fails to keep warming to levels required by the Paris Agreement. For the Sufficitarian strategy, 50 % of the runs keep warming below 2 degrees, and extreme warming above 3 degrees is rare (< % 8 of the runs). The Prioritarian performs even better with keeping 65 % of the runs below 2 degrees and reaching only 2 % of the cases above 3 degrees at the end of this century. This is explained by the fact that the Prioritarian policy aims at net zero 10 years before the Sufficitarian strategy.

Although the need to fast abatement seems high to prevent worst-off cases, figure 11.4 also shows high emission pathways that limit warming to 2 degrees Celsius in 2100. These pathways are rarer, less than 14 % and 21 % of the Egalitarian and Nordhaus strategy. These are pathways with very low climate sensitivities that allow higher emissions without strong warming. As expected SSP5: Fossil fuel development is over-represented regarding high warming outcomes across all strategies. While SSP4 en SSP3 are over-represented in medium to high warming outcomes between 3 and 5 degrees.

Secondly, the results show that negative emissions are very important in the cases without a low climate sensitivity to obtain low heating outcomes. Thus, there is considerable dependability on reforestation & afforestation, and BECCS to limit warming. With the large scale deployment of CDR, limiting warming to 2 or preferably to 1.5 degrees is possible within many scenarios within the Sufficitarian and Prioritarian strategies. However, a group of scenarios (29 %) reaches higher atmospheric warming in the range of 2 to 3 degrees or higher at the end of this century with negative emissions. This shows that even with the most stringent abatement policies thinkable, high-temperature outcomes are still a possibility because of high climate sensitivities.

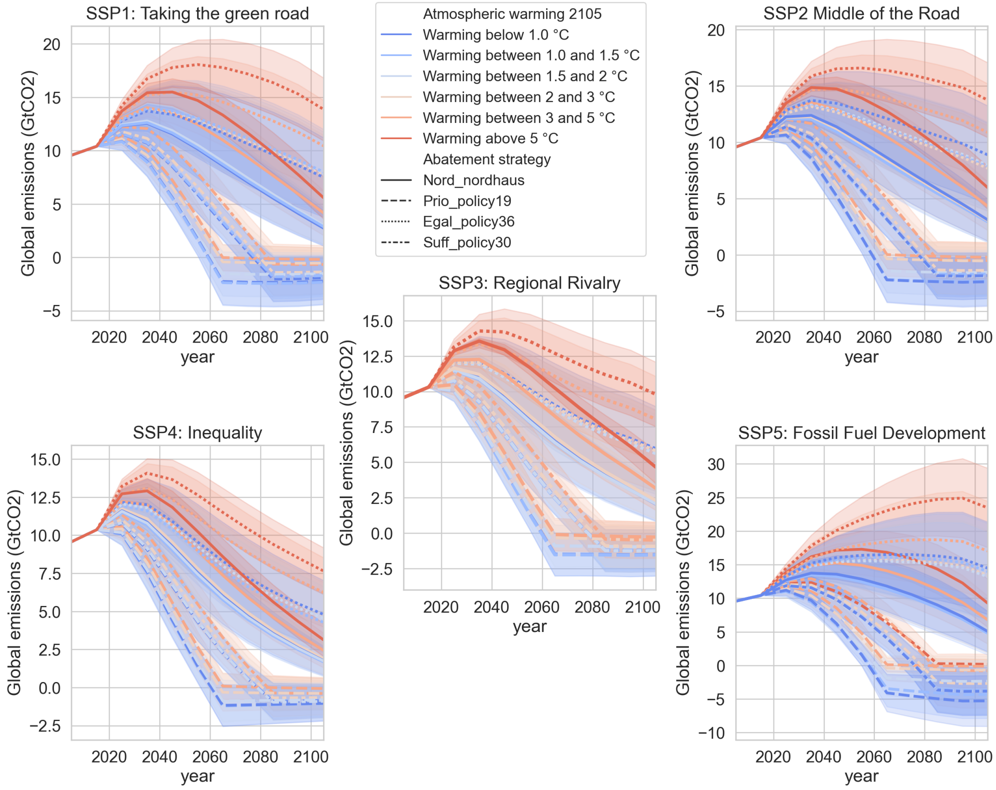
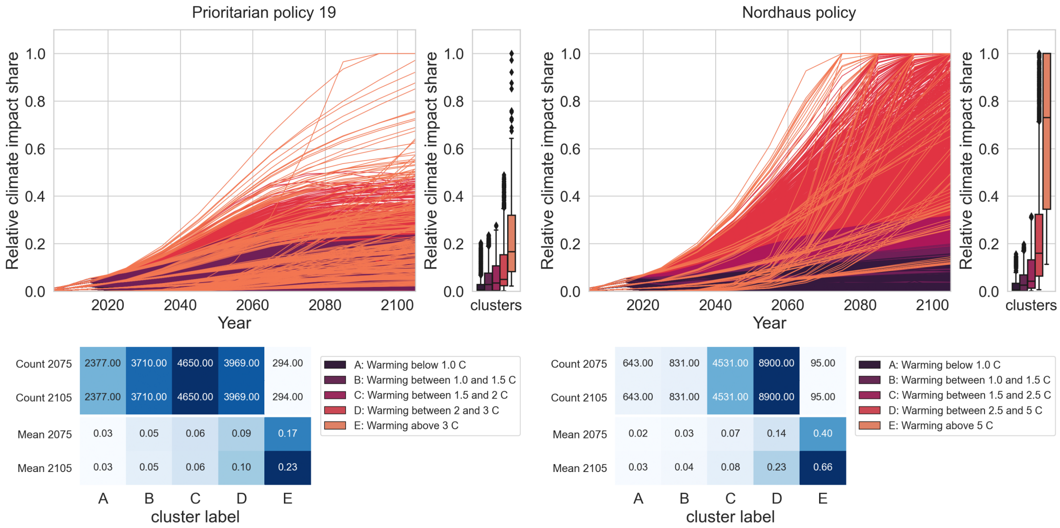


Figure 11.4: Emission pathway per principle, atmospheric heating outcome and economic scenario

11.2.2 Atmospheric warming and relative climate impact for the worst-off

The figure below shows the Prioritarian and Nordhaus strategy results for relative climate impact clustered on five temperature labels. The Nordhaus policy leads to higher relative climate impact levels for the worst-off compared to the best performing Prioritarian strategy (Policy 19). In 20 % of the scenarios, more than 30 % of the consumption at the lowest levels is lost due to climate change impact. This is only roughly 3 % for the Prioritarian strategy. Only 10% of the pathways of the Nordhaus policy limit warming to 1.5 degrees. For these cases, it keeps relative climate impacts lower than 25%.



	A	B	C	D	E
Count 2075	2377.00	3710.00	4650.00	3969.00	294.00
Count 2105	2377.00	3710.00	4650.00	3969.00	294.00
Mean 2075	0.03	0.05	0.06	0.09	0.17
Mean 2105	0.03	0.05	0.06	0.10	0.23

	A	B	C	D	E
Count 2075	643.00	831.00	4531.00	8900.00	95.00
Count 2105	643.00	831.00	4531.00	8900.00	95.00
Mean 2075	0.02	0.03	0.07	0.14	0.40
Mean 2105	0.03	0.04	0.08	0.23	0.66

Figure 11.5: Sufficitarian and Nordhaus strategy relative climate impact clustering

11.2.3 Atmospheric warming and global climate impact

The Nordhaus policy is outperformed in terms of overall damages to the economy. The Sufficitarian policy acts as a hedge against extreme climate impact, with only a few cases surpassing the 100 trillion $ in 2105. Although the difference with the Nordhaus policy is less significant compared to the relative climate impact. Many scenarios still result in a low level of damage up to 20 trillion $ in 2105. The observed behavior regarding damages is not because the overall economy is bigger see section 11.2.4.

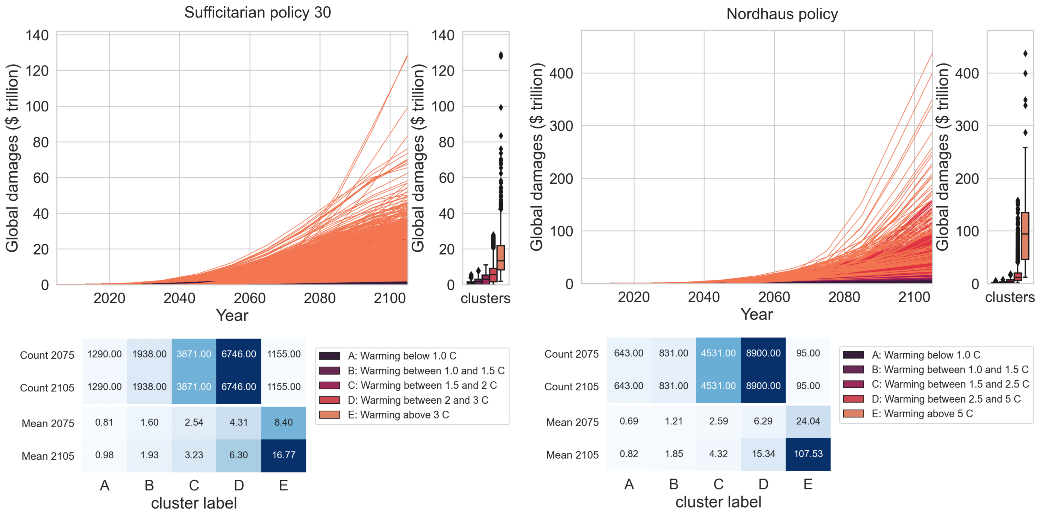


Figure 11.6: Sufficitarian and Nordhaus strategy global damages clustering

11.2.4 Effect distributive principle on global economic output

In the previous section, significant higher damages were present for the Nordhaus policy. One common argument in favor of the Utilitarian principle is that it may lead to more serious damages, but still, the optimized economic output compensates for that. The figure below shows that this reasoning does not hold. Compared with the Sufficitarian policy, the world economy's size is equal for both strategies in many scenarios. This is also the case for the Prioritarian policy 19. In the Utilitarian Nordhaus policy, more cases with declining world GDP exists, represented by the lines going sharply down. Furthermore, the Sufficitarian strategy performs better than the Nordhaus policy: high economic output cases (global output > 500) are more frequent in the Sufficitarian strategy.

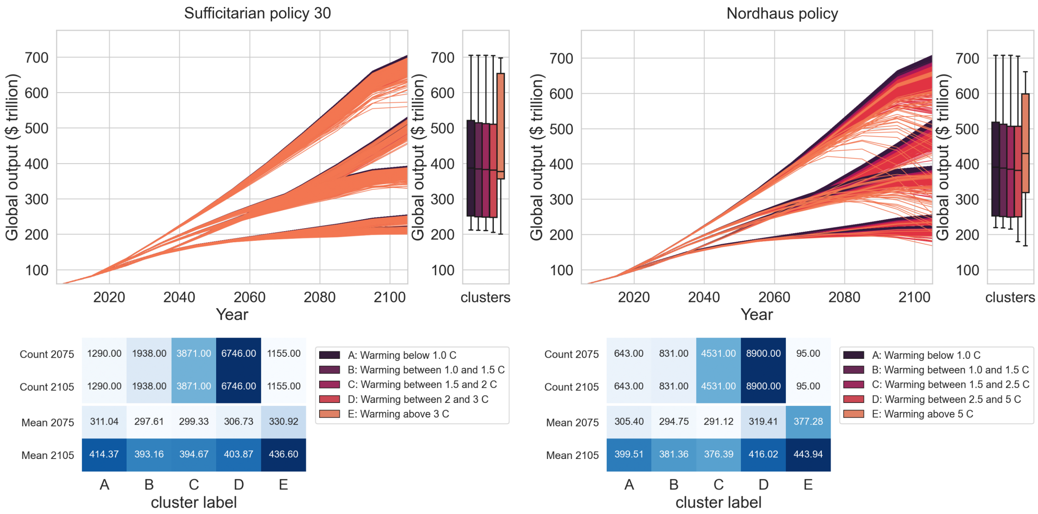
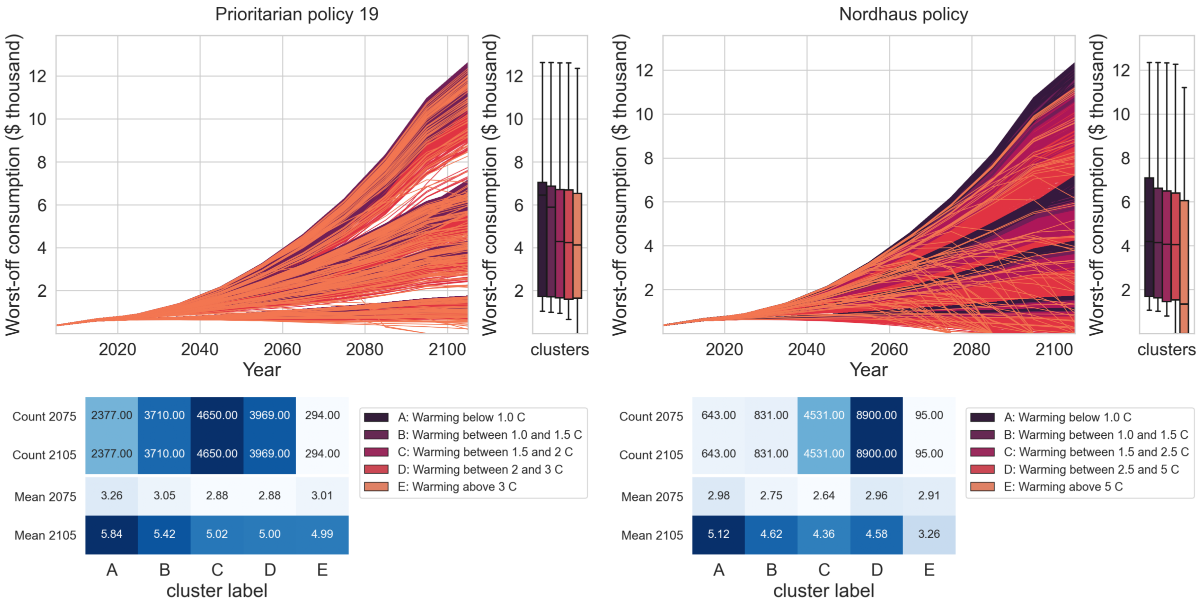


Figure 11.7: Sufficitarian and Nordhaus strategy global output clustering

11.2.5 Protection of the consumption level of the worst-off

The clustering results show that the lowest income level declines significantly to the end of the century in the Nordhaus policy in many scenarios. This is consistent with the previous analysis, with high relative climate impact occurring in 20 % of the scenarios. Especially the yellow and red clusters show rapidly deteriorating economic levels for the worst-off. The Prioritarian policy is more robust, with fewer cases show deteriorating income levels. Worst cases are also mostly prevented within the Prioritarian policy. But the average difference between the Prioritarian and Nordhaus policy is not so big. This is because climate impact is small in the first decades because of the slow response of the earth's heating system.



Prioritarian policy 19	A	B	C	D	E
Count 2075	2377.00	3710.00	4650.00	3969.00	294.00
Count 2105	2377.00	3710.00	4650.00	3969.00	294.00
Mean 2075	3.26	3.05	2.88	2.88	3.01
Mean 2105	5.84	5.42	5.02	5.00	4.99

Nordhaus policy	A	B	C	D	E
Count 2075	643.00	831.00	4531.00	8900.00	95.00
Count 2105	643.00	831.00	4531.00	8900.00	95.00
Mean 2075	2.98	2.75	2.64	2.96	2.91
Mean 2105	5.12	4.62	4.36	4.58	3.26

Figure 11.8: Prioritarian and Nordhaus strategy worst-off consumption clustering

11.3 INTERGENERATIONAL TRADE-OFFS

Climate change is a commonly used example of intergenerational justice. To support the analysis of intergenerational trade-offs, present in the alternative distributive principles, the long term trade-offs within the Egalitarian and Prioritarian objectives have been analyzed. This is also because their temporal component did not affect the generation of strategies within these principles (see section 12.2: limitations)

11.3.1 Trade-offs within the Prioritarian principle

Figure 11.9 shows the worst-off income development across four time periods. High abatement efforts in the Prioritarian policy result in lower economic growth in the short term because of the high mitigation costs. Therefore economic growth is suppressed, which affects income growth for the worst-off groups. Income growth of the worst-off group starts to accelerate beyond 2105. Thus, the Prioritarian strategy has the trade-off that the worst-off position in the short term is sacrificed to improve the worst-off's economic situation in the long-term. In some cases, the sacrifice by previous generations is not enough. In extreme cases, consumption declines after 2205 due to delayed climate impact caused by sea-level rise.

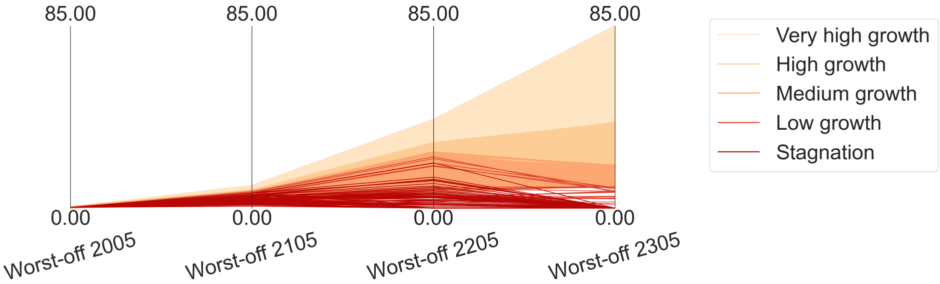


Figure 11.9: Intergenerational trade-offs worst-off consumption

Although income growth starts to accelerate for generations living around 2100, this is counteracted by the rising climate impact in that same period (see development relative climate impact, Appendix L1 - L4). Then, the lowest income groups' consumption becomes significantly lower than it could have been without climate change. Under favorable conditions, relative impact peaks around 2105 to decline afterward. In non-favorable conditions, climate impact further rises or stabilizes after 2105.

11.3.2 Trade-offs within the Egalitarian principle

Previous results have shown that the Egalitarian principle tends to favor lowering inequality today by low climate action and low savings behavior. Or to prevent higher inequality in the future by strong climate action and higher savings. This can be observed in two example policies policy 14 (slow abatement) and policy 42 (high abatement). In the slow abatement policy, inequality in consumption can 'bounce' back towards present inequality levels. The 'bouncing back' is independent of the economic scenario (figure 11.10). Contrary to that, the high abatement Egalitarian policy reduces spatial inequality in all tested scenarios. The level of inequality reduction depends on the economic scenario.

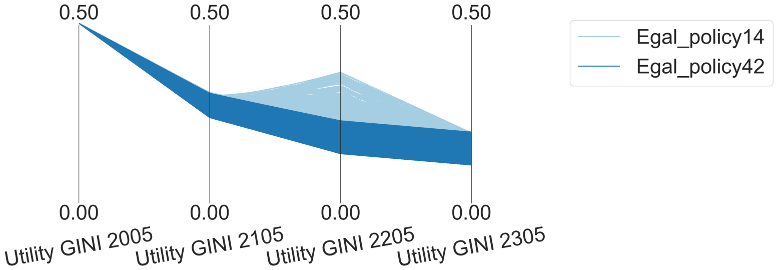


Figure 11.10: Trade-offs spatial inequality in consumption, low inequality 2305

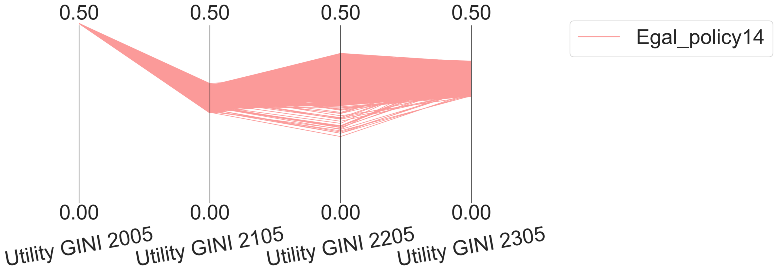


Figure 11.11: Trade-offs spatial inequality in consumption, high inequality 2305

The trade-off plots of impact inequality (Appendix L: fig L.6) show that in both Egalitarian policies (slow and fast abatement), impact inequality between regions remains high. Thus, the economic catch-up process is not enough to oppose the negative effect of the low-income regions' rising climate impact. There is a clear trade-off between generations in that relative climate impact peaks in 2105 and starts to decline to 2205 and 2305. This occurs mostly in scenarios where temperature peaks around 2100 and declines afterward combined with a temperature-dependent damage function such as Weitzman and Newbold. In scenarios where the damage function also considers sea-level rise, relative climate impact can rise even when atmospheric warming drops. This confirms the large intergenerational inequity that occurs when severe sea-level rise is triggered.

11.4 SUMMARY OF SCENARIO DISCOVERY

The scenario discovery made it possible to distinguish significant behavior differences over the tested strategies' model objectives. The worst-case discovery identified the characteristics and outcomes of the worst-case vulnerabilities. Together, these insights can answer the sixth research question:

Research question 5

Which clusters and trade-offs are present within the outcomes of the alternative abatement strategies?

First of all, no trade-off has been found between following 'economy optimal' Utilitarian-led strategies and more equitable trajectories concerning the height of total global GDP. Utilitarian-led strategies actually have a worse overall economic performance compared to the Sufficitarian and Prioritairan strategies. Furthermore, the Utilitarian policies are more exposed to the perfect-storm conditions identified in the worst-case discovery.

Sufficitarian policies perform better at reducing the risk towards climate extremes. While the Prioritairan strategy has a better overall performance in improving the worst-off's economic position, especially in positive economic scenarios. Within the Sufficitarian strategy, there is a trade-off between reducing the risk of lowering economic growth and minimizing exposure to climate extremes. Whereas within the Prioritairan principle, there is the trade-off between striving for higher consumption levels for the worst off and higher exposure to extreme cases. Utilitarian and Egalitarian strategies are more exposed to high economic growth scenarios with lower efficiency growths such as SSP5 and the Nordhaus reference scenario. In contrast, the Prioritarian and Sufficitarian approaches are more susceptible to lower growth scenarios.

Regarding trade-offs in intergenerational justice, the best performing Sufficitarian policy adopts an 'inheritance-discounting' principle. This implicates that utility is only discounted when future generations inherit the world the same or better as it is today. For all Sufficitarian strategies, inheritance discounting resulted in the most robust strategy. Inheritance discounting is less conservative than Sustainable Growth discounting (SDU) as the SDU requires some level of economic growth to discount future utility. Thus, there is a trade-off between placing too much emphasis on future generations (SDU) and strategy performance across all scenarios. An explanation is that putting too much focus on future generations results in conservative strategies regarding savings rate and emission abatement rates. This then negatively affects overall economic performance.

Within the Utilitarian strategies, the best performing strategy is a prescriptive discounted strategy. This underlines that if more emphasis is placed on future generations, more conservative and robust policies can be obtained. This prescriptive strategy has the same average performance as the Nordhaus policy but significantly better robustness against climate extremes. Within Egalitarian strategies, strong intergenerational trade-offs are present between the present and future generations. Egalitarian strategies tend to favor either consumption growth in the short term (low savings abatement) or in the long term (high savings abatement). Slow abatement policies fail to sustainably reduce inequality over all periods because of rising climate impact.

Prioritatian and Sufficitarian strategies sacrifice a part of the worst-off economic consumption in the short term to improve the economic well-being of later generations. Although income growth rises after 2100 for the Worst-off, this generation can be relatively most affected by climate change especially under the Weitzman and Newbold Dignaut damage function.

IV

ETHICAL REFLECTION

12 RESEARCH LIMITATIONS

In this research, an exploratory modeling approach has been applied to the RICE model in which distributive principles have served as the input for a Many Objective Robust Decision Making (MORDM) approach. An overview of four prominent distributive principles within IAM analysis has been made for the Utilitarian principle, Egalitarian, Sufficitarian and Prioritarian principle. To apply these principles to the RICE model, several model elements have been added. The single objective of aggregated utility has been replaced with an ensemble of principle specific objectives. Pareto optimal strategies have been generated, from which 29 strategies have been chosen as example strategies. These 29 strategies have been stress-tested for their performance across a diverse set of scenarios in both the short term (to 2105) and in the long term (2305). The characteristics of the worst-case outcomes have been identified. Finally, the uncertainty outcomes have been used to perform a clustering of the result to identify interesting outcome regions.

Considerable practical decisions had to be made to make this analysis possible and feasible within the limited time available. This chapter lists the limitations of this research and considers how the limitations have influenced the research findings. First, the limitations of the RICE model to serve as an example IAM will be assessed. Then the limitations to the generated policies will be given. Finally, an overview will be given of the limitations of the analysis concerning the example policies' outcomes.

12.1 MODEL LIMITATIONS

The RICE model is a scientifically grounded simple IAM commonly used in climate research to assess the relationship between climate change and the economy. But still, its model structure resembles a simplified image of the world. The RICE model lacks important socio-economic drivers such as changes in educational level and lifestyle changes, which are present within the SSPs [Masson-Delmotte et al., 2018]. Therefore, it was not possible to incorporate all SSP narrative components in the PyRICE model. There is no one to one mapping of the SSP outcomes in more complex models concerning the PyRICE model's outcomes. Thus, the research results are not entirely comparable with the more complex IAMs built to fit the SSPs. This needs to be kept in mind when comparing the outcomes in chapter 13.

One example of a simplified model component in PyRICE is the economic model. Within PyRICE, the savings rate converges towards one equilibrium value in all regions. But in reality, the savings rate would be dynamically altered under different climate impact scenarios. For example, if there would be more climate impact and uncertainty, the economic rationale would be to save more. Furthermore, the return on capital would also not be static but would be affected [Fankhauser and Tol, 2005]. Both developments can have a significant impact on the trajectory of global emissions.

Although the RICE model consists of a climate sub-model with a sea-level rise component, the implemented climate sub-model is still relatively simple. A more detailed climate model can also improve the accuracy regarding changes in land usage, which is set to a constant emission contribution in RICE. Furthermore, RICE lacks a good representation of non CO_2 feedback loops, such as permafrost components, which can lead to an underestimation of the longer-term temperature response [Hallegatte and Rozenberg, 2017].

Although this research uses more diverse input scenarios than the SSPs, the GDP-Population component was an influential driver of the uncertainty analysis results. The GPD-population component was entirely based on the SSP scenarios. Therefore, the used scenarios resemble the characteristics of the SPPs in terms of population and economic development. Although this makes the research results more comparable to the SSPs, it limits the diversity of the used 35000 scenarios. Thus, not the full potential of economic developments has been fully covered for the short-term uncertainty analysis. Nonetheless, this is partially resolved by the long-term uncertainty analysis, where economic drivers have been sampled over a continuous range. This enhances diversity, although the growth in the long run scenario was always positive for every region. This implicates that the uncertainty analysis step lacks a continuous exploration of negative economic growth scenarios, especially on more extended time frames.

12.2 GENERATION OF ALTERNATIVE STRATEGIES

The alternative strategies have been generated using the Nordhaus reference scenario. This resulted in policies that are optimized for an optimistic economic scenario. Furthermore, the policies were not optimized for extreme outcomes such as low efficiency, Weitzman damage function, Cauchy distributed climate sensitivity, and so on. Although, the Nordhaus reference scenario still includes the SLR driven damage function. Compared with the DICE2013 model, this results in greater damages due to the ongoing impact decoupled from atmospheric warming. Therefore, the reference scenario still considers relative high climate impact compared to other IAMs, which could have improved the generated policies' robustness.

Second, it is important to highlight the limitation of using only one economically optimistic reference scenario for generating strategies. It is possible that the order of robustness, where the Sufficitarian and Prioritarian strategies have the highest robustness within this research, could change if the principles were optimized over multiple scenarios. This could mean that other distributive principles would perform better and obtain more equitable strategies when implemented in IAMs. Although it seems unlikely that the Utilitarian policy would outperform the Sufficitarian and Prioritarian principle. This is because these principles already allow minimal climate impact to occur, even in the optimistic reference scenario.

Due to computational constraints, not all policies could be stress-tested for uncertainty. Only 30 out of roughly all 500 generated policies in the approximate Pareto set have been tested. Because these strategies have been chosen on their diversity to span the entire policy space, some non-chosen policies may have higher robustness than the selected policies. But the uncertainty analysis has shown that principle specific clusters can be identified within the uncertainty analysis results. This indicates that performance difference is not strategy but principle specific. This gives confidence in the results because, in that case, altering the distributive principle in IAMs can have a significant effect on obtaining more robust and equitable emission abatement pathways.

The Prioritarian and Egalitarian problem formulation only made use of Prioritarian and Egalitarian goals. No classical Utilitarian objectives are present within the problem formulation. The strict formulation of the Prioritarian and Egalitarian principle means that utility considerations did not influence the generated policies' optimization direction. Therefore intergenerational aspects that involve discounting and utility levels did not influence the optimization process. Although this approach is consistent from a distributive principle point of view, analyzing intergenerational distributive components' influence was more difficult. Because zero discounting or conditional discounting did not influence the generated policies. No conclusion can be attached to how these components steer the strategies in a specific direction and what this means for intergenerational trade-offs.

12.3 LIMITATIONS OF THE OUTCOME ANALYSIS

The limitations of the outcome analysis consist of two major pitfalls. Firstly, not all generated policies have been applied to the scenario discovery step. This could have the result that some vulnerabilities of the generated policies have been missed. Because of computational limitations, no clusters have been made between policies and also not between principles. This is one of the drawbacks of the exploratory approach where so much data is being generated, which is difficult to fully utilize. However, the robustness score has provided a basic metric of the performance of each principle specific policy on each objective. This partly overcomes that not all policies have been clustered. Another limitation is that within each policy set of scenario outcomes, not all scenarios have been used as input for the clustering step. This was because the computational burden was too large. Finally, the randomized selection method does not guarantee an equal spread of all scenario outcomes in the clustering set. This might have left some high impact cases out of the clustering set.

13 IMPLICATIONS FOR INTEGRATED ASSESSMENT MODELS

One of this thesis' goals was to investigate whether alternative distributive principles can help overcome the inequities arising from applying the Utilitarian principle in Integerated Assessment Models. This is reflected in research question 6:

Research question 6

How can Integrated Assessment Models benefit from the usage of alternative distributive principles?

To answer this question, first, a reflection is performed on the relationship between robustness and alternative distributive principles (section 13.1). Then in section 13.2, the alternative principles' performance is discussed and reflected on. Thirdly, a normative reflection on the ethical principles' performance has been carried out (section 13.3). This leads to proposed improvements for the RICE model and Integrated Assessment Model in general (section 13.4).

13.1 DISTRIBUTIVE PRINCIPLES AND ROBUSTNESS

Within the results, the emphasis has been placed on the robustness of principle specific abatement strategy via the SNR average robustness and the Max regret criterion. But what is the moral relation between robustness, robustness metrics, and distributive justice?

Within Utilitarian CBA, often the approach to deal with uncertainty is to obtain probabilities of all possible states [Adler, 2019; Hammond, 1981]. Then, all expected utilities can be calculated to rank each strategy [Fleurbaey, 2018]. But often, in the presence of deep uncertainty, this is not possible as the probabilities are unknown. There exists little literature on the connection of distributive principles, deep uncertainty, and robustness metrics. But some literature exists on the connection between intergenerational distributive justice and uncertainty. Within the Utilitarian principle, one approach to deal with uncertainty is the usage of Declining Discount Rates to deal with uncertainty in future rates of return [Arrow et al., 2014; Freeman et al., 2015]. The rationale is as we do not know what the economic situation and corresponding market rate will be in the future, we should take a cautious approach and only discount in the short term [Dasgupta, 2008]. Similar ideas form the basis for the conditional discounting schemes implemented in both the Prioritarian and Sufficitarian principles. Here, discounting is only applied when future generations are better off as a hedge against negative consequences for future generations. For the Egalitarian case, no discounting is applied, indicating that the present and future generations should be valued equally in terms of uncertainty.

What does this implicate for the relation between robustness metrics and the applied distributive principle? As negative shocks have the most profound effect on the lower-income regions, the Sufficitarian and Prioritarian principle by nature favor robustness gains regarding regret. The social planner's priority is then to improve the position of the worst-off or prevent sub-minimal welfare levels. Regarding the Egalitarian principle, average robustness is favored as this ensures good average performance across many possible scenarios. This contributes to an equalizing effect in as many scenario's as possible. Within the Utilitarian principle, it depends on whether the prescriptive or descriptive view is chosen. The prescriptive approach places more emphasis on future generations, indicating that regret-based robustness is valued higher than the descriptive view. The following section (section 13.3) will argue that it is more just to adopt Sufficitarian/Prioritarian principles given the injustices in current climate governance. Therefore more emphasis should be placed on the regret robustness metric.

13.2 DISCUSSION OF ALTERNATIVE PRINCIPLES

The following paragraphs reflect on the main findings of using alternative distributive principles in IAMs in relation to the Nordhaus policy. The Prioritarian and Sufficitarian principles possess very similar characteristics, such as early abatement target years, which is why these are taken together in the discussion of the alternative principles.

13.2.1 Prioritarian & Sufficitarian principle

Compared to the Utilitarian policies, including the Nordhaus principle, Pareto approximate Sufficitarian and Prioritarian policies have faster abatement targets. They reach net-zero emissions in 2065 to 2100 compared to Utilitarian strategies aiming for zero emissions in 2135. Within the optimization process of abatement strategies, the minimum emission control rate target year is capped at 2065 to obtain realistic reduction targets. Many Sufficitarian and Prioritarian strategies have emission targets near the minimum target year. Thus, if policymakers would place more emphasis on the position of the poor and vulnerable, significantly faster abatement trajectories would be preferred by IAMs. These results are in line with [Dietz and Asheim, 2012; Dennig et al., 2015; Adler et al., 2017] that climate abatement strategies become more stringent under Prioritarian and Sufficiatarian goals. The fact that many Sufficitarian and Prioritarian policies have near minimum target year outcomes shows that even faster abatement than 2065 would be preferred if that would be an option. This indicates that all extra warming is sub-optimal to protect the poor and vulnerable compared to the economic gains reaped from slower abatement. This differs significantly from the Utilitarian principle, where the emission control rate target is concentrated in the range of 2115 - 2135. This allows significant warming to occur in the range of 2-4 degrees Celsius and considerate economic damages in the process.

In the Ramsey–Cass–Koopmans growth model, the savings rate co-determines the level of consumption [Nordhaus, 2011]. The savings rate in the Prioritarian policies spans a broader range compared with the Utilitarian strategies. In contrast, the savings rate within Sufficitarian strategies is more comparable with that of many Utilitarian strategies. An explanation for this is that the Sufficitarian principle shares the goal of utility maximization above the threshold, hereby having similar characteristics as the Utilitarian principle. Within the Prioritarian principle, lower savings rates are justified in the short term to improve the worst-off position. However, in the RKC-model, very low savings rates are problematic because they are sub-optimal economically in the long-term. Moreover, they are also not consistent with current market savings rates. The Prioritarian principle aims at maximizing the economic position of the worst-off. In the PyRICE model, this can only directly happen from lowering the savings rate. But it can also be done by various economic re-distributional policies, for example, by capital transfers from high-income regions to lower-income regions and capital transfers within regions. These policy options are not tested within this research. Still, low savings rates indicate that redistribution in the short term is required if policymakers would emphasize Prioritarian goals for climate governance.

Prioritarian & Sufficitarian strategies outcomes

The outcomes of the scenario discovery have shown that in Utilitarian abatement strategies, the lowest income group's economic consumption is lower than that of the Sufficitarian and Prioritarian principle. Furthermore, Sufficitarian and Prioritarian principle have lower regret in the short- and in the long term because faster abatement protects from the most extreme cases. Sufficitarian and Prioritarian policies protect better against extreme cases where the earth would be extremely harsh for lower-income groups. Furthermore, the long-term uncertainty analysis indicates that Sufficitarian and Prioritarian principles have higher overall robustness. This means that they perform better on all objectives across the scenarios than the Nordhaus policy. Thus, the Utilitarian principle might perform well on aggregated objectives. But it is outperformed by the Sufficitarian and Prioritarian strategies on protecting the poor and minimizing the number of people ending up under the threshold. Overall, this indicates that Prioritarian and Sufficitarian principles contribute more to sustainable and equitable growth of the world economy.

Regarding the Sufficitarian strategies, the problem of specifying the Sufficitarian threshold remains. In many cases, economic growth is such that the total world population lives above the threshold level. Thus, the suffictiarian principle's usefulness to steer to equitable re-distributional abatement trajectories is sensitive to the height of the Sufficitarian threshold. This study had difficulty specifying the threshold as minimum consumption norms differ from country to country, and poverty is often measured relatively [Adler, 2019]. Within this research, the minimum Sufficitarian threshold was specified as the extreme poverty line by the World Bank, increasing with the average global economic growth. The start threshold level was set over a range of 700 to 2400 $ a year to test this threshold's sensibility. Relatively low sensitivity to the threshold has been found in this research. Because all sufficitarian policies with various threshold levels performed well. Therefore, the Sufficitarian threshold can be seen as a protector against hazardous climate change instead as the minimum welfare level. In this way, the threshold resembles the level of robustness required to protect against extreme climate change. This also explains why the most robust Sufficitarian policy has the highest starting threshold level of 2400 $.

13.2.2 Egalitarian principle

Compared to the Nordhaus (Utilitarian) policy, the performance of the Egalitarian principle is more mixed. Within the Egalitarian strategies, slow abatement and fast abatement are deemed optimal depending on which objective is optimized. The results clearly show that formulating climate policies solely on the need for equality has significant negative side-effects on the experienced climate damage, economic consumption, and therefore on experienced utility. This underlines the critique on Egalitarian policies that the Egalitarian principle leads to higher equality but results in a situation where everybody is worse-off [Adler, 2019]. Low savings rates imply that inequality is minimized in the short term as economic consumption of the worst-off is shifted up, thereby decreasing relative inequality. This has the side effect that in the long term, sustained growth is smaller. This leaves everybody worse-off in the long term. A similar effect occurs with slow abatement targets, which lead to higher consumption in the short term due to the absence of costly climate abatement. But it leads to negative economic consequences in the long run due to the exposure to extreme climate impact. Higher savings rates can increase economic welfare in the long term, thereby lowering intergenerational inequality. However, extreme high savings rates tend to increase inequality within regions as consumption levels between countries are amplified.

No Egalitarian policy has been found that has high robustness in both the short and long term. This does not mean that the Egalitarian principle does not have its merits for climate policy formulation. In this research, the Egalitarian formulation has been extreme as the egalitarian principle only focuses on reducing inequality. This specific optimization is blind to the economic optimality of a generated strategy. Therefore, many Egalitarian strategies in the

Pareto approximate set have considerable negative side-effects. This study found that Egalitarian objectives can be a good indicator for unevenly distributed climate impact, as shown by the impact of sea-level rise in worst-case scenarios. This can help to inform policymakers on evenly distributed climate impact.

13.2.3 Utilitarian principle

Within the Utilitarian principle, two specific cases of the Utilitarian approach have been tested: the Utilitarian principle under prescriptive and descriptive discounting. Surprisingly, the significant difference in abatement trajectories found in the Stern review (prescriptive) compared to that of the Nordhaus policy (descriptive) was not found in this research. Descriptive approaches did not result in slower abatement trajectories compared to the prescriptive approaches. This does not mean that the discount rate does not affect the formulation of abatement trajectories. For both the descriptive as the prescriptive case, multiple points in time have been optimized, thereby lowering the effect of a single aggregated objective in the DICE/RICE model. More importantly, the PyRICE model assumes that even when lower discount rates are enforced, return on capital stays high. This lowers the effect of using much lower discount rates. If different capital returns relative to the discount rate had been adopted, the difference between the prescriptive and descriptive approach would probably have been more significant. Still, on average, the descriptive method results in a ten-year difference in reduction target, with the prescriptive approach requiring faster abatement. This matches previous literature that prescriptive discounting demands for faster emission reductions [Stern, 2007; Dasgupta, 2008].

The prescriptive strategies do have a lower savings rate than the descriptive policies indicating that economic development should be slow down or that economic consumption should be increased if more emphasis is placed on later generations. The analysis also shows that other Utilitarian policies outperform the original Nordhaus policy in terms of robustness. This shows that the procedure in which the optimal Nordhaus policy has been generated is susceptible to the specific model setup.

13.3 NORMATIVE ASSESSMENT OF PRINCIPLES' EQUITABILITY

In the previous sections, the Nordhaus policy has been compared to the alternative strategies. This showed several key take away points: Prioritarian and Sufficitarian strategies call for immediate climate action, while Utilitarian policies only demand for medium but still challenging abatement speeds. Egalitarian strategies focus either on reducing equality within regions or between generations by extreme investment patterns and low or high abatement rates.

However, which principle works best overall? What can be said about which principle should be used within Integrated Assessment Models? Which principle makes alternative climate abatement principles more equitable?

What is at the core of this discussion is what is seen as more equitable. This goes back to the beginning of this research, which started by introducing the double inequity present in global climate change. Low-income regions have historically contributed the least to already induced climate change. Furthermore, their current per capita emissions are an order size smaller than that of western regions such as the United States, Australia and Europe. Future climate impacts, which this research showed could be very severe, will be felt hardest by those who bear the least guilt of climate change. Because of these deep inequities regarding climate change and its effects, this research makes the case that the global community has the responsibility to protect the vulnerable from the detrimental effects of climate change. This means that more emphasis should be placed on regret based robustness to account for negative shocks that especially affect the lower bound of the income hierarchy (see section 13.2.1). The question is then, which principles contribute the most to meet this objective?

First, the rationale of many economists has been that by optimizing economic growth, we can invest ourselves out of the climate crisis [Storm, 2017]. For example, by making the economic pie big enough, everybody will be better off. This idea is adopted in IAMs through the objective of utility maximization. This research shows that this argument does not hold. The Utilitarian policies perform worse on overall economic growth due to higher exposure to negative shocks. Furthermore, Utilitarian policies do not lead to an economic pie that is big enough for the vulnerable to overcome exposure to extreme climate hazards. In many cases of the Utilitarian runs, the worst-off 20 % is worse off than it is now. Or it will not experience the consumption growth that it could have had under Prioritarian and Sufficitarian policies.

Secondly, regarding the Egalitarian principle, this resulted in a more equal distribution of climate impact and economic consumption. However, this comes at the cost of high absolute levels of climate damages and low overall economic output. Regarding the low-income regions globally, this means a double blow as lower economic growth leads to fewer opportunities for a catching-up process. Furthermore, high climate impact results in a further deterioration of the bottom 20 %. This can not be the goal of policymakers trying to oppose inequities arising from climate change. Therefore, the stand-alone strict Egalitarian principle is not suitable as a dominant new principle for Integrated Assessment Models.

Finally, regarding the Sufficitarian and Prioritarian policies, especially the Sufficitarian policies are the most robust. This can be explained from the fact that the Sufficitarian principle combines utility maximization with a correction at the bottom of the distribution in the form of the Sufficitarian threshold. Also, the Prioritarian strategies that focus solely on the worst-off's economic position performed well in overall robustness compared to the other principles. Thus, the Prioritarian and Sufficitarian principle generate policies that are optimized in economic terms and corrected at the bottom of the income distribution. Therefore, Integrated Assessment Models can benefit most from adopting parts of the Prioritarian and Suffitarian problem formulations. This not only improves overall economic performance but also increases robustness. This will lead to better protection of the poor and vulnerable, which is desperately needed in climate abatement trajectories. Only then, the double objective of reducing economic inequalities while protecting the environment can be achieved simultaneously.

13.4 REPAIRING THE UTILITARIAN BASED IAM

In the previous section, the case has been made that Utilitarian based IAMs are in need of improvement via the adoption of Sufficitarian and Prioritarian objectives. Furthermore, the uncertainty analysis has shown that the RICE model and resulting Utilitarian pathways are sensitive to economic and climate uncertainties. Therefore, three main recommendations for repairing the Utilitarian model have been made:

1. Make use of a variety of Sufficitarian and Prioritarian objectives within IAMs to correct the Utilitarian principle at the bottom of the income distribution
2. Expand the usage of IAMs towards evaluating the equity of emission abatement trajectories
3. Utilize a wide variety of scenarios to select robust and effective abatement strategies

13.4.1 Adoption of multiple alternative distributive objectives

The first recommendation implies that a successful correction of the Utilitarian principle has the form of a many objective optimization problem as multiple objectives are optimized. To enable IAMs to make use of equity improving multi-objective problem formulations, IAMs should report more detailed outputs regarding inequality in economic position and climate impact. Models can not optimize over data that they do not effectively measure. IAMs that only report outputs in an aggregated manner will not be able to estimate the severity of climate impact across heterogeneous populations. This research took the approach of Dennig et al. [2015] as a first step to provide more insight into the position of the worst-off. More sophisticated approaches can be implemented. For example, by more detailed mapping of geospatial climate risk and the inclusion of income specific climate hazards. This makes it possible to distinguish between climate hazards, which are already linked to higher atmospheric warming, such as droughts [Masson-Delmotte et al., 2018].

Including Prioritarian objectives in IAMs would account for the worst-off position currently being neglected in many IAMs. Sufficitarian objectives focusing on threshold utility can help to generate strategies that are robust for extreme climate events. Together they can enhance the performance across all objectives. As no absolute method exists for specifying the Sufficitarian threshold, it can be seen as a protector against hazardous climate change. This makes it simpler to establish the level of the Sufficitarian threshold.

The inclusion of Egalitarian objectives that measure inequality can help avoid strategies that increase climate impact inequality masked by economic differences between those regions. One example of this is the sea level rise, primarily impacting lower laying low-income regions because these regions do not have the means to change to the risen sea level. Egalitarian objectives could help to correct climate abatement trajectories to minimize these climate impact inequalities.

13.4.2 Expanding the usage of IAMs

In the previous section, several ways have been proposed how IAMs can be expanded with additional objectives to generate more equitable abatement strategies. These imply a shift away from a complete ranking of CBA optimized trajectories for a given carbon budget towards a partial ranking of a Pareto optimal set of abatement trajectories. In general, this means a broadening of the information base which policymakers use to choose abatement pathways. This is in line with Sen [2009] in which Sen argues that in decision problems with high imperfect knowledge on the outcomes, a more just society can be pursued by better comparison of the possible choice alternatives [Lempert et al., 2013]. Therefore, a more thorough comparison of alternatives across multiple objectives can be seen as morally more just.

To broaden the information base, the next step is to make more use of IAMs to analyze the distributional effects of global abatement strategies. The SSPs framework has led to the development of research on policy focusing on the relation between poverty and the climate [O'Neill et al., 2020]. However, in many of the SSPs and IAMs quantified parameters, communities' adaptation and resilience capabilities are still lacking. A better understanding of future resilience would improve further projections of consumption levels, especially at the bottom of the income hierarchy [Hallegatte and Rozenberg, 2017]. This would enable policymakers to focus on testing policies that are broader than just emission pathways. For example, by focusing on the resilience effects of social protection, financial inclusion, strengthening of pension funds, education, and health care access [O'Neill et al., 2020].

When IAMs are more used to analyses distributional effects, regionally distributed impacts become more apparent within climate governance. Then, the advantages are two-fold. First, citizens become aware of the exposure they face toward climate injustices. In turn, they can plead their case for better protection against climate extremes by more stringent abatement targets and demanding more adaptive capacity. Second, governments will become more aware of the distributed impact arising from abatement strategies on heterogeneous groups. Regions with relatively high climate impact on their lower-income classes, even in the richer regions, will be pointed out that in order to prevent this, more action is needed [Chancel, 2020]. Overall, this has the potential to steer the policymakers towards a better-informed decision-making process and more equitable abatement strategies.

13.4.3 Adoption of robust analysis in IAMs

Furthermore, a successful correction of the Utilitarian-led abatement trajectory is only useful when combined with testing policies over a broader range of scenarios. The Nordhaus policy is among the worst-performing tested policies in both the short and long term. The cause of this problem is the practice of many climate economists to focus on single scenario optimality instead of robustness across multiple scenarios. When considering the relationship between robustness and principle performance, the uncertainty results shown that scenario factors play a more significant role than the chosen principle in contributing to the model outcomes. Especially factors such as the damage function and the chosen economic scenario have a high impact on the model outcomes across all scenarios. Uncertainties such as the elasticity of damages can significantly influence principle specific objectives such as the economic position of the worst-off.

The fact that many IAM based research such as the work carried out by Nordhaus [2010]; Anthoff and Tol [2013]; Page [2007] only consider single scenario optimization models is worrisome to say the least. However, even the broader community of the IPPC mostly focuses on the limited framework of the Shared Socioeconomic Pathways for scenario analysis as input for the more complex models [Lamontagne et al., 2019]. The partial factorial scenario analysis over 35000 scenarios highlighted important conclusions that cannot be derived from running five distinct SSP scenarios. The tested principles' performance differences could only be distinguished by thorough scenario analysis and to evaluate extreme outcomes. Therefore, policies generated with single or sparsely scenario-driven research face the risk of severe exposure to worst-off cases. Therefore, this research underlines the need for more robust decision making analysis around IAMs also underlined by Lamontagne et al. [2018, 2019]; Lingeswaran [2019]; Frisch [2013]; Beck and Krueger [2016]; O'Neill et al. [2020]. The longer run time of complex IAMs will make it difficult to simulate large amounts of scenarios. But this does not necessarily mean that complex IAMs can just omit robust evaluation. To deal with the long run time, complex IAMs could evaluate worst-case scenarios as an extra test for abatement policies. Or a broader range of scenarios could be drafted from which multiple example scenarios would be chosen to check for robustness.

The importance of the economic scenario in this research has shown that more diverse socioeconomic scenarios are needed within the IPCC community. This is connected to the critique that some SSP/RCP pathways are outdated. For example, RCP8.5 has been criticized by Hausfather and Peters [2020] for its overvalued usage of coal that leads to unrealistically high emissions. This drives extreme outcomes for climate impact studies that take the RCP8.5 as a business as usual scenario. Such a conservative approach, similar to regret based robustness considerations, may be wise in the face of fat-tailed climate change outcomes. However, the SSPs are too important and widely used to be only updated once in 10 years. Therefore, the SSP framework should be updated more often in the future and should include a wider variety of scenarios, including diverse economic futures, to effectively generate and test climate strategies.

14 IMPLICATIONS FOR POLICY

The previous chapter has stated various ways to expand the usage of IAMs to obtain more equitable abatement strategies. However, what are the normative implications of the distributive principles for policymakers? This forms the focus of the last research question.

Research question 7

What are the policy implications of the usage of alternative distributive principles within IAMs for global climate governance?

To answer this question, the abatement trajectories of the most robust Prioritarian and Sufficitarian strategies are compared with that of the emission pathways set by the IPCC (section 14.1). The results have shown that policymakers, besides implementing emission reductions, can reduce climate impact by strengthening economic resilience. Section 14.2 states supplementary equitable strategies that can support equitable emission trajectories that focus on reducing economic inequalities within the world.

14.1 COMPARISON GLOBAL ABATEMENT PATHWAYS

If policymakers would prefer to follow the well-performing Prioritarian and Sufficiatarian principles, what would this imply for the shape of abatement trajectories? How does this compare to the abatement trajectories set out in the Paris accord?

In 2016, the Paris agreement was signed by 196 states to oppose global climate change. The Paris Agreement's long-term goal is to keep the global average temperature well below 2 degrees above pre-industrial levels; and pursue efforts to limit the increase to 1.5 degrees. The Paris accord follows a bottom-up approach where states make nationally determined contributions (NDCs). Together, the NDCs establish a global abatement path providing a > 66 % chance of staying below 2 degrees warming in 2100 [Masson-Delmotte et al., 2018]. But the current pledges in the Paris accord are already insufficient to reach these goals [du Pont et al., 2017]. Current *Pledges Targets* would only limit warming to 2.3 - 2.6 degrees. Staying well below 2 degrees is important as this significantly reduces the risk of severe climate impact [Masson-Delmotte et al., 2018], which is also shown in this research.

When assessing the trajectory *Pledges Targets*, this emission trajectory shows similarity with the non-robust Nordhaus policy, with emissions reaching net-zero well after 2100. This research showed that the Nordhaus policy lacks robustness to protect the poor and vulnerable. Also, it performs worse on average on all other objectives. Therefore, a strong case can be made that extra pledges are needed to prevent the Nordhaus trajectory's negative effects found in this research. This will benefit the welfare of all income groups across all regions.

When comparing the Sufficitarian and Prioritarian emission trajectories with that of the Paris accord, the PyRICE estimated trajectories are similar to the *1.5 consistent* trajectories. The *1.5 consistent* pathway reaches net-zero emissions in 2060 - 2070, whereas the most robust Prioritarian and Sufficitarian policies reach net-zero emissions in 2055 and 2065, respectively. The *1.5 consistent* emission trajectory shows how challenging the task at hand is. Within the *1.5 consistent* trajectory, emissions have to peak immediately, after which rapid reduction is

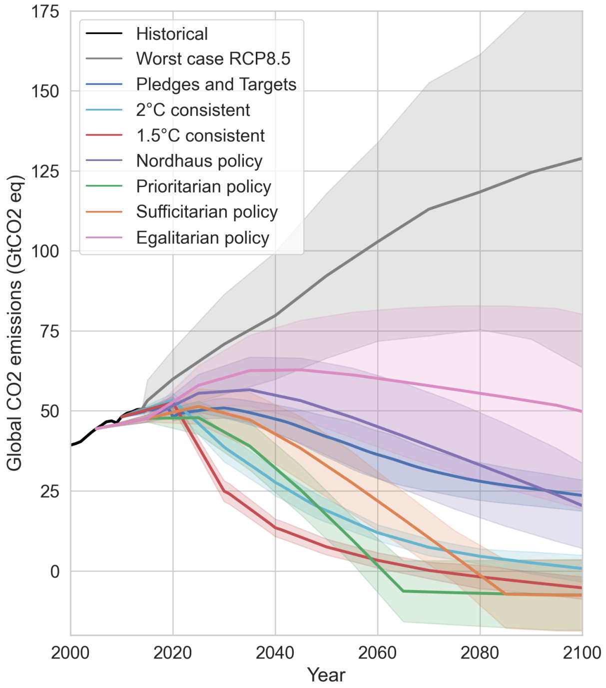


Figure 14.1: Principle pathways international pathways (data source: Climate Action Tracker)

required to reach net-zero emissions in 2060 - 2070. Overall, this research is consistent with the IPCC report *a global warming of 1.5*°C that immediate wide-scale climate action is required to avert profound climate impact on the low-income regions.

Interchangeability of principles

Within decision-making under uncertainty, adaptivity is of interest to overcome lock-ins to be able to adjust policies towards emerged external factors [Kwakkel and Haasnoot, 2012]. If we were to follow one of the emission pathways set out by one of the principles, would there still be the option to switch to another principle in terms of emission pathways? Moreover, until which point would we be able to make the switch?

There is an immediate split between the emission trajectories of the Utilitarian principle compared to that of the Prioritarian and the Sufficitarian principle (figure 11.4). Switching to another principle can, in theory, be done by accelerating the speed of abatement to match the carbon budget of the target principle. This only holds for situations where the carbon budget of the target principle has not already been exceeded. These non-overshoot switches can be done through emission reductions in various sectors, for example, through major lifestyle changes such as sustainable food consumption [Vuuren et al., 2018] and rapid reduction of the usage of fossil fuels [Hallegatte and Rozenberg, 2017]. Within *a global warming of 1.5*°C there are pathways in which low use of fossil fuels combined with profound lifestyle changes produce a rapid shift towards low emissions [Masson-Delmotte et al., 2018]. Overall, the possibility of switching between pathways is restrained by what is practically and morally feasible to ask from this and the next generations.

Switching from Utilitarian emissions pathways that exceed the CO_2 budget of the target principle indicates an overshoot of the CO_2 emission budget. Switching between principles can then, in theory, only be done by implementing Carbon Dioxide Removal techniques (CDR) on a vast scale to match the net CO_2 carbon budgets of the target principle. Many pathways of *a global warming of 1.5*°C make use of CDR through BECCS and afforestation and reforestation [Masson-Delmotte et al., 2018]. CDR may only work if the overshoot is not too high, leading to higher atmospheric warming with high climate impacts. Furthermore, it possesses the risk of activating tipping points in which CO_2 emissions from melting permafrost limit the effectiveness of negative emissions [Jones et al., 2016]. Also, [Tokarska and Zickfeld, 2015] found that induced sea-level rise from emission overshoots are not reversed by the deployment of large amounts of negative emissions. This limits the effectiveness of CDR to prevent high climate impact on lower laying low-income regions.

To conclude, the societal, environmental, and economic feasibility of CDR techniques to produce vast negative emissions remains highly uncertain. The IPCC states in 2018 that: "Carbon cycle and climate system understanding is still limited about the effectiveness of net negative emissions to reduce temperatures after they peak" [Masson-Delmotte et al., 2018, Ch.1, p.17]. Therefore, the possibilities for switching towards other principles are limited and can only be done in the short term, in the 2020 - 20230 range. To some extent, lifestyle changes and afforestation and reforestation can contribute to this in some scenarios [Masson-Delmotte et al., 2018]. However, the conclusion is that if we were to focus on Prioritarian and Sufficitarian goals, the best bet is to do that right from the start. Otherwise, a dependency on the feasibility of large-scale CDR is likely, and more importantly, a lock-in of considerable climate impact on the future poor.

14.2 SUPPLEMENTARY EQUITABLE STRATEGIES

Principles of distributive justice were central in the Kyoto Protocol agreed in 1992. Distributive justice principles such as the 'common but differentiated responsibility' linked to the polluter pays principle and 'respective capabilities' reflecting the capability approach had an important place in the agreement [du Pont et al., 2017]. Because of the different historical contributions to climate change, significant differences in emission reduction targets arose between states that signed the agreement. This led to an impasse in which countries refused to further cooperate in climate conferences if potential future polluters were not limited by more stringent emission reduction targets [Okereke and Coventry, 2016]. This led to the more pragmatic approach of the bottom-up National Determined Contributions which formed the cornerstone of the Paris agreement [Chancel, 2020]. Clear principles of distributive justice were deliberately left out in the Paris accord. The focus was on how to pragmatically obtain enough emission reductions to limit global warming below 2 degrees and preferably to 1.5 degrees [du Pont et al., 2017]. In some ways, equity considerations are addressed within NDCs, such as the requirement for each country to state in his NDCs how to contribute to 'equitable contributions' and to do its 'fair share'. For example, by pledging financial support for climate adaption projects in low-income countries [Masson-Delmotte et al., 2018].

The need for adaptation has been clearly highlighted in this research. The results have shown that considerable climate impact is still a significant possibility even under the most robust policies implementing rapid emission abatement. This shows that only emission reductions will not be enough to reach an equitable global climate strategy. To protect the poor and vulnerable, extra focus should lie on supporting the low-income groups' economic resilience in all regions. The task at hand is broader than just the rich regions that have to support the low-income regions. Climate hazards such as widespread bush fires will happen more often in the future [Masson-Delmotte et al., 2018; Stott et al., 2016]. Even in high-income countries, such as the United States, climate hazards such as hurricanes events magnify existing economic inequalities. Not only had richer constituents of New Orleans more means to get out on time to reduce physical impact, their homes were also located in better-protected locations towards the storm [Chancel, 2020]. Similar characteristics have been identified for many other climate hazards [Hallegatte and Rozenberg, 2017]. This has led to the adoption of the elasticity of climate impact in this research [Chancel, 2020; Dennig, 2014; Masson-Delmotte et al., 2018]. Redistributive policies can modify the elasticity of climate impact by increasing the resilience of the lower-income classes. The next section identifies some example policy instruments that can be applied to improve the lower income groups' resilience.

Possible policy instruments

What are the possible policy instruments that can help to strengthen economic resilience? The vast scale of possible policies is too big to cover here fully. The IPCC has dedicated large shares of *a global warming of 1.5°C* to this, see Masson-Delmotte et al. [2018]. Specific to this research, policies aimed at reducing economic inequalities could favor Prioritarian and Sufficitarian objectives. To reduce inequality within regions, investments by the nation-state in public services such as education, sustainable energy, and water systems and transportation infrastructure are needed [Chancel, 2020]. These can lead to significant spillover effects that will strengthen the resilience of the low-income classes within regions. Through ecological taxation, the financial means can be brought together to make these investments possible within nation-states. In rich countries, ecological taxation is often regressive, having a bigger impact on the lower-income classes' consumption level. Because taxing products such as electricity and fossil fuels takes relatively larger shares of the lower income groups' exposable income. Therefore, ecological taxation to redistribute wealth needs to be accompanied by compensation for lower-income groups to contribute to Prioritarian and Sufficitarian goals successfully.

Ecological taxation in developing countries currently has a more progressive character because the higher income classes dominantly consume the taxed goods. Applying ecological taxation on these 'luxury goods' could be an effective way to overcome the problem of 'hiding behind the poor'. This argument is being made to call out the higher income classes in low-income countries that are omitted from re-distributional efforts in global climate negotiations. Although, it is likely that within most developing nations, ecological taxation will not lead to the collection of enough public funds needed for investments to reduce existing inequalities. Furthermore, this approach is also arguably not socially just because of the high unequal contribution to historical and future climate change. Therefore, significant capital transfers from the OECD-countries to the developing regions are needed to overcome these injustices. Capital transfers are included in the Paris accord leading to objectives such as "finance flows consistent with a pathway towards low greenhouse gas emissions and climate-resilient development." [Masson-Delmotte et al., 2018, ch.4, p.370]. However, up to now these capital transfers have not been implemented on the scale to make the required impact [Ha et al., 2016].

Therefore, policymakers in the developed countries, including the Netherlands, should put significantly more effort into executing capital transfers between the OECD-countries towards the low-income regions. Only then can policymakers steer the transition path towards more favorable impact scenarios such as the SSP1 and SSP2. In these scenarios, big climate impact on the vulnerable in especially the low-income regions, is less frequent. The SSP projections are not scenarios that will probabilistically happen to us. The OECD-countries well have the means to steer the world towards favorable scenarios. Furthermore, as the results show, in cases where the elasticity of damages (as a proxy for resilience) is lower, detrimental impact on the lower-income classes can often be prevented.

To summarize, when economic inequalities are reduced by international redistribution and equitable growth within nations, the starting position of a big part of the world population will be significantly improved. With this achieved, the impact of climate extremes is reduced which contributes to obtain more equitable climate abatement strategies.

15 CONCLUSION

Within this section, the main research question will be answered (section 15.1). Thereafter, an assessment will be made of the implications for the scientific field regarding IAMs (section 15.2). Then, avenues for future research will be given (section 15.3).

15.1 MAIN RESEARCH QUESTION

In this thesis, alternative distributive principles have been used to generate more equitable abatement strategies. Four main principles have been tested: the Prioritarian, Sufficitarian, Egalitarian, and the Utilitarian principle. Within each principle, two intergenerational approaches have been implemented. The resulting eight unique distribution principles have been used to generate abatement strategies by executing the MORDM method. Pareto approximate policies have been stress-tested within a short and long term uncertainty analysis. The short term analysis has compared the performance of the principles within the SSP framework. The long term uncertainty analysis tested the performance of the alternative principles regarding long term climate change. Scenario Discovery has been applied to structure the output and identify vulnerabilities. The simulation steps' output formed the input for the ethical reflection, which states this thesis's implications for IAMs and policymakers. The final step is to answer the main research question:

MAIN RESEARCH QUESTION

What is the effect of applying alternative distributive principles to the RICE model on global CO_2 abatement pathways under deep uncertainty?

The concluding answer can be split up into model-based implications (section 15.1.1) and policy-based implications (15.1.2).

15.1.1 Model based implications

The generated strategies have shown that especially Prioritarian and Sufficitarian policies call for faster emission reductions compared to the Utilitarian and especially the Egalitarian principle. The Sufficitarian principle had the most consistent emission targets, with all generated policies possessing targets in the 2065-2075 range. The Prioritarian principle also calls for fast emissions reductions, but the generated policies' variance is bigger. Most Prioritarian net zero emission targets are in the 2055 - 2105 range. This difference arises because the Sufficitarian principle aims at reducing extreme climate impact while the Prioritarian principle also focuses on income growth, hereby accepting the risk of higher atmospheric warming.

The Egalitarian principle generates slow emission abatement targets and extreme savings rates to maximize equality in consumption. This comes at the expense of high risk to severe climate impacts and poor economic performance. Not surprisingly, the Utilitarian strategies have high similarity with the Nordhaus policy, as this is an example of a Utilitarian based policy. Utilitarian policies have medium abatement rates in the range of 2145 - 2155. Prescriptive policies aim for slightly faster abatement than the descriptive variant.

When comparing the performance of the various principles, the results clearly indicate that the Nordhaus policy, and Utilitarian policies in general, have high exposure to climate change extremes in many scenarios. This leads to a significant income decline in the lowest income groups. The Egalitarian strategies fail to deliver on the promise of equality. Egalitarian policies are not economically optimal in any way and lead to unacceptable risk to climate change. Therefore the Egalitarian principle is not suitable as a driver of the generation of climate abatement policies. The global economic performance of robust Prioritarian and Sufficitarian strategies are similar to or better than that of the Utilitarian principle. Whereas the exposure to climate extremes is better for the Prioritarian and especially the Sufficitarian policy.

The Sufficitarian principle is an example of a partly Utilitarian-based principle with correction at the bottom of the income distribution. The Sufficitarian principle showed good average performance while protecting against extreme climate impact. This shows that Utilitarian economic objectives can contribute to a good performance across many scenarios. Because the economic catch-up process for lower-income countries is favored by economically optimal abatement strategies. Sufficitarian policies add to this by lowering the risk of climate extremes that can threaten the low-income quintiles' consumption level. Based on the significant performance difference between the Utilitarianand the Sufficitarian and Prioritarian policies, three recommendations are proposed to improve the effectiveness and robustness of Utilitarian based IAMs. Together, these three recommendations can contribute to overcoming the inequities arising from the usage of Utilitarian-based IAM.

- Make use of a variety of Sufficitarian and Prioritarian objectives within IAMs to correct the Utilitarian principle at the bottom of the income distribution
- Expand the usage of IAMs towards evaluating the equity of emission abatement trajectories
- Utilize a wide variety of scenarios to choose robust and effective abatement strategies

A first starting point for IAMs would be to make use of objective formulations that use a Sufficitarian threshold to account for climate extremes, a Prioritarian objective such as economic consumption for the worst-off to promote economic growth for lower-income regions, and a Utilitarian objective to steer generated policies into overall economic optimality. The first recommendation implies switching from single objective optimality towards a partial ranking of a Pareto optimal set of abatement trajectories. Most complex IAMs optimize for welfare given a specific temperature goal. This means that the model structure of complex IAMs should be changed to support a many-objective optimization problem formulation.

The second recommendation uses the broadened information base to enable policymakers to use IAMs for analyzing the distributional effects of global abatement strategies. It enables policymakers to focus on testing policies that are broader than just emission pathways. For example, by focusing on the effects of social protection, financial inclusion, strengthening of education, and health care access. Which can counteract the negative impact of already locked-in climate change.

A successful correction of Utilitarian-led abatement trajectory is only useful in conjunction with stress-testing abatement trajectories over a broad range of scenarios. Trajectories generated with single or sparse scenarios face the risk of severe exposure to regret shown by the Nordhaus policy's bad performance. The longer run time of complex IAMs poses barriers to how many scenarios can be used. Because of the economic scenario's influence, using a more diverse set of economic scenarios can already contribute to testing the robustness of generated abatement strategies. Furthermore, abatement pathways could be stress-tested against worst-cases or against a subset of a broader scenario set. Thus, the longer run time of complex IAMs can not be a reason to abolish robustness considerations when selecting abatement strategies.

15.1.2 Policy based implications

Besides the model-based implications, alternative distributive principles have a wide variety of implications for current climate policies. Firstly, if policymakers would focus more on Prioritarian and Sufficitarian goals, abatement strategies should aim at reaching net zero-emission in 2065 - 2085. Current pledges by the 196 countries making up the Paris agreement will reach net-zero emissions well beyond 2100 [du Pont et al., 2017]. This has the potential of triggering detrimental impacts on the poor and vulnerable. To prevent this, higher pledges for emissions cuts are needed to aim for the emission pathway of the Sufficitarian and Prioritarian pathways. A good indicator is the pathway of *a global warming of 1.5* set out by the IPCC, which is consistent with the most robust Sufficitarian and Prioritarian pathways found in this research [Masson-Delmotte et al., 2018].

Furthermore, if policymakers would aim for equitable emissions pathways, it is the best way to do this right from the start. In CO_2 emission overshoots regarding Sufficitarian and Prioritarian pathways, sea-level rise can be triggered. These delayed impacts threaten the economic well-being of lower-income groups with lower-laying areas. These impacts can possibly not be reversed by large scale negative emissions in the [Jones et al., 2016]. Even in non-overshoot pathways, there is a big dependency on the feasibility of large-scale CDR. This means that policymakers should aim for pathways that use efficiency gains and lifestyle changes to minimize the lock-in of large scale CDR in the future.

Besides the focus on stronger abatement, policymakers should focus on reducing economic inequalities and improving the resilience of the bottom income class. The model results have shown that if policymakers would succeed in strengthening the resilience of the worst-off, this can prevent worst-case outcomes regarding Sufficitarian and Prioritarian goals. Strengthening economic resilience can be accomplished in various ways, such as public investment in education, health, energy, and transportation infrastructure. These investments should be achieved not only in the developing world but also in the developed world. Economic inequalities in the developed world have been widened in the previous decades [Piketty, 2014], which negatively affects resilience against climate shocks [Chancel, 2020]. Therefore, the Green New Deal, named in numerous other literature such as Chancel [2020]; Piketty [2014]; Masson-Delmotte et al. [2018], has the potential to steer the global community away from vulnerable scenarios such as SSP4 and SSP5.

Likely, the low-income regions will not have the financial means to accomplish the needed public investment on their own. Policymakers in the developed countries, including the Netherlands, should put significantly more effort into executing capital transfers between the OECD-countries towards the low-income regions. The financial transfers asked for IPCC reports such as *a global warming of 1.5 degrees* [Masson-Delmotte et al., 2018] are needed to reduce existing economic inequalities between and within regions. When economic inequalities are reduced by international redistribution and equitable growth within nations, the world's starting position to withstand incoming climate impact will be significantly improved.

15.2 SCIENTIFIC IMPLICATIONS

This research contributes to the scientific community in various ways. to the writer's best knowledge, it was the first research to combine an overarching view of the effects of applying multiple distributive principles in an IAM under deep uncertainty. Previous research applied alternative distributive principles, mostly focusing on Prioritarian approaches, such as Adler et al. [2017]; Dennig et al. [2015]; Tol [2013], and on Utilitarian approaches, such as Tol [2001]; Arrow et al. [2014]. These research mostly focused on the implications for the social cost of carbon. These research did not provide a broad overview of alternative principles' implications on lower-income groups. The research field only consists of a few studies focusing on the Sufficitarian [Dietz and Asheim, 2012] principle. First, this research has shown the high capacity of the Sufficitarian principle to generate emission pathways that are robust against climate extremes, improve equity of consumption, and are economically optimal. Secondly, this study also showed the lack of robustness of the Utilitarian principle compared to the Prioritarian and Sufficitarian principle. Thirdly, this research showed that equitable goals can significantly improve robustness of abatement pathways. These three points have been undervalued in previous research.

Secondly, many researchers have used different models and scenario inputs to test various principles. Therefore an inter-study comparison of alternative principles was difficult. This research provided a clear comparison between the four mainstream distributive principles used within the IAM community. Furthermore, the result can be compared with many other climate studies because of the usage of the SSPs to drive the results of the short-term uncertainty analysis. This has not been done earlier mentioned in previous research. This research showed the similarity of the pathway of *A global warming of 1.5 degrees* with that of Sufficitarian and Prioritarian pathways. This strengthens the case for following the pathways of *a global warming of 1.5 degrees* if policymakers would focus on equitable goals within emission abatement pathways.

Previous research focused on improving spatial and temporal distributive justice in IAMs have not applied a many objective evolutionary algorithm (MOEA) to generate alternative strategies. This research once more highlighted the usefulness of using MOEAs for the generation of Pareto optimal policies within climate models. This has previously been highlighted by Lingeswaran [2019]; Kulkarni [2020] which applied MOEAs to the DICE model. This research adds to this by successfully using search algorithms to generate more equitable climate abatement strategies. Following the recommendations mentioned in section 15.1, these could be adopted in more complex IAMs to develop more equitable abatement pathways.

Finally, none of the previous research has executed a thorough scenario analysis to test the robustness of emission pathways generated by applying alternative distributive principles within IAMs. The scientific IAM-community still widely uses single reference scenario models to find one-off optimal policies [Stanton et al., 2009]. This conclusion has previously been underlined by Lingeswaran [2019]; Lamontagne et al. [2018]; Stanton et al. [2009]. This research has shown that, under the influence of uncertainty, the global population at the bottom of the income hierarchy faces significant climate risk in established emission pathways. In many scenarios, the socio-economic position of the lowest 20 % will be worse in the short and long-term future relative to that of today. The global eradication of poverty is certainly not guaranteed under the influence of uncertainties embedded within climate change. Therefore, this research underlines the call to make more use of robust scenario sampling for policy evaluation within IAMs for the sake of equitability.

15.3 FUTURE RESEARCH

One limitation of this research is that alternative policies have been generated over only one reference scenario, namely the Nordhaus RICE2010 scenario. The robustness of strategies could be improved by optimizing over multiple diverse scenarios in the policy generation step. This would imply following a MORO-method approach during the generation of the alternative abatement pathways. Further research could assess if the ordering of the principles in terms of robustness is consistent when principles are optimized over multiple scenarios.

A second avenue for future research is to focus more on optimizing the intergenerational objectives within the alternative principles. Due to the problem formulation of the Egalitarian and Prioritarian, intergenerational objectives did not influence the generation of strategies. Because welfare-based objectives were deliberately left out of the problem formulation to make each principle more strict to simplify the comparison between principles. Therefore, intergenerational model components of the Egalitarian and Prioritarian principle could be assessed in the future, such as conditional and zero discounting approaches.

As noted earlier, one of the main limitations of this research is the limited predictive capacity of the RICE model. Therefore, it would be interesting to apply the developed principles to more complex IAMs such as the Integrated Model to Assess the Global Environment (IMAGE). The IMAGE model serves as one of the five main models used to estimate climate effects within the IPCC reports [Masson-Delmotte et al., 2018]. The complex IAMs are more able to incorporate all narrative components of the SSPs. This can also improve the comparison of the alternative principles to Utilitarian based pathways within the IPCC reports.

It is unlikely that this research's exploratory workflow can directly be applied to the more complex IMAGE model. This is because these models have a far longer run time than the PyRICE model. Possible workarounds are restricting the size of the policy space by putting in constraints. This could result in a faster generation of policy alternatives. The lessons learned within this research can provide some indication of where to constraint the policy space. A first starting point would be to use a problem formulation that uses a Sufficitarian threshold to account for climate extremes, a Prioritarian objective for the worst-off, and a Utilitarian objective to steer generated policies into economic optimality. Constraints could be placed on extremely high or low savings rates and slow abatement rates. Generated policies could then be stress-tested over multiple representative scenarios or a full scenario range depending on the used IAM's computational limits. Together, this approach makes it possible to test the alternative principles' performance in more influential Integrated Assessment Models.

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V

APPENDICES

A OUTCOMES BASE CASE

The following figures gives an overview of the outcomes of the base case over all model objectives that are used within the alternative principles. The results of the Nordhaus policy under the reference scenario thus forms a reference to the performance of the alternative principles.

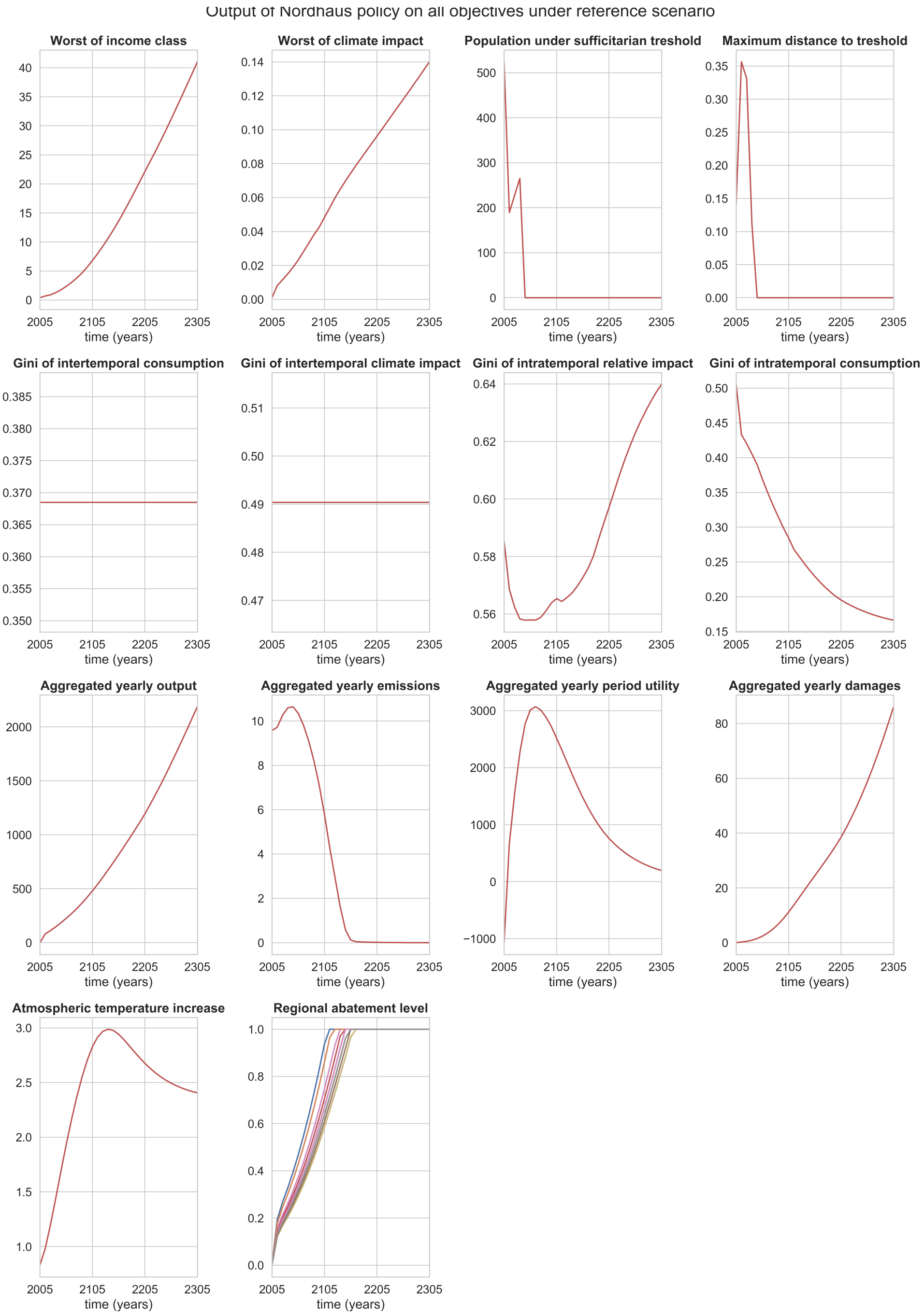


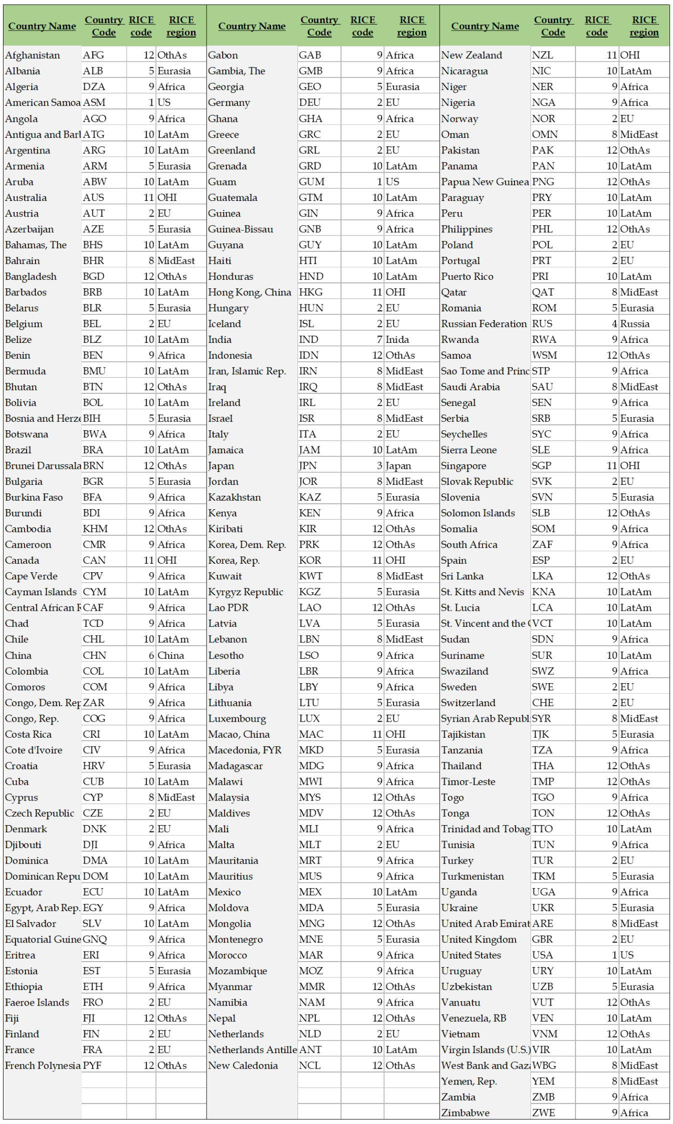
Figure A.1: Overview of Nordhaus policy under reference scenario on all objectives

B MODEL INPUTS

The following figures show the most important new model inputs for the PyRICE model. All other standard RICE model inputs are adopted from and described in Nordhaus [2011]; Lingeswaran [2019]; Dennig et al. [2015] and will not be further elaborated here. See chapter 6 and 7 for the specification for the model inputs uncertainties.

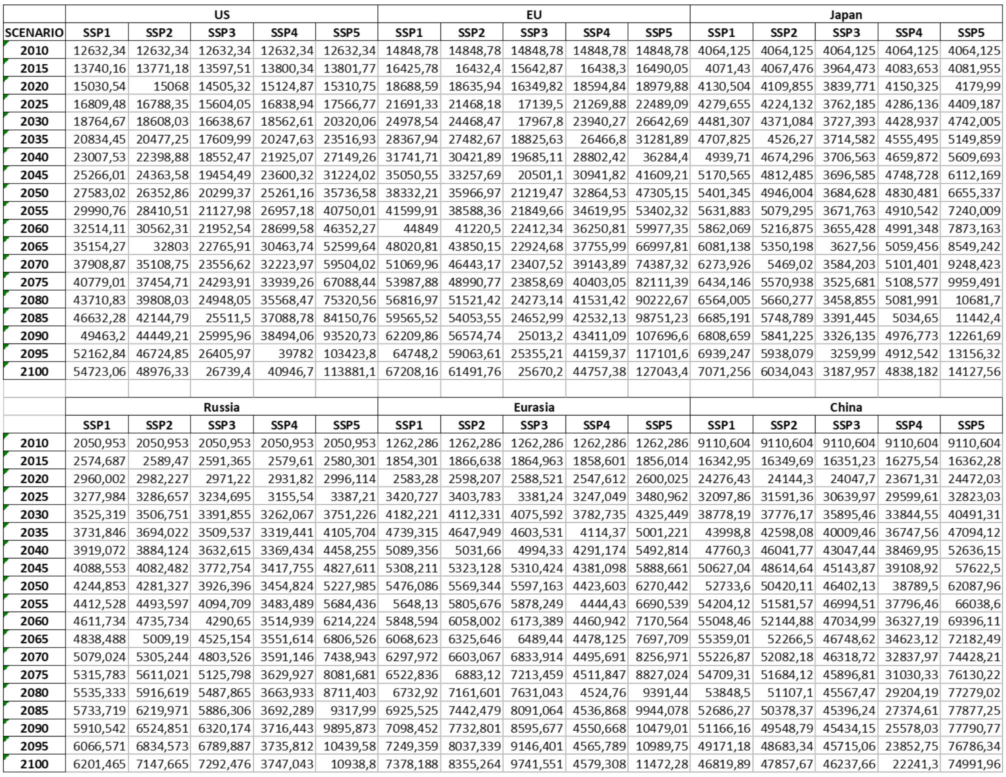
Inputs SSPs

Figure 17.1 shows the mapping of the countries within the SSPs to the regions in the RICE model. Figure 17.2 to 17.5 show the development of the GDP and population for every RICE region. This values have been aquired using the original RICE model and the country to RICE region mapping in figure 17.1.



Country Name	Country Code	RICE code	RICE region	Country Name	Country Code	RICE code	RICE region	Country Name	Country Code	RICE code	RICE region
Afghanistan	AFG	12	OthAs	Gabon	GAB	9	Africa	New Zealand	NZL	11	OHI
Albania	ALB	5	Eurasia	Gambia, The	GMB	9	Africa	Nicaragua	NIC	10	LatAm
Algeria	DZA	9	Africa	Georgia	GEO	5	Eurasia	Niger	NER	9	Africa
American Samoa	ASM	1	US	Germany	DEU	2	EU	Nigeria	NGA	9	Africa
Angola	AGO	9	Africa	Ghana	GHA	9	Africa	Norway	NOR	2	EU
Antigua and Barl	ATG	10	LatAm	Greece	GRC	2	EU	Oman	OMN	8	MidEast
Argentina	ARG	10	LatAm	Greenland	GRL	2	EU	Pakistan	PAK	12	OthAs
Armenia	ARM	5	Eurasia	Grenada	GRD	10	LatAm	Panama	PAN	10	LatAm
Aruba	ABW	10	LatAm	Guam	GUM	1	US	Papua New Guinea	PNG	12	OthAs
Australia	AUS	11	OHI	Guatemala	GTM	10	LatAm	Paraguay	PRY	10	LatAm
Austria	AUT	2	EU	Guinea	GIN	9	Africa	Peru	PER	10	LatAm
Azerbaijan	AZE	5	Eurasia	Guinea-Bissau	GNB	9	Africa	Philippines	PHL	12	OthAs
Bahamas, The	BHS	10	LatAm	Guyana	GUY	10	LatAm	Poland	POL	2	EU
Bahrain	BHR	8	MidEast	Haiti	HTI	10	LatAm	Portugal	PRT	2	EU
Bangladesh	BGD	12	OthAs	Honduras	HND	10	LatAm	Puerto Rico	PRI	10	LatAm
Barbados	BRB	10	LatAm	Hong Kong, China	HKG	11	OHI	Qatar	QAT	8	MidEast
Belarus	BLR	5	Eurasia	Hungary	HUN	2	EU	Romania	ROM	5	Eurasia
Belgium	BEL	2	EU	Iceland	ISL	2	EU	Russian Federation	RUS	4	Russia
Belize	BLZ	10	LatAm	India	IND	7	Inida	Rwanda	RWA	9	Africa
Benin	BEN	9	Africa	Indonesia	IDN	12	OthAs	Samoa	WSM	12	OthAs
Bermuda	BMU	10	LatAm	Iran, Islamic Rep.	IRN	8	MidEast	Sao Tome and Princ	STP	9	Africa
Bhutan	BTN	12	OthAs	Iraq	IRQ	8	MidEast	Saudi Arabia	SAU	8	MidEast
Bolivia	BOL	10	LatAm	Ireland	IRL	2	EU	Senegal	SEN	9	Africa
Bosnia and Herze	BIH	5	Eurasia	Israel	ISR	8	MidEast	Serbia	SRB	5	Eurasia
Botswana	BWA	9	Africa	Italy	ITA	2	EU	Seychelles	SYC	9	Africa
Brazil	BRA	10	LatAm	Jamaica	JAM	10	LatAm	Sierra Leone	SLE	9	Africa
Brunei Darussala	BRN	12	OthAs	Japan	JPN	3	Japan	Singapore	SGP	11	OHI
Bulgaria	BGR	5	Eurasia	Jordan	JOR	8	MidEast	Slovak Republic	SVK	2	EU
Burkina Faso	BFA	9	Africa	Kazakhstan	KAZ	5	Eurasia	Slovenia	SVN	5	Eurasia
Burundi	BDI	9	Africa	Kenya	KEN	9	Africa	Solomon Islands	SLB	12	OthAs
Cambodia	KHM	12	OthAs	Kiribati	KIR	12	OthAs	Somalia	SOM	9	Africa
Cameroon	CMR	9	Africa	Korea, Dem. Rep.	PRK	12	OthAs	South Africa	ZAF	9	Africa
Canada	CAN	11	OHI	Korea, Rep.	KOR	11	OHI	Spain	ESP	2	EU
Cape Verde	CPV	9	Africa	Kuwait	KWT	8	MidEast	Sri Lanka	LKA	12	OthAs
Cayman Islands	CYM	10	LatAm	Kyrgyz Republic	KGZ	5	Eurasia	St. Kitts and Nevis	KNA	10	LatAm
Central African F	CAF	9	Africa	Lao PDR	LAO	12	OthAs	St. Lucia	LCA	10	LatAm
Chad	TCD	9	Africa	Latvia	LVA	5	Eurasia	St. Vincent and the (	VCT	10	LatAm
Chile	CHL	10	LatAm	Lebanon	LBN	8	MidEast	Sudan	SDN	9	Africa
China	CHN	6	China	Lesotho	LSO	9	Africa	Suriname	SUR	10	LatAm
Colombia	COL	10	LatAm	Liberia	LBR	9	Africa	Swaziland	SWZ	9	Africa
Comoros	COM	9	Africa	Libya	LBY	9	Africa	Sweden	SWE	2	EU
Congo, Dem. Rep	ZAR	9	Africa	Lithuania	LTU	5	Eurasia	Switzerland	CHE	2	EU
Congo, Rep.	COG	9	Africa	Luxembourg	LUX	2	EU	Syrian Arab Republ	SYR	8	MidEast
Costa Rica	CRI	10	LatAm	Macao, China	MAC	11	OHI	Tajikistan	TJK	5	Eurasia
Cote d'Ivoire	CIV	9	Africa	Macedonia, FYR	MKD	5	Eurasia	Tanzania	TZA	9	Africa
Croatia	HRV	5	Eurasia	Madagascar	MDG	9	Africa	Thailand	THA	12	OthAs
Cuba	CUB	10	LatAm	Malawi	MWI	9	Africa	Timor-Leste	TMP	12	OthAs
Cyprus	CYP	8	MidEast	Malaysia	MYS	12	OthAs	Togo	TGO	9	Africa
Czech Republic	CZE	2	EU	Maldives	MDV	12	OthAs	Tonga	TON	12	OthAs
Denmark	DNK	2	EU	Mali	MLI	9	Africa	Trinidad and Tobag	TTO	10	LatAm
Djibouti	DJI	9	Africa	Malta	MLT	2	EU	Tunisia	TUN	9	Africa
Dominica	DMA	10	LatAm	Mauritania	MRT	9	Africa	Turkey	TUR	2	EU
Dominican Repu	DOM	10	LatAm	Mauritius	MUS	9	Africa	Turkmenistan	TKM	5	Eurasia
Ecuador	ECU	10	LatAm	Mexico	MEX	10	LatAm	Uganda	UGA	9	Africa
Egypt, Arab Rep.	EGY	9	Africa	Moldova	MDA	5	Eurasia	Ukraine	UKR	5	Eurasia
El Salvador	SLV	10	LatAm	Mongolia	MNG	12	OthAs	United Arab Emirat	ARE	8	MidEast
Equatorial Guine	GNQ	9	Africa	Montenegro	MNE	5	Eurasia	United Kingdom	GBR	2	EU
Eritrea	ERI	9	Africa	Morocco	MAR	9	Africa	United States	USA	1	US
Estonia	EST	5	Eurasia	Mozambique	MOZ	9	Africa	Uruguay	URY	10	LatAm
Ethiopia	ETH	9	Africa	Myanmar	MMR	12	OthAs	Uzbekistan	UZB	5	Eurasia
Faeroe Islands	FRO	2	EU	Namibia	NAM	9	Africa	Vanuatu	VUT	12	OthAs
Fiji	FJI	12	OthAs	Nepal	NPL	12	OthAs	Venezuela, RB	VEN	10	LatAm
Finland	FIN	2	EU	Netherlands	NLD	2	EU	Vietnam	VNM	12	OthAs
France	FRA	2	EU	Netherlands Antille	ANT	10	LatAm	Virgin Islands (U.S.)	VIR	10	LatAm
French Polynesia	PYF	12	OthAs	New Caledonia	NCL	12	OthAs	West Bank and Gaz	WBG	8	MidEast
								Yemen, Rep.	YEM	8	MidEast
								Zambia	ZMB	9	Africa
								Zimbabwe	ZWE	9	Africa

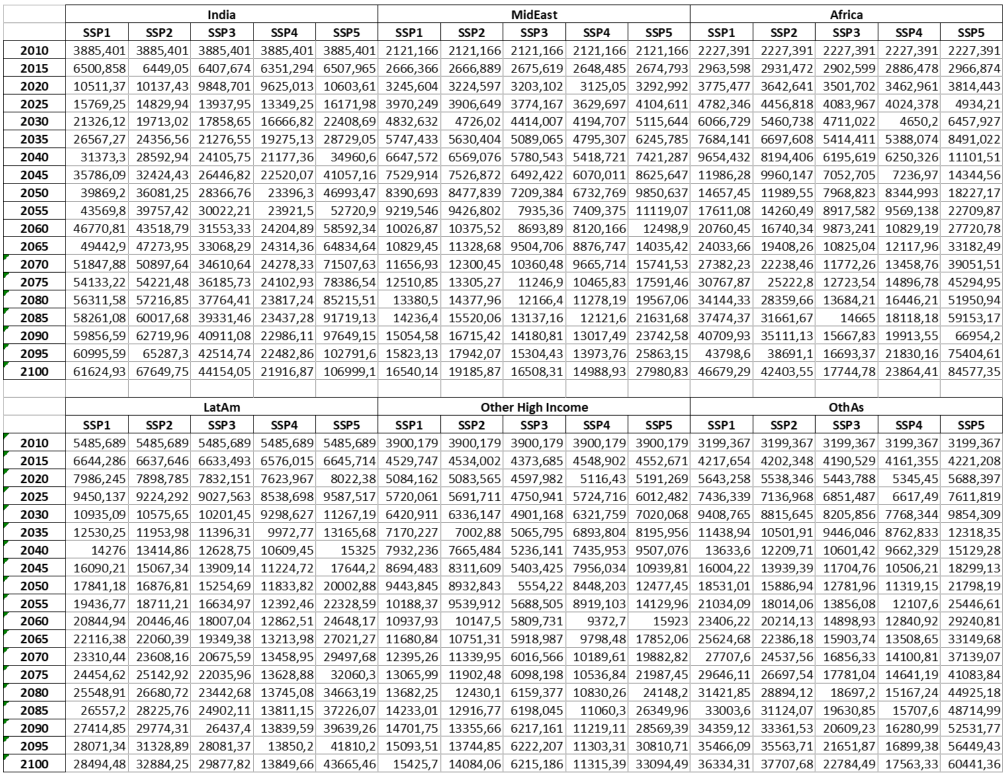
Figure B.1: SSP to RICE country mapping



	US					EU					Japan				
SCENARIO	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2010	12632,34	12632,34	12632,34	12632,34	12632,34	14848,78	14848,78	14848,78	14848,78	14848,78	4064,125	4064,125	4064,125	4064,125	4064,125
2015	13740,16	13771,18	13597,51	13800,34	13801,77	16425,78	16432,4	15642,87	16438,3	16490,05	4071,43	4067,476	3964,473	4083,653	4081,955
2020	15030,54	15068	14505,32	15124,87	15310,75	18688,59	18635,94	16349,82	18594,84	18979,88	4130,504	4109,855	3839,771	4150,325	4179,99
2025	16809,48	16788,35	15604,05	16838,94	17566,77	21691,33	21468,18	17139,5	21269,88	22489,09	4279,655	4224,132	3762,185	4286,136	4409,187
2030	18764,67	18608,03	16638,67	18562,61	20320,06	24978,54	24468,47	17967,8	23940,27	26642,69	4481,307	4371,084	3727,393	4428,937	4742,005
2035	20834,45	20477,25	17609,99	20247,63	23516,93	28367,94	27482,67	18825,63	26466,8	31281,89	4707,825	4526,27	3714,582	4555,495	5149,859
2040	23007,53	22398,88	18552,47	21925,07	27149,26	31741,71	30421,89	19685,11	28802,42	36284,4	4939,71	4674,296	3706,563	4659,872	5609,693
2045	25266,01	24363,58	19454,49	23600,32	31224,02	35050,55	33257,69	20501,1	30941,82	41609,21	5170,565	4812,485	3696,585	4748,728	6112,169
2050	27583,02	26352,86	20299,37	25261,16	35736,58	38332,21	35966,97	21219,47	32864,53	47305,15	5401,345	4946,004	3684,628	4830,481	6655,337
2055	29990,76	28410,51	21127,98	26957,18	40750,01	41599,91	38588,36	21849,66	34619,95	53402,32	5631,883	5079,295	3671,763	4910,542	7240,009
2060	32514,11	30562,31	21952,54	28699,58	46352,27	44849	41220,5	22412,34	36250,81	59977,35	5862,069	5216,875	3655,428	4991,348	7873,163
2065	35154,27	32803	22765,91	30463,74	52599,64	48020,81	43850,15	22924,68	37755,99	66997,81	6081,138	5350,198	3627,56	5059,456	8549,242
2070	37908,87	35108,75	23556,62	32223,97	59504,02	51069,96	46443,17	23407,52	39143,89	74387,32	6273,926	5469,02	3584,203	5101,401	9248,423
2075	40779,01	37454,71	24293,91	33939,26	67088,44	53987,88	48990,77	23858,69	40403,05	82111,39	6434,146	5570,938	3525,681	5108,577	9959,491
2080	43710,83	39808,03	24948,05	35568,47	75320,56	56816,97	51521,42	24273,14	41531,42	90222,67	6564,005	5660,277	3458,855	5081,991	10681,7
2085	46632,28	42144,79	25511,5	37088,78	84150,76	59565,52	54053,55	24652,99	42532,13	98751,23	6685,191	5748,789	3391,445	5034,65	11442,4
2090	49463,2	44449,21	25995,96	38494,06	93520,73	62209,86	56574,74	25013,2	43411,09	107696,6	6808,659	5841,225	3326,135	4976,773	12261,69
2095	52162,84	46724,85	26405,97	39782	103423,8	64748,2	59063,61	25355,21	44159,37	117101,6	6939,247	5938,079	3259,99	4912,542	13156,32
2100	54723,06	48976,33	26739,4	40946,7	113881,1	67208,16	61491,76	25670,2	44757,38	127043,4	7071,256	6034,043	3187,957	4838,182	14127,56

	Russia					Eurasia					China				
	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2010	2050,953	2050,953	2050,953	2050,953	2050,953	1262,286	1262,286	1262,286	1262,286	1262,286	9110,604	9110,604	9110,604	9110,604	9110,604
2015	2574,687	2589,47	2591,365	2579,61	2580,301	1854,301	1866,638	1864,963	1858,601	1856,014	16342,95	16349,69	16351,23	16275,54	16362,28
2020	2960,002	2982,227	2971,22	2931,82	2996,114	2583,28	2598,207	2588,521	2547,612	2600,025	24276,43	24144,3	24047,7	23671,31	24472,03
2025	3277,984	3286,657	3234,695	3155,54	3387,21	3420,727	3403,783	3381,24	3247,049	3480,962	32097,86	31591,36	30639,97	29599,61	32823,03
2030	3525,319	3506,751	3391,855	3262,067	3751,226	4182,221	4112,331	4075,592	3782,735	4325,449	38778,19	37776,17	35895,46	33844,55	40491,31
2035	3731,846	3694,022	3509,537	3319,441	4105,704	4739,315	4647,949	4603,531	4114,37	5001,221	43998,8	42598,08	40009,46	36747,56	47094,12
2040	3919,072	3884,124	3632,615	3369,434	4458,255	5089,356	5031,66	4994,33	4291,174	5492,814	47760,3	46041,77	43047,44	38469,95	52636,15
2045	4088,553	4082,482	3772,754	3417,755	4827,611	5308,211	5323,128	5310,424	4381,098	5888,661	50627,04	48614,64	45143,87	39108,92	57622,5
2050	4244,853	4281,327	3926,396	3454,824	5227,985	5476,086	5569,344	5597,163	4423,603	6270,442	52733,6	50420,11	46402,13	38789,5	62087,96
2055	4412,528	4493,597	4094,709	3483,489	5684,436	5648,13	5805,676	5878,249	4444,43	6690,539	54204,12	51581,57	46994,51	37796,46	66038,6
2060	4611,734	4735,734	4290,65	3514,939	6214,224	5848,594	6058,002	6173,389	4460,942	7170,564	55048,46	52144,88	47034,99	36327,19	69396,11
2065	4838,488	5009,19	4525,154	3551,614	6806,526	6068,623	6325,646	6489,44	4478,125	7697,709	55359,01	52266,5	46748,62	34623,12	72182,49
2070	5079,024	5305,244	4803,526	3591,146	7438,943	6297,972	6603,067	6833,914	4495,691	8256,971	55226,87	52082,18	46318,72	32837,97	74428,21
2075	5315,783	5611,021	5125,798	3629,927	8081,681	6522,836	6883,12	7213,459	4511,847	8827,024	54709,31	51684,12	45896,81	31030,33	76130,22
2080	5535,333	5916,619	5487,865	3663,933	8711,403	6732,92	7161,601	7631,043	4524,76	9391,44	53848,5	51107,1	45567,47	29204,19	77279,02
2085	5733,719	6219,971	5886,306	3692,289	9317,99	6925,525	7442,479	8091,064	4536,868	9944,078	52686,27	50378,37	45396,24	27374,61	77877,25
2090	5910,542	6524,851	6320,174	3716,443	9895,873	7098,452	7732,801	8595,677	4550,668	10479,01	51166,16	49548,79	45434,15	25578,03	77790,77
2095	6066,571	6834,573	6789,887	3735,812	10439,58	7249,359	8037,339	9146,401	4565,789	10989,75	49171,18	48683,34	45715,06	23852,75	76786,34
2100	6201,465	7147,665	7292,476	3747,043	10938,8	7378,188	8355,264	9741,551	4579,308	11472,28	46819,89	47857,67	46237,66	22241,3	74991,96

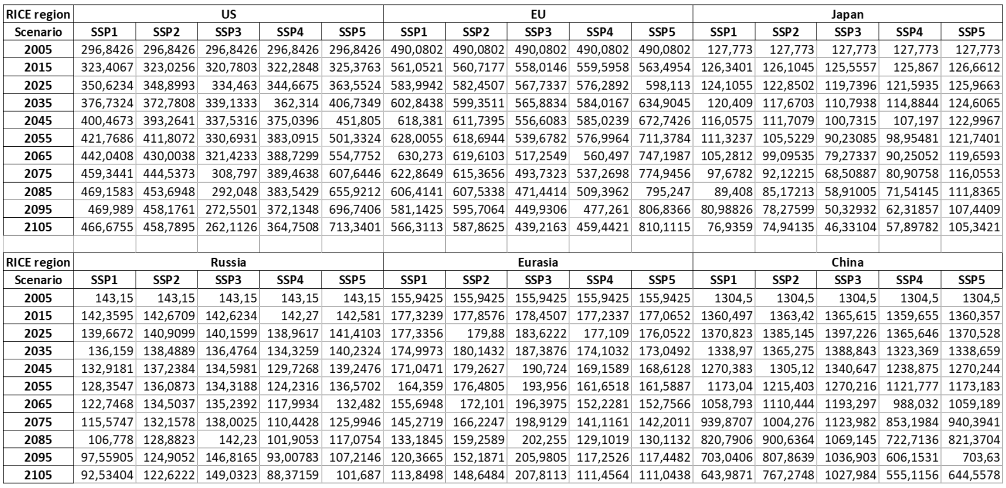
Figure B.2: SSP regional GDP development per SSP scenario (6/12 regions)



	India					MidEast					Africa				
	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2010	3885,401	3885,401	3885,401	3885,401	3885,401	2121,166	2121,166	2121,166	2121,166	2121,166	2227,391	2227,391	2227,391	2227,391	2227,391
2015	6500,858	6449,05	6407,674	6351,294	6507,965	2666,366	2666,889	2675,619	2648,485	2674,793	2963,598	2931,472	2902,599	2886,478	2966,874
2020	10511,37	10137,43	9848,701	9625,013	10603,61	3245,604	3224,597	3203,102	3125,05	3292,992	3775,477	3642,641	3501,702	3462,961	3814,443
2025	15769,25	14829,94	13937,95	13349,25	16171,98	3970,249	3906,649	3774,167	3629,697	4104,611	4782,346	4456,818	4083,967	4024,378	4934,21
2030	21326,12	19713,02	17858,65	16666,82	22408,69	4832,632	4726,02	4414,007	4194,707	5115,644	6066,729	5460,738	4711,022	4650,2	6457,927
2035	26567,27	24356,56	21276,55	19275,13	28729,05	5747,433	5630,404	5089,065	4795,307	6245,785	7684,141	6697,608	5414,411	5388,074	8491,022
2040	31373,3	28592,94	24105,75	21177,36	34960,6	6647,572	6569,076	5780,543	5418,721	7421,287	9654,432	8194,406	6195,619	6250,326	11101,51
2045	35786,09	32424,43	26446,82	22520,07	41057,16	7529,914	7526,872	6492,422	6070,011	8625,647	11986,28	9960,147	7052,705	7236,97	14344,56
2050	39869,2	36081,25	28366,76	23396,3	46993,47	8390,693	8477,839	7209,384	6732,769	9850,637	14657,45	11989,55	7968,823	8344,993	18227,17
2055	43569,8	39757,42	30022,21	23921,5	52720,9	9219,546	9426,802	7935,36	7409,375	11119,07	17611,08	14260,49	8917,582	9569,138	22709,87
2060	46770,81	43518,79	31553,33	24204,89	58592,34	10026,87	10375,52	8693,89	8120,166	12498,9	20760,45	16740,34	9873,241	10829,19	27720,78
2065	49442,9	47273,95	33068,29	24314,36	64834,64	10829,45	11328,68	9504,706	8876,747	14035,42	24033,66	19408,26	10825,04	12117,96	33182,49
2070	51847,88	50897,64	34610,64	24278,33	71507,63	11656,93	12300,45	10360,48	9665,714	15741,53	27382,23	22238,46	11772,26	13458,76	39051,51
2075	54133,22	54221,48	36185,73	24102,93	78386,54	12510,85	13305,27	11246,9	10465,83	17591,46	30767,87	25222,8	12723,54	14896,78	45294,95
2080	56311,58	57216,85	37764,41	23817,24	85215,51	13380,5	14377,96	12166,4	11278,19	19567,06	34144,33	28359,66	13684,21	16446,21	51950,94
2085	58261,08	60017,68	39331,46	23437,28	91719,13	14236,4	15520,06	13137,16	12121,6	21631,68	37474,37	31661,67	14665	18118,18	59153,17
2090	59856,59	62719,96	40911,08	22986,11	97649,15	15054,58	16715,42	14180,81	13017,49	23742,58	40709,93	35111,13	15667,83	19913,55	66954,2
2095	60995,59	65287,3	42514,74	22482,86	102791,6	15823,13	17942,07	15304,43	13973,76	25863,15	43798,6	38691,1	16693,37	21830,16	75404,61
2100	61624,93	67649,75	44154,05	21916,87	106999,1	16540,14	19185,87	16508,31	14988,93	27980,83	46679,29	42403,55	17744,78	23864,41	84577,35

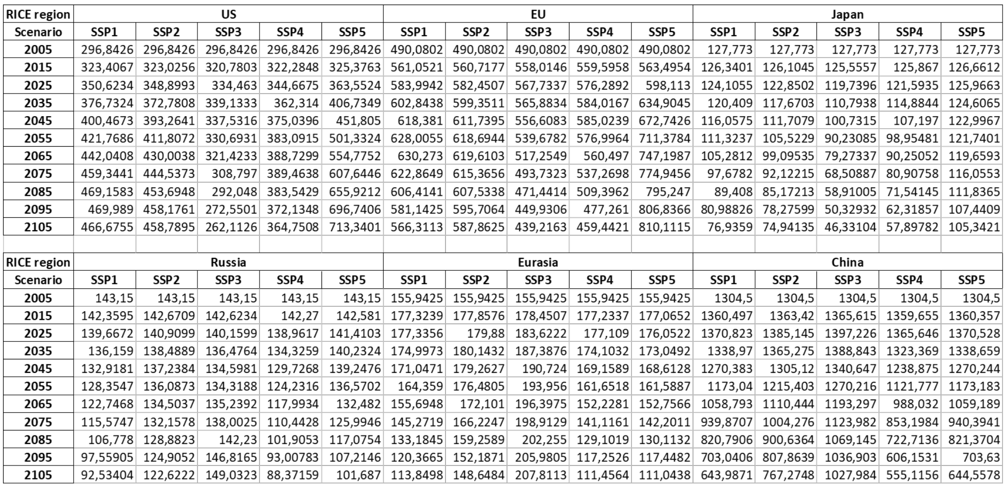
	LatAm					Other High Income					OthAs				
	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2010	5485,689	5485,689	5485,689	5485,689	5485,689	3900,179	3900,179	3900,179	3900,179	3900,179	3199,367	3199,367	3199,367	3199,367	3199,367
2015	6644,286	6637,646	6633,493	6576,015	6645,714	4529,747	4534,002	4373,685	4548,902	4552,671	4217,654	4202,348	4190,529	4161,355	4221,208
2020	7986,245	7898,785	7832,151	7623,967	8022,38	5084,162	5083,565	4597,982	5116,43	5191,269	5643,258	5538,346	5443,788	5345,45	5688,397
2025	9450,137	9224,292	9027,563	8538,698	9587,517	5720,061	5691,711	4750,941	5724,716	6012,482	7436,339	7136,968	6851,487	6617,49	7611,819
2030	10935,09	10575,65	10201,45	9298,627	11267,19	6420,911	6336,147	4901,168	6321,759	7020,068	9408,765	8815,645	8205,856	7768,344	9854,309
2035	12530,25	11953,98	11396,31	9972,77	13165,68	7170,227	7002,88	5065,795	6893,804	8195,956	11438,94	10501,91	9446,046	8762,833	12318,35
2040	14276	13414,86	12628,75	10609,45	15325	7932,236	7665,484	5236,141	7435,953	9507,076	13633,6	12209,71	10601,42	9662,329	15129,28
2045	16090,21	15067,34	13909,14	11224,72	17644,2	8694,483	8311,609	5403,425	7956,034	10939,81	16004,22	13939,39	11704,76	10506,21	18299,13
2050	17841,18	16876,81	15254,69	11833,82	20002,88	9443,845	8932,843	5554,22	8448,203	12477,45	18531,01	15886,94	12781,96	11319,15	21798,19
2055	19436,77	18711,21	16634,97	12392,46	22328,59	10188,37	9539,912	5688,505	8919,103	14129,96	21034,09	18014,06	13856,08	12107,6	25446,61
2060	20844,94	20446,46	18007,04	12862,51	24648,17	10937,93	10147,5	5809,731	9372,7	15923	23406,22	20214,13	14898,93	12840,92	29240,81
2065	22116,38	22060,39	19349,38	13213,98	27021,27	11680,84	10751,31	5918,987	9798,48	17852,06	25624,68	22386,18	15903,74	13508,65	33149,68
2070	23310,44	23608,16	20675,59	13458,95	29497,68	12395,26	11339,95	6016,566	10189,61	19882,82	27707,6	24537,56	16856,33	14100,81	37139,07
2075	24454,62	25142,92	22035,96	13628,88	32060,3	13065,99	11902,48	6098,198	10536,84	21987,45	29646,11	26697,54	17781,04	14641,19	41083,84
2080	25548,91	26680,72	23442,68	13745,08	34663,19	13682,25	12430,1	6159,377	10830,26	24148,2	31421,85	28894,12	18697,2	15167,24	44925,18
2085	26557,2	28225,76	24902,11	13811,15	37226,07	14233,01	12916,77	6198,045	11060,3	26349,96	33003,6	31124,07	19630,85	15707,6	48714,99
2090	27414,85	29774,31	26437,4	13839,59	39639,26	14701,75	13355,66	6217,161	11219,11	28569,39	34359,12	33361,53	20609,23	16280,99	52531,77
2095	28071,34	31328,89	28081,37	13850,2	41810,2	15093,51	13744,85	6222,207	11303,31	30810,71	35466,09	35563,71	21651,87	16899,38	56449,43
2100	28494,48	32884,25	29877,82	13849,66	43665,46	15425,7	14084,06	6215,186	11315,39	33094,49	36334,31	37707,68	22784,49	17563,33	60441,36

Figure B.3: SSP regional GDP development per SSP scenario (12/12 regions)



RICE region	US					EU					Japan				
Scenario	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2005	296,8426	296,8426	296,8426	296,8426	296,8426	490,0802	490,0802	490,0802	490,0802	490,0802	127,773	127,773	127,773	127,773	127,773
2015	323,4067	323,0256	320,7803	322,2848	325,3763	561,0521	560,7177	558,0146	559,5958	563,4954	126,3401	126,1045	125,5557	125,867	126,6612
2025	350,6234	348,8993	334,463	344,6675	363,5524	583,9942	582,4507	567,7337	576,2892	598,113	124,1055	122,8502	119,7396	121,5935	125,9663
2035	376,7324	372,7808	339,1333	362,314	406,7349	602,8438	599,3511	565,8834	584,0167	634,9045	120,409	117,6703	110,7938	114,8844	124,6065
2045	400,4673	393,2641	337,5316	375,0396	451,805	618,381	611,7395	556,6083	585,0239	672,7426	116,0575	111,7079	100,7315	107,197	122,9967
2055	421,7686	411,8072	330,6931	383,0915	501,3324	628,0055	618,6944	539,6782	576,9964	711,3784	111,3237	105,5229	90,23085	98,95481	121,7401
2065	442,0408	430,0038	321,4233	388,7299	554,7752	630,273	619,6103	517,2549	560,497	747,1987	105,2812	99,09535	79,27337	90,25052	119,6593
2075	459,3441	444,5373	308,797	389,4638	607,6446	622,8649	615,3656	493,7323	537,2698	774,9456	97,6782	92,12215	68,50887	80,90758	116,0553
2085	469,1583	453,6948	292,048	383,5429	655,9212	606,4141	607,5338	471,4414	509,3962	795,247	89,408	85,17213	58,91005	71,54145	111,8365
2095	469,989	458,1761	272,5501	372,1348	696,7406	581,1425	595,7064	449,9306	477,261	806,8366	80,98826	78,27599	50,32932	62,31857	107,4409
2105	466,6755	458,7895	262,1126	364,7508	713,3401	566,3113	587,8625	439,2163	459,4421	810,1115	76,9359	74,94135	46,33104	57,89782	105,3421
RICE region	Russia					Eurasia					China				
Scenario	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2005	143,15	143,15	143,15	143,15	143,15	155,9425	155,9425	155,9425	155,9425	155,9425	1304,5	1304,5	1304,5	1304,5	1304,5
2015	142,3595	142,6709	142,6234	142,27	142,581	177,3239	177,8576	178,4507	177,2337	177,0652	1360,497	1363,42	1365,615	1359,655	1360,357
2025	139,6672	140,9099	140,1599	138,9617	141,4103	177,3356	179,88	183,6222	177,109	176,0522	1370,823	1385,145	1397,226	1365,646	1370,528
2035	136,159	138,4889	136,4764	134,3259	140,2324	174,9973	180,1432	187,3876	174,1032	173,0492	1338,97	1365,275	1388,843	1323,369	1338,659
2045	132,9181	137,2384	134,5981	129,7268	139,2476	171,0471	179,2627	190,724	169,1589	168,6128	1270,383	1305,12	1340,647	1238,875	1270,244
2055	128,3547	136,0873	134,3188	124,2316	136,5702	164,359	176,4805	193,956	161,6518	161,5887	1173,04	1215,403	1270,216	1121,777	1173,183
2065	122,7468	134,5037	135,2392	117,9934	132,482	155,6948	172,101	196,3975	152,2281	152,7566	1058,793	1110,444	1193,297	988,032	1059,189
2075	115,5747	132,1578	138,0025	110,4428	125,9946	145,2719	166,2247	198,9129	141,1161	142,2011	939,8707	1004,276	1123,982	853,1984	940,3941
2085	106,778	128,8823	142,23	101,9053	117,0754	133,1845	159,2589	202,255	129,1019	130,1132	820,7906	900,6364	1069,145	722,7136	821,3704
2095	97,55905	124,9052	146,8165	93,00783	107,2146	120,3665	152,1871	205,9805	117,2526	117,4482	703,0406	807,8639	1036,903	606,1531	703,63
2105	92,53404	122,6222	149,0323	88,37159	101,687	113,8498	148,6484	207,8113	111,4564	111,0438	643,9871	767,2748	1027,984	555,1156	644,5578

Figure B.4: SSP regional population development per SSP scenario (6/12 regions)

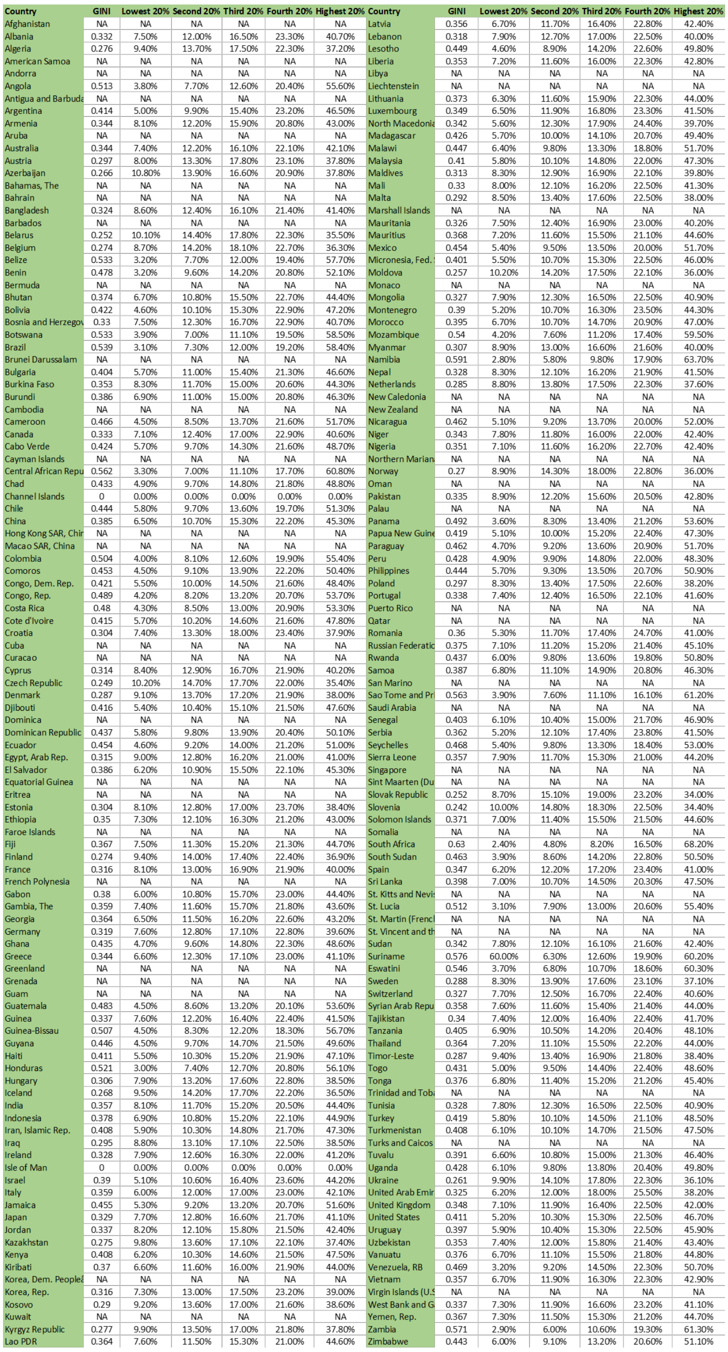


RICE region	US					EU					Japan				
Scenario	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2005	296,8426	296,8426	296,8426	296,8426	296,8426	490,0802	490,0802	490,0802	490,0802	490,0802	127,773	127,773	127,773	127,773	127,773
2015	323,4067	323,0256	320,7803	322,2848	325,3763	561,0521	560,7177	558,0146	559,5958	563,4954	126,3401	126,1045	125,5557	125,867	126,6612
2025	350,6234	348,8993	334,463	344,6675	363,5524	583,9942	582,4507	567,7337	576,2892	598,113	124,1055	122,8502	119,7396	121,5935	125,9663
2035	376,7324	372,7808	339,1333	362,314	406,7349	602,8438	599,3511	565,8834	584,0167	634,9045	120,409	117,6703	110,7938	114,8844	124,6065
2045	400,4673	393,2641	337,5316	375,0396	451,805	618,381	611,7395	556,6083	585,0239	672,7426	116,0575	111,7079	100,7315	107,197	122,9967
2055	421,7686	411,8072	330,6931	383,0915	501,3324	628,0055	618,6944	539,6782	576,9964	711,3784	111,3237	105,5229	90,23085	98,95481	121,7401
2065	442,0408	430,0038	321,4233	388,7299	554,7752	630,273	619,6103	517,2549	560,497	747,1987	105,2812	99,09535	79,27337	90,25052	119,6593
2075	459,3441	444,5373	308,797	389,4638	607,6446	622,8649	615,3656	493,7323	537,2698	774,9456	97,6782	92,12215	68,50887	80,90758	116,0553
2085	469,1583	453,6948	292,048	383,5429	655,9212	606,4141	607,5338	471,4414	509,3962	795,247	89,408	85,17213	58,91005	71,54145	111,8365
2095	469,989	458,1761	272,5501	372,1348	696,7406	581,1425	595,7064	449,9306	477,261	806,8366	80,98826	78,27599	50,32932	62,31857	107,4409
2105	466,6755	458,7895	262,1126	364,7508	713,3401	566,3113	587,8625	439,2163	459,4421	810,1115	76,9359	74,94135	46,33104	57,89782	105,3421
RICE region	Russia					Eurasia					China				
Scenario	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5	SSP1	SSP2	SSP3	SSP4	SSP5
2005	143,15	143,15	143,15	143,15	143,15	155,9425	155,9425	155,9425	155,9425	155,9425	1304,5	1304,5	1304,5	1304,5	1304,5
2015	142,3595	142,6709	142,6234	142,27	142,581	177,3239	177,8576	178,4507	177,2337	177,0652	1360,497	1363,42	1365,615	1359,655	1360,357
2025	139,6672	140,9099	140,1599	138,9617	141,4103	177,3356	179,88	183,6222	177,109	176,0522	1370,823	1385,145	1397,226	1365,646	1370,528
2035	136,159	138,4889	136,4764	134,3259	140,2324	174,9973	180,1432	187,3876	174,1032	173,0492	1338,97	1365,275	1388,843	1323,369	1338,659
2045	132,9181	137,2384	134,5981	129,7268	139,2476	171,0471	179,2627	190,724	169,1589	168,6128	1270,383	1305,12	1340,647	1238,875	1270,244
2055	128,3547	136,0873	134,3188	124,2316	136,5702	164,359	176,4805	193,956	161,6518	161,5887	1173,04	1215,403	1270,216	1121,777	1173,183
2065	122,7468	134,5037	135,2392	117,9934	132,482	155,6948	172,101	196,3975	152,2281	152,7566	1058,793	1110,444	1193,297	988,032	1059,189
2075	115,5747	132,1578	138,0025	110,4428	125,9946	145,2719	166,2247	198,9129	141,1161	142,2011	939,8707	1004,276	1123,982	853,1984	940,3941
2085	106,778	128,8823	142,23	101,9053	117,0754	133,1845	159,2589	202,255	129,1019	130,1132	820,7906	900,6364	1069,145	722,7136	821,3704
2095	97,55905	124,9052	146,8165	93,00783	107,2146	120,3665	152,1871	205,9805	117,2526	117,4482	703,0406	807,8639	1036,903	606,1531	703,63
2105	92,53404	122,6222	149,0323	88,37159	101,687	113,8498	148,6484	207,8113	111,4564	111,0438	643,9871	767,2748	1027,984	555,1156	644,5578

Figure B.5: SSP regional population development per SSP scenario (12/12 regions)

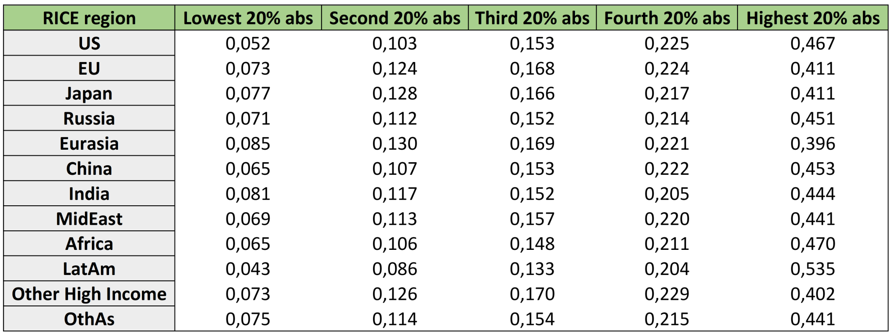
Disaggregated income share inputs

The following figures show the taken income share distributions per country (figure B.6) based on The World Bank [2020] and the resulting regional distribution (figure B.7).



Country	GINI	Lowest 20%	Second 20%	Third 20%	Fourth 20%	Highest 20%	Country	GINI	Lowest 20%	Second 20%	Third 20%	Fourth 20%	Highest 20%
Afghanistan	NA	NA	NA	NA	NA	NA	Latvia	0.356	6.70%	11.70%	16.40%	22.80%	42.40%
Albania	0.332	7.50%	12.00%	16.50%	23.30%	40.70%	Lebanon	0.318	7.90%	12.70%	17.00%	22.50%	40.00%
Algeria	0.276	9.40%	13.70%	17.50%	22.30%	37.20%	Lesotho	0.449	4.60%	8.90%	14.20%	22.60%	49.80%
American Samoa	NA	NA	NA	NA	NA	NA	Liberia	0.353	7.20%	11.60%	16.00%	22.30%	42.80%
Andorra	NA	NA	NA	NA	NA	NA	Libya	NA	NA	NA	NA	NA	NA
Angola	0.513	3.80%	7.70%	12.60%	20.40%	55.60%	Liechtenstein	NA	NA	NA	NA	NA	NA
Antigua and Barbuda	NA	NA	NA	NA	NA	NA	Lithuania	0.373	6.30%	11.60%	15.90%	22.30%	44.00%
Argentina	0.414	5.00%	9.90%	15.40%	23.20%	46.50%	Luxembourg	0.349	6.50%	11.90%	16.80%	23.30%	41.50%
Armenia	0.344	8.10%	12.20%	15.90%	20.80%	43.00%	North Macedonia	0.342	5.60%	12.30%	17.90%	24.40%	39.70%
Aruba	NA	NA	NA	NA	NA	NA	Madagascar	0.426	5.70%	10.00%	14.10%	20.70%	49.40%
Australia	0.344	7.40%	12.20%	16.10%	22.10%	42.10%	Malawi	0.447	6.40%	9.80%	13.30%	18.80%	51.70%
Austria	0.297	8.00%	13.30%	17.80%	23.10%	37.80%	Malaysia	0.41	5.80%	10.10%	14.80%	22.00%	47.30%
Azerbaijan	0.266	10.80%	13.90%	16.60%	20.90%	37.80%	Maldives	0.313	8.30%	12.90%	16.90%	22.10%	39.80%
Bahamas, The	NA	NA	NA	NA	NA	NA	Mali	0.33	8.00%	12.10%	16.20%	22.50%	41.30%
Bahrain	NA	NA	NA	NA	NA	NA	Malta	0.292	8.50%	13.40%	17.60%	22.50%	38.00%
Bangladesh	0.324	8.60%	12.40%	16.10%	21.40%	41.40%	Marshall Islands	NA	NA	NA	NA	NA	NA
Barbados	NA	NA	NA	NA	NA	NA	Mauritania	0.326	7.50%	12.40%	16.90%	23.00%	40.20%
Belarus	0.252	10.10%	14.40%	17.80%	22.30%	35.50%	Mauritius	0.368	7.20%	11.60%	15.50%	21.10%	44.60%
Belgium	0.274	8.70%	14.20%	18.10%	22.70%	36.30%	Mexico	0.454	5.40%	9.50%	13.50%	20.00%	51.70%
Belize	0.533	3.20%	7.70%	12.00%	19.40%	57.70%	Micronesia, Fed.	0.401	5.50%	10.70%	15.30%	22.50%	46.00%
Benin	0.478	3.20%	9.60%	14.20%	20.80%	52.10%	Moldova	0.257	10.20%	14.20%	17.50%	22.10%	36.00%
Bermuda	NA	NA	NA	NA	NA	NA	Monaco	NA	NA	NA	NA	NA	NA
Bhutan	0.374	6.70%	10.80%	15.50%	22.70%	44.40%	Mongolia	0.327	7.90%	12.30%	16.50%	22.50%	40.90%
Bolivia	0.422	4.60%	10.10%	15.30%	22.90%	47.20%	Montenegro	0.39	5.20%	10.70%	16.30%	23.50%	44.30%
Bosnia and Herzegov	0.33	7.50%	12.30%	16.70%	22.90%	40.70%	Morocco	0.395	6.70%	10.70%	14.70%	20.90%	47.00%
Botswana	0.533	3.90%	7.00%	11.10%	19.50%	58.50%	Mozambique	0.54	4.20%	7.60%	11.20%	17.40%	59.50%
Brazil	0.539	3.10%	7.30%	12.00%	19.20%	58.40%	Myanmar	0.307	8.90%	13.00%	16.60%	21.60%	40.00%
Brunei Darussalam	NA	NA	NA	NA	NA	NA	Namibia	0.591	2.80%	5.80%	9.80%	17.90%	63.70%
Bulgaria	0.404	5.70%	11.00%	15.40%	21.30%	46.60%	Nepal	0.328	8.30%	12.10%	16.20%	21.90%	41.50%
Burkina Faso	0.353	8.30%	11.70%	15.00%	20.60%	44.30%	Netherlands	0.285	8.80%	13.80%	17.50%	22.30%	37.60%
Burundi	0.386	6.90%	11.00%	15.00%	20.80%	46.30%	New Caledonia	NA	NA	NA	NA	NA	NA
Cambodia	NA	NA	NA	NA	NA	NA	New Zealand	NA	NA	NA	NA	NA	NA
Cameroon	0.466	4.50%	8.50%	13.70%	21.60%	51.70%	Nicaragua	0.462	5.10%	9.20%	13.70%	20.00%	52.00%
Canada	0.333	7.10%	12.40%	17.00%	22.90%	40.60%	Niger	0.343	7.80%	11.80%	16.00%	22.00%	42.40%
Cabo Verde	0.424	5.70%	9.70%	14.30%	21.60%	48.70%	Nigeria	0.351	7.10%	11.60%	16.20%	22.70%	42.40%
Cayman Islands	NA	NA	NA	NA	NA	NA	Northern Marian	NA	NA	NA	NA	NA	NA
Central African Repu	0.562	3.30%	7.00%	11.10%	17.70%	60.80%	Norway	0.27	8.90%	14.30%	18.00%	22.80%	36.00%
Chad	0.433	4.90%	9.70%	14.80%	21.80%	48.80%	Oman	NA	NA	NA	NA	NA	NA
Channel Islands	0	0.00%	0.00%	0.00%	0.00%	0.00%	Pakistan	0.335	8.90%	12.20%	15.60%	20.50%	42.80%
Chile	0.444	5.80%	9.70%	13.60%	19.70%	51.30%	Palau	NA	NA	NA	NA	NA	NA
China	0.385	6.50%	10.70%	15.30%	22.20%	45.30%	Panama	0.492	3.60%	8.30%	13.40%	21.20%	53.60%
Hong Kong SAR, Chin	NA	NA	NA	NA	NA	NA	Papua New Guine	0.419	5.10%	10.00%	15.20%	22.40%	47.30%
Macao SAR, China	NA	NA	NA	NA	NA	NA	Paraguay	0.462	4.70%	9.20%	13.60%	20.90%	51.70%
Colombia	0.504	4.00%	8.10%	12.60%	19.90%	55.40%	Peru	0.428	4.90%	9.90%	14.80%	22.00%	48.30%
Comoros	0.453	4.50%	9.10%	13.90%	22.20%	50.40%	Philippines	0.444	5.70%	9.30%	13.50%	20.70%	50.90%
Congo, Dem. Rep.	0.421	5.50%	10.00%	14.50%	21.60%	48.40%	Poland	0.297	8.30%	13.40%	17.50%	22.60%	38.20%
Congo, Rep.	0.489	4.20%	8.20%	13.20%	20.70%	53.70%	Portugal	0.338	7.40%	12.40%	16.50%	22.10%	41.60%
Costa Rica	0.48	4.30%	8.50%	13.00%	20.90%	53.30%	Puerto Rico	NA	NA	NA	NA	NA	NA
Cote d'Ivoire	0.415	5.70%	10.20%	14.60%	21.60%	47.80%	Qatar	NA	NA	NA	NA	NA	NA
Croatia	0.304	7.40%	13.30%	18.00%	23.40%	37.90%	Romania	0.36	5.30%	11.70%	17.40%	24.70%	41.00%
Cuba	NA	NA	NA	NA	NA	NA	Russian Federatio	0.375	7.10%	11.20%	15.20%	21.40%	45.10%
Curacao	NA	NA	NA	NA	NA	NA	Rwanda	0.437	6.00%	9.80%	13.60%	19.80%	50.80%
Cyprus	0.314	8.40%	12.90%	16.70%	21.90%	40.20%	Samoa	0.387	6.80%	11.10%	14.90%	20.80%	46.30%
Czech Republic	0.249	10.20%	14.70%	17.70%	22.00%	35.40%	San Marino	NA	NA	NA	NA	NA	NA
Denmark	0.287	9.10%	13.70%	17.20%	21.90%	38.00%	Sao Tome and Pri	0.563	3.90%	7.60%	11.10%	16.10%	61.20%
Djibouti	0.416	5.40%	10.40%	15.10%	21.50%	47.60%	Saudi Arabia	NA	NA	NA	NA	NA	NA
Dominica	NA	NA	NA	NA	NA	NA	Senegal	0.403	6.10%	10.40%	15.00%	21.70%	46.90%
Dominican Republic	0.437	5.80%	9.80%	13.90%	20.40%	50.10%	Serbia	0.362	5.20%	12.10%	17.40%	23.80%	41.50%
Ecuador	0.454	4.60%	9.20%	14.00%	21.20%	51.00%	Seychelles	0.468	5.40%	9.80%	13.30%	18.40%	53.00%
Egypt, Arab Rep.	0.315	9.00%	12.80%	16.20%	21.00%	41.00%	Sierra Leone	0.357	7.90%	11.70%	15.30%	21.00%	44.20%
El Salvador	0.386	6.20%	10.90%	15.50%	22.10%	45.30%	Singapore	NA	NA	NA	NA	NA	NA
Equatorial Guinea	NA	NA	NA	NA	NA	NA	Sint Maarten (Du	NA	NA	NA	NA	NA	NA
Eritrea	NA	NA	NA	NA	NA	NA	Slovak Republic	0.252	8.70%	15.10%	19.00%	23.20%	34.00%
Estonia	0.304	8.10%	12.80%	17.00%	23.70%	38.40%	Slovenia	0.242	10.00%	14.80%	18.30%	22.50%	34.40%
Ethiopia	0.35	7.30%	12.10%	16.30%	21.20%	43.00%	Solomon Islands	0.371	7.00%	11.40%	15.50%	21.50%	44.60%
Faroe Islands	NA	NA	NA	NA	NA	NA	Somalia	NA	NA	NA	NA	NA	NA
Fiji	0.367	7.50%	11.30%	15.20%	21.30%	44.70%	South Africa	0.63	2.40%	4.80%	8.20%	16.50%	68.20%
Finland	0.274	9.40%	14.00%	17.40%	22.40%	36.90%	South Sudan	0.463	3.90%	8.60%	14.20%	22.80%	50.50%
France	0.316	8.10%	13.00%	16.90%	21.90%	40.00%	Spain	0.347	6.20%	12.20%	17.20%	23.40%	41.00%
French Polynesia	NA	NA	NA	NA	NA	NA	Sri Lanka	0.398	7.00%	10.70%	14.50%	20.30%	47.50%
Gabon	0.38	6.00%	10.80%	15.70%	23.00%	44.40%	St. Kitts and Nevis	NA	NA	NA	NA	NA	NA
Gambia, The	0.359	7.40%	11.60%	15.70%	21.80%	43.60%	St. Lucia	0.512	3.10%	7.90%	13.00%	20.60%	55.40%
Georgia	0.364	6.50%	11.50%	16.20%	22.60%	43.20%	St. Martin (French	NA	NA	NA	NA	NA	NA
Germany	0.319	7.60%	12.80%	17.10%	22.80%	39.60%	St. Vincent and th	NA	NA	NA	NA	NA	NA
Ghana	0.435	4.70%	9.60%	14.80%	22.30%	48.60%	Sudan	0.342	7.80%	12.10%	16.10%	21.60%	42.40%
Greece	0.344	6.60%	12.30%	17.10%	23.00%	41.10%	Suriname	0.576	60.00%	6.30%	12.60%	19.90%	60.20%
Greenland	NA	NA	NA	NA	NA	NA	Eswatini	0.546	3.70%	6.80%	10.70%	18.60%	60.30%
Grenada	NA	NA	NA	NA	NA	NA	Sweden	0.288	8.30%	13.90%	17.60%	23.10%	37.10%
Guam	NA	NA	NA	NA	NA	NA	Switzerland	0.327	7.70%	12.50%	16.70%	22.40%	40.60%
Guatemala	0.483	4.50%	8.60%	13.20%	20.10%	53.60%	Syrian Arab Repu	0.358	7.60%	11.60%	15.40%	21.40%	44.00%
Guinea	0.337	7.60%	12.20%	16.40%	22.40%	41.50%	Tajikistan	0.34	7.40%	12.00%	16.40%	22.40%	41.70%
Guinea-Bissau	0.507	4.50%	8.30%	12.20%	18.30%	56.70%	Tanzania	0.405	6.90%	10.50%	14.20%	20.40%	48.10%
Guyana	0.446	4.50%	9.70%	14.70%	21.50%	49.60%	Thailand	0.364	7.20%	11.10%	15.50%	22.20%	44.00%
Haiti	0.411	5.50%	10.30%	15.20%	21.90%	47.10%	Timor-Leste	0.287	9.40%	13.40%	16.90%	21.80%	38.40%
Honduras	0.521	3.00%	7.40%	12.70%	20.80%	56.10%	Togo	0.431	5.00%	9.50%	14.40%	22.40%	48.60%
Hungary	0.306	7.90%	13.20%	17.60%	22.80%	38.50%	Tonga	0.376	6.80%	11.40%	15.20%	21.20%	45.40%
Iceland	0.268	9.50%	14.20%	17.70%	22.20%	36.50%	Trinidad and Toba	NA	NA	NA	NA	NA	NA
India	0.357	8.10%	11.70%	15.20%	20.50%	44.40%	Tunisia	0.328	7.80%	12.30%	16.50%	22.50%	40.90%
Indonesia	0.378	6.90%	10.80%	15.20%	22.10%	44.90%	Turkey	0.419	5.80%	10.10%	14.50%	21.10%	48.50%
Iran, Islamic Rep.	0.408	5.90%	10.30%	14.80%	21.70%	47.30%	Turkmenistan	0.408	6.10%	10.10%	14.70%	21.50%	47.50%
Iraq	0.295	8.80%	13.10%	17.10%	22.50%	38.50%	Turks and Caicos	NA	NA	NA	NA	NA	NA
Ireland	0.328	7.90%	12.60%	16.30%	22.00%	41.20%	Tuvalu	0.391	6.60%	10.80%	15.00%	21.30%	46.40%
Isle of Man	0	0.00%	0.00%	0.00%	0.00%	0.00%	Uganda	0.428	6.10%	9.80%	13.80%	20.40%	49.80%
Israel	0.39	5.10%	10.60%	16.40%	23.60%	44.20%	Ukraine	0.261	9.90%	14.10%	17.80%	22.30%	36.10%
Italy	0.359	6.00%	12.00%	17.00%	23.00%	42.10%	United Arab Emir	0.325	6.20%	12.00%	18.00%	25.50%	38.20%
Jamaica	0.455	5.30%	9.20%	13.20%	20.70%	51.60%	United Kingdom	0.348	7.10%	11.90%	16.40%	22.50%	42.00%
Japan	0.329	7.70%	12.80%	16.60%	21.70%	41.10%	United States	0.411	5.20%	10.30%	15.30%	22.50%	46.70%
Jordan	0.337	8.20%	12.10%	15.80%	21.50%	42.40%	Uruguay	0.397	5.90%	10.40%	15.30%	22.50%	45.90%
Kazakhstan	0.275	9.80%	13.60%	17.10%	22.10%	37.40%	Uzbekistan	0.353	7.40%	12.00%	15.80%	21.40%	43.40%
Kenya	0.408	6.20%	10.30%	14.60%	21.50%	47.50%	Vanuatu	0.376	6.70%	11.10%	15.50%	21.80%	44.80%
Kiribati	0.37	6.60%	11.60%	16.00%	21.90%	44.00%	Venezuela, RB	0.469	3.20%	9.20%	14.50%	22.30%	50.70%
Korea, Dem. Peopleâ	NA	NA	NA	NA	NA	NA	Vietnam	0.357	6.70%	11.90%	16.30%	22.30%	42.90%
Korea, Rep.	0.316	7.30%	13.00%	17.50%	23.20%	39.00%	Virgin Islands (U.S	NA	NA	NA	NA	NA	NA
Kosovo	0.29	9.20%	13.60%	17.00%	21.60%	38.60%	West Bank and G	0.337	7.30%	11.90%	16.60%	23.20%	41.10%
Kuwait	NA	NA	NA	NA	NA	NA	Yemen, Rep.	0.367	7.30%	11.50%	15.30%	21.20%	44.70%
Kyrgyz Republic	0.277	9.90%	13.50%	17.00%	21.80%	37.80%	Zambia	0.571	2.90%	6.00%	10.60%	19.30%	61.30%
Lao PDR	0.364	7.60%	11.50%	15.30%	21.00%	44.60%	Zimbabwe	0.443	6.00%	9.10%	13.20%	20.60%	51.10%

Figure B.6: Income shares per country based on The World Bank [2020]



RICE region	Lowest 20% abs	Second 20% abs	Third 20% abs	Fourth 20% abs	Highest 20% abs
US	0,052	0,103	0,153	0,225	0,467
EU	0,073	0,124	0,168	0,224	0,411
Japan	0,077	0,128	0,166	0,217	0,411
Russia	0,071	0,112	0,152	0,214	0,451
Eurasia	0,085	0,130	0,169	0,221	0,396
China	0,065	0,107	0,153	0,222	0,453
India	0,081	0,117	0,152	0,205	0,444
MidEast	0,069	0,113	0,157	0,220	0,441
Africa	0,065	0,106	0,148	0,211	0,470
LatAm	0,043	0,086	0,133	0,204	0,535
Other High Income	0,073	0,126	0,170	0,229	0,402
OthAs	0,075	0,114	0,154	0,215	0,441

Figure B.7: Income shares summary RICE regions

C OUTCOMES REFERENCE SCENARIO

The following figure shows the outcomes of the 29 example strategies and the Nordhaus policy on all objectives used with the problem formulations.

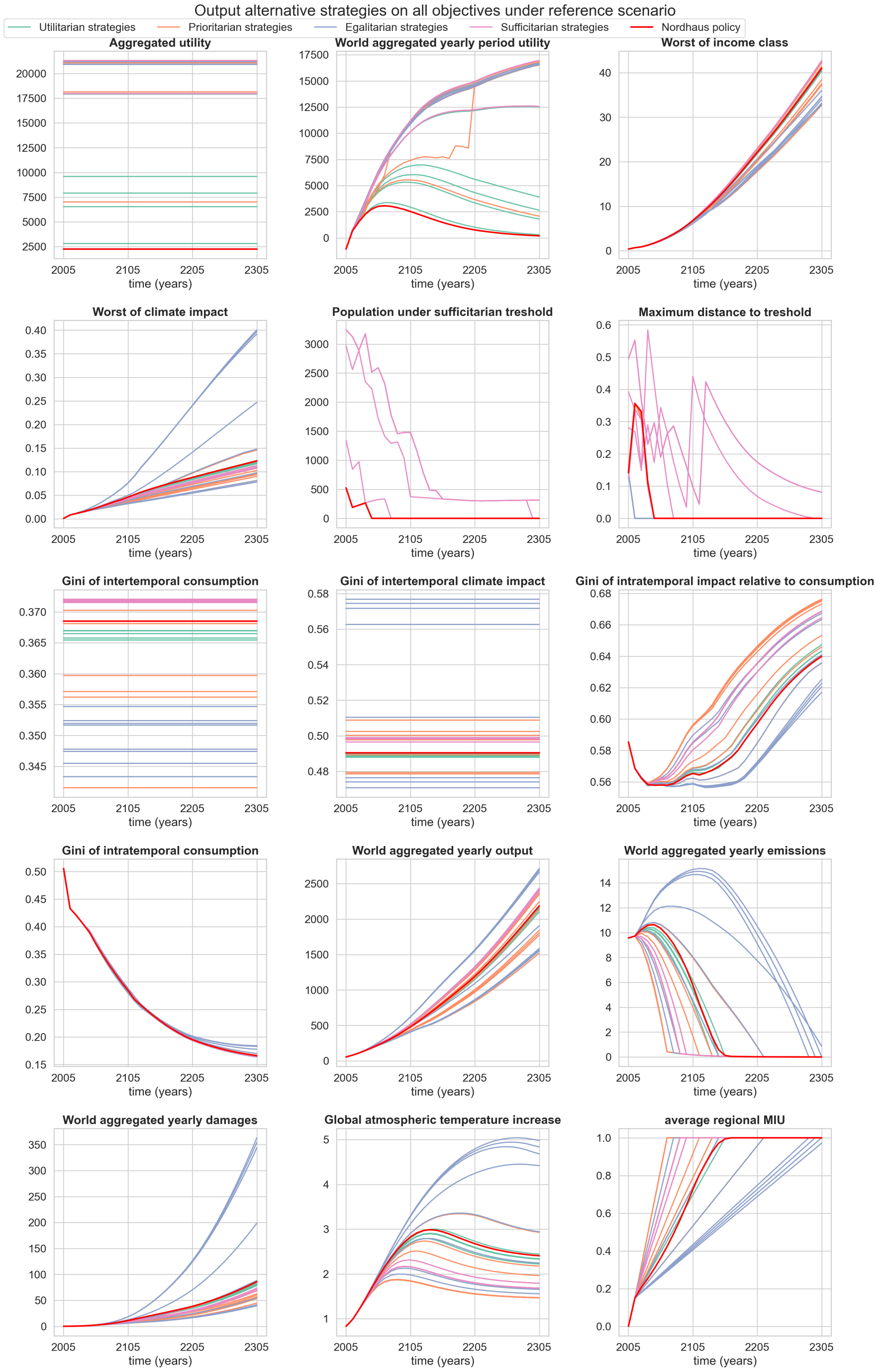
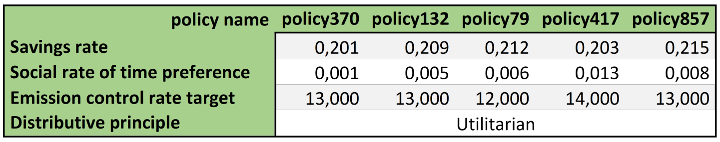


Figure C.1: Outcomes reference scenario overview

D SUMMARY CHOSEN EXAMPLE STRATEGIES

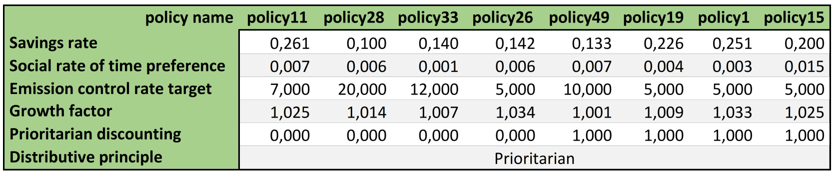
Utilitarian policies



policy name	policy370	policy132	policy79	policy417	policy857
Savings rate	0,201	0,209	0,212	0,203	0,215
Social rate of time preference	0,001	0,005	0,006	0,013	0,008
Emission control rate target	13,000	13,000	12,000	14,000	13,000
Distributive principle	Utilitarian				

Figure D.1: Overview of characteristics Utilitarian policies

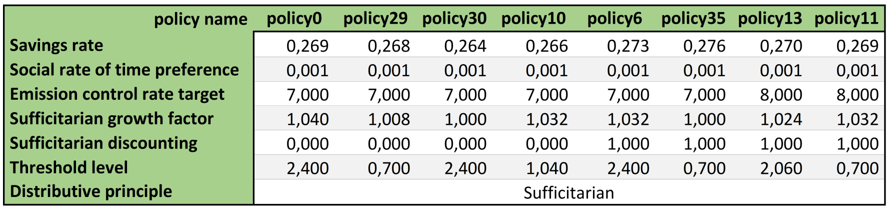
Prioritarian policies



policy name	policy11	policy28	policy33	policy26	policy49	policy19	policy1	policy15
Savings rate	0,261	0,100	0,140	0,142	0,133	0,226	0,251	0,200
Social rate of time preference	0,007	0,006	0,001	0,006	0,007	0,004	0,003	0,015
Emission control rate target	7,000	20,000	12,000	5,000	10,000	5,000	5,000	5,000
Growth factor	1,025	1,014	1,007	1,034	1,001	1,009	1,033	1,025
Prioritarian discounting	0,000	0,000	0,000	0,000	1,000	1,000	1,000	1,000
Distributive principle	Prioritarian							

Figure D.2: Overview of characteristics Prioritarian policies

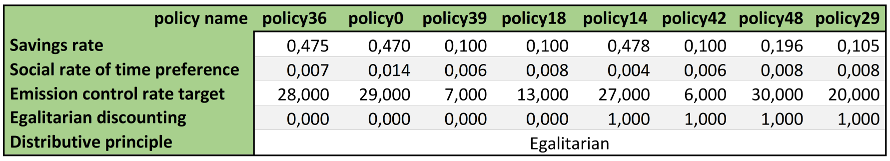
Sufficitarian policies



policy name	policy0	policy29	policy30	policy10	policy6	policy35	policy13	policy11
Savings rate	0,269	0,268	0,264	0,266	0,273	0,276	0,270	0,269
Social rate of time preference	0,001	0,001	0,001	0,001	0,001	0,001	0,001	0,001
Emission control rate target	7,000	7,000	7,000	7,000	7,000	7,000	8,000	8,000
Sufficitarian growth factor	1,040	1,008	1,000	1,032	1,032	1,000	1,024	1,032
Sufficitarian discounting	0,000	0,000	0,000	0,000	1,000	1,000	1,000	1,000
Threshold level	2,400	0,700	2,400	1,040	2,400	0,700	2,060	0,700
Distributive principle	Sufficitarian							

Figure D.3: Overview of characteristics Sufficitarian policies

Egalitarian policies



policy name	policy36	policy0	policy39	policy18	policy14	policy42	policy48	policy29
Savings rate	0,475	0,470	0,100	0,100	0,478	0,100	0,196	0,105
Social rate of time preference	0,007	0,014	0,006	0,008	0,004	0,006	0,008	0,008
Emission control rate target	28,000	29,000	7,000	13,000	27,000	6,000	30,000	20,000
Egalitarian discounting	0,000	0,000	0,000	0,000	1,000	1,000	1,000	1,000
Distributive principle	Egalitarian							

Figure D.4: Overview of characteristics Egalitarian policies

E OUTCOMES OVER REFERENCE SCENARIO

When running the alternative strategies over the reference scenario, it becomes clear that the Prioritarian indeed achieves high protection for the lowest income groups (figure E.1). Although the difference with other policies is small. This is because the maximum height of the consumption level is partly locked-in with the economic scenario. Therefore, across all strategies, rapid consumption growth is observed. The relative climate impact to consumption shows that the Egalitarian case has some deteriorating consumption levels for the lowest 20 % where up to 40 % of income is lost due to climate impact. This is due to the slow climate action in many Egalitarian policies, which leads to high climate impact. The Prioritarian case performs best at protecting the poor, not surpassing 10 % of relative climate impact. The difference with the Nordhaus policy is striking: in the Nordhaus policy the relative climate impact felt by the worst-off is almost two times higher than in the best performing Prioritarian policy.

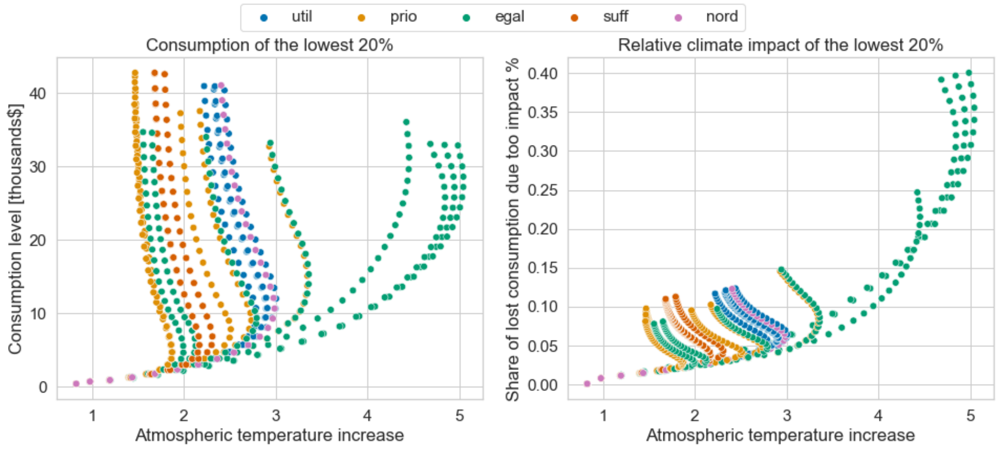


Figure E.1: Development of Prioritarian objectives under Nordhaus scenario

Effect on Sufficitarian objectives under the reference scenario

The plot on the next page (E.2) shows the effect of the strategies on the Sufficitarian objectives over time. At first sight, it might seem that the Sufficitarian objective performs worst than the other principles in minimizing the number of people under and distance to the threshold. But this can be explained by the fact that in the Sufficitarian case, the threshold level is varied at higher and lower levels, whereas with the other strategies, it is kept at a constant low level. Therefore the outcomes are hard to compare. However, what is clear is that the Nordhaus reference scenario is rather optimistic as over all strategies, the world swiftly goes beyond the threshold level. When looking at the aggregated utility, both Sufficitarian, Egalitarian and Prioritarian strategies result in higher aggregated utility which can be explained by the lower discounting rates used within those strategies.

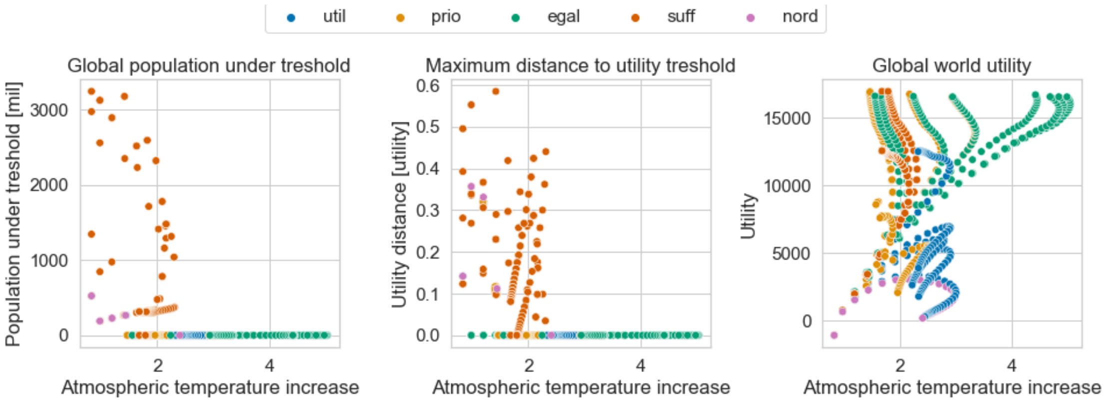


Figure E.2: Development of Sufficitarian objectives under Nordhaus scenario

Effect on Egalitarian objectives under the reference scenario

The Egalitarian principle aims at minimizing inequality in climate impact and consumption between and within generations. Relative improvements in inequality reduction from the other principles seem small and come potentially at a cost. In some strategies, this leads to justifying slow climate action and high temperature increases up to 5 degrees. This means exposure to high climate impacts. Some Egalitarian strategies result in possibly unwanted behaviour; although inequality in climate impact is reduced, everyone is worse off as the population experiences high climate impact. Hereby reducing inequality in climate impact but losing the goal of minimization of climate impact. The same reasoning can be made for the stronger reduction in intragenerational climate impact (subplot bottom right, E.3).

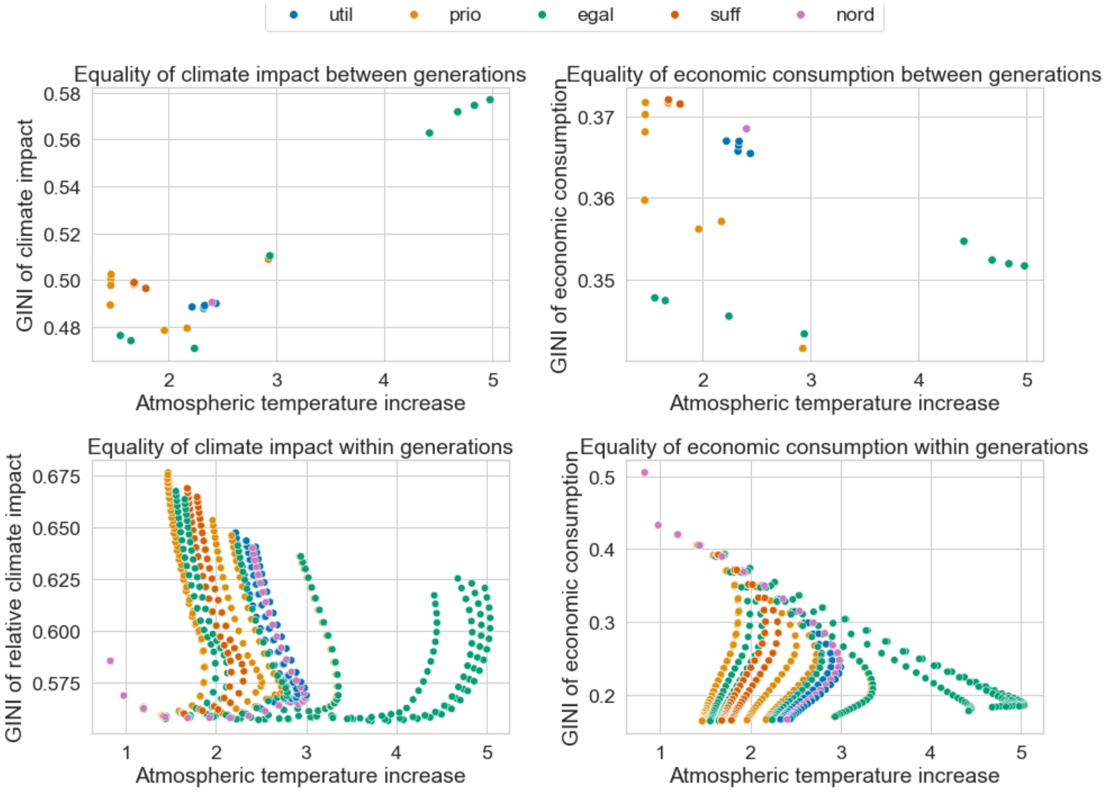


Figure E.3: Development of Egalitarian objectives under Nordhaus scenario

Effect on Utilitarian objectives under the reference scenario

The Utilitarian case consists of two objectives, namely the total aggregated utility across all time steps and the period utility. The period utility is influenced by the normatively set discount rate, which differs across strategies. Therefore, it is hard to compare strategies only on their level of utility. What is clear though, is due to lower set discount rate, the utility of people further in the future is valued higher in almost all scenarios compared to the Nordhaus policy. This also explains the difference in emission control rate of the Sufficitarian (fast abatement) and the Utilitarian principle (modest abatement). As the utility of generations far in the future is valued high, faster abatement becomes more optimal. This reasoning is in line with research in the field such as Stern [2007]; Nordhaus [2011]; Adler et al. [2017]; Dennig et al. [2015]; Tol [2013], which highlighted the influence of the social discount rate in determining what is optimal.

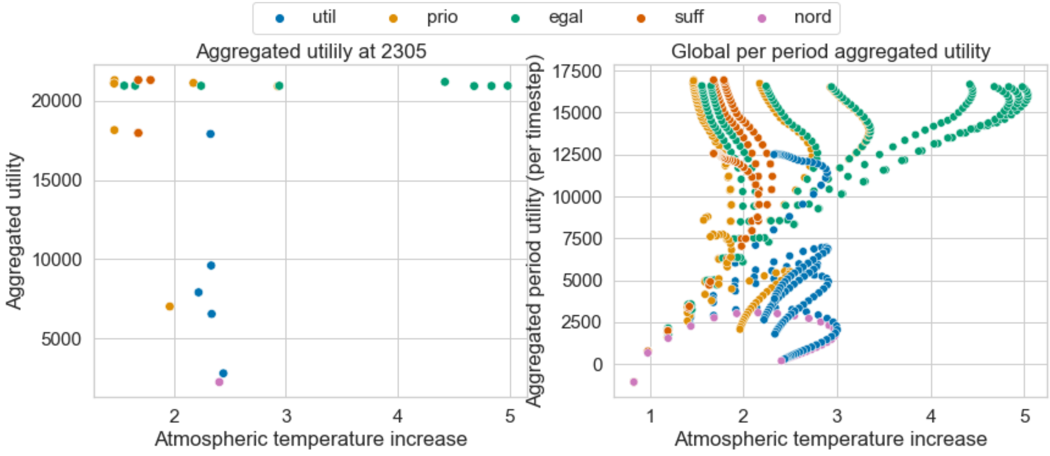


Figure E.4: Development of Utilitarian objectives under Nordhaus scenario

F | SHORT TERM UNCERTAINTY: OUTCOMES

Sufficitarian outcomes

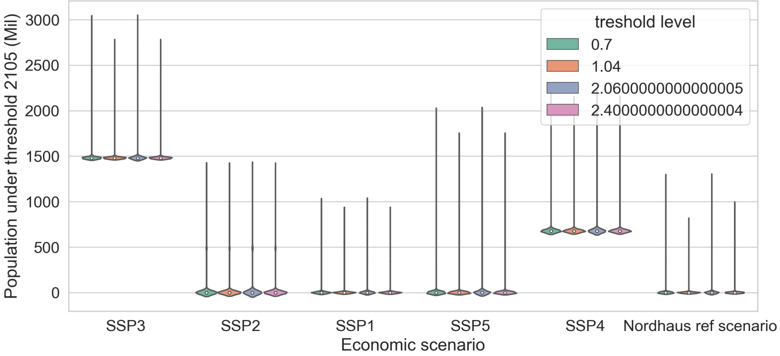


Figure F.1: Influence of threshold level on population below threshold

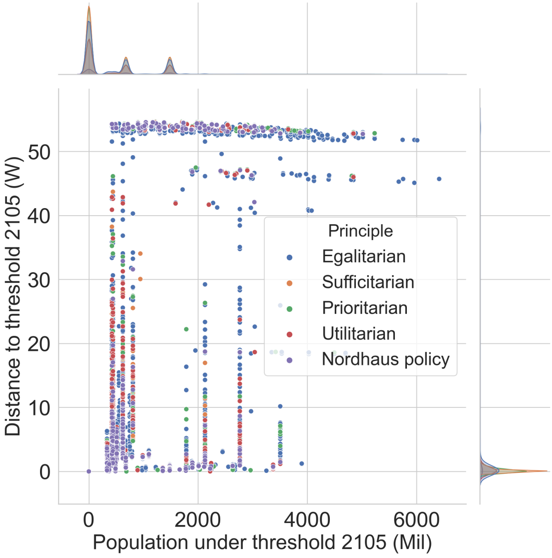


Figure F.2: Distribution of population under and distance to threshold

Prioritarian outcomes

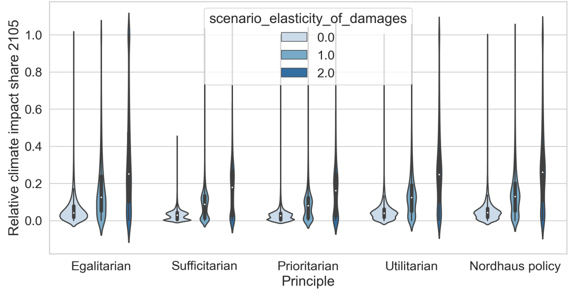


Figure F.3: Influence of elasticity of damages on relative climate impact

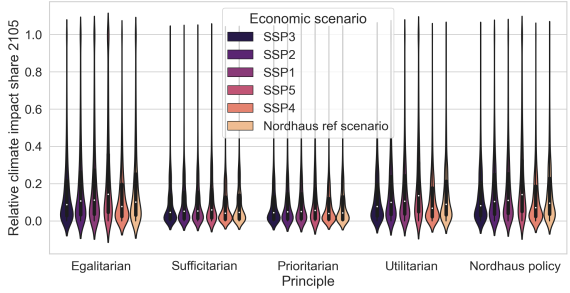


Figure F.4: Influence of economic scenario on relative climate impact

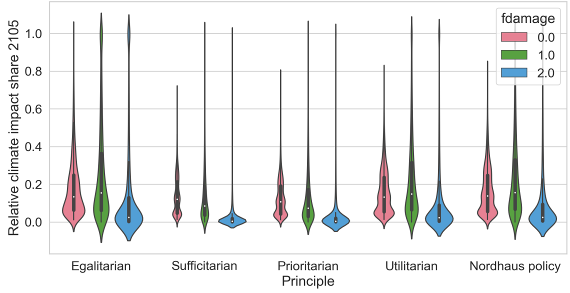


Figure F.5: Influence of damage function on relative climate impact

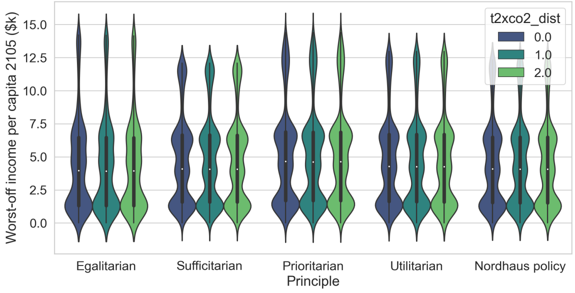


Figure F.6: Influence of climate sensitivity distribution on worst-off income

G

SHORT TERM UNCERTAINTY: ROBUSTNESS HEAT MAPS

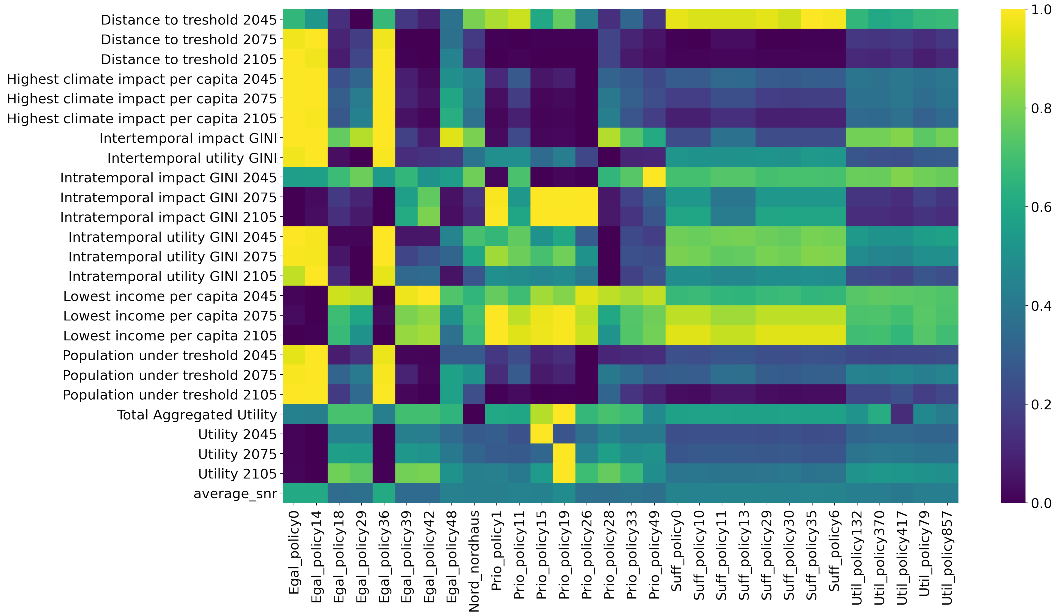


Figure G.1: Heat map signal to noise ratio short term uncertainty analysis

Figure G.2: Heat map maximum regret short term uncertainty analysis

H LONG TERM UNCERTAINTY ANALYSIS: OUTCOMES

The uncertainty range of the long term economic scenario is in the long term uncertainty analysis is based on the Nordhaus reference scenario. In this optimistic scenario, all world regions experience rapid economic growth. Therefore only in a few extreme cases the world population finds themselves under Sufficitarian threshold. Here the threshold is the poverty line of the World Bank indexed with the average growth of the world economy. Because of the optimistically used economic scenario, the long term scenario analysis is less suited for conclusion on the Sufficitarian approach.

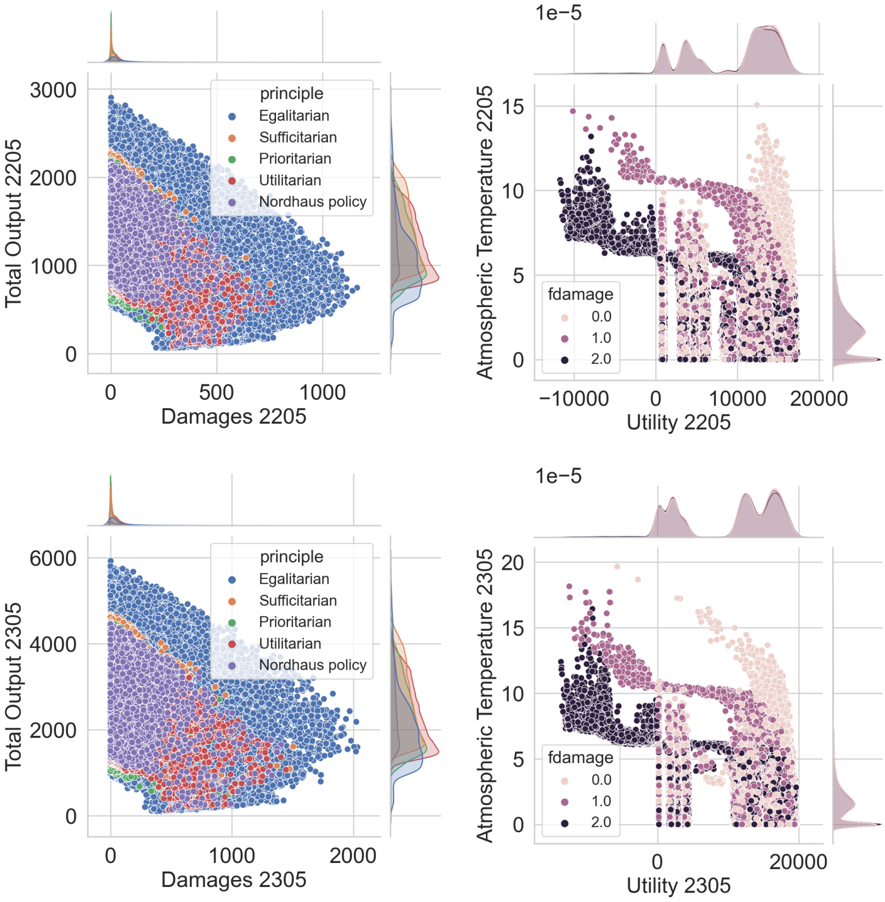


Figure H.1: Long term uncertainty outcomes Utilitarian objectives

Surprisingly, all principles outperform the Egalitarian principle in equalizing climate impact inequality across generations. The explanation for this is twofold, the other principles tend to have more optimized savings rates which lead to more sustained economic growth in the long run. Furthermore, faster abatement simply leads to less climate impact in the long run which increases equality in climate impact as the difference in climate impact experienced by current generations and generations in the next centuries is reduced.

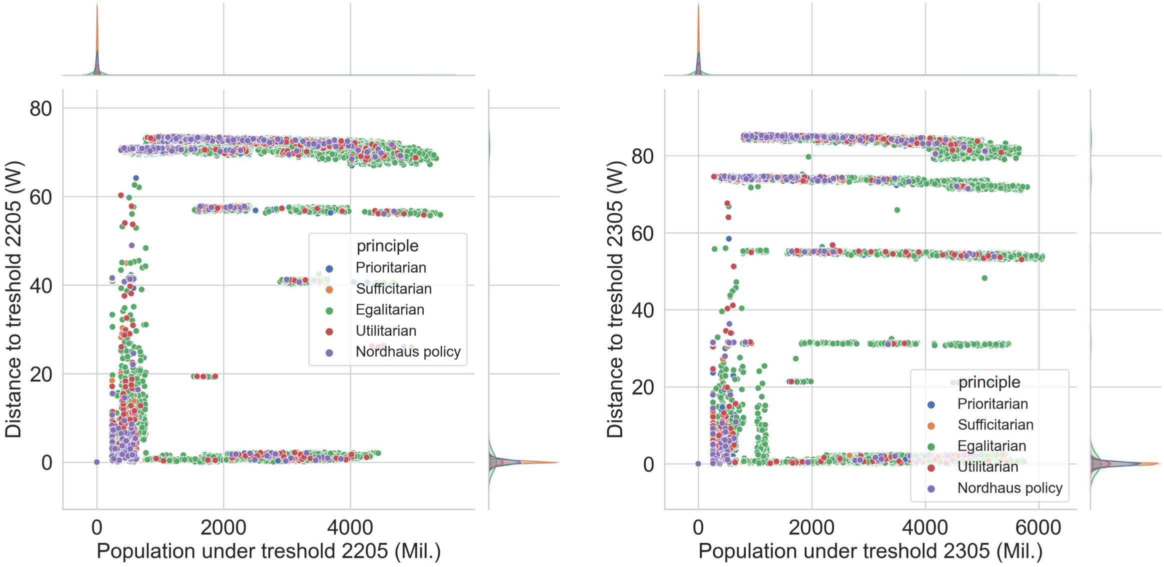


Figure H.2: Long term uncertainty outcomes Sufficitarian objectives

Regarding equality in impact within generations, the damage relation between warming and the economy is significant. When assuming the Nordhaus damage function, inequality between regions is high. This can be explained from the fact that the Nordhaus damage assumes regional dependent damage from Sea level rise disproportionally affecting distinct regions hereby contributing to an increase in climate impact between regions. The Weitzman damage function also contributes to higher climate impact between regions due too more extreme climate impact assumptions. This means that lower income regions are relatively more affected leading to a higher inequity of climate impact especially in the long run. Regarding differences in intragenerational Egalitarian strategies are more prone to extreme cases of inequality which has been observed earlier for Utilitarian objectives as well.

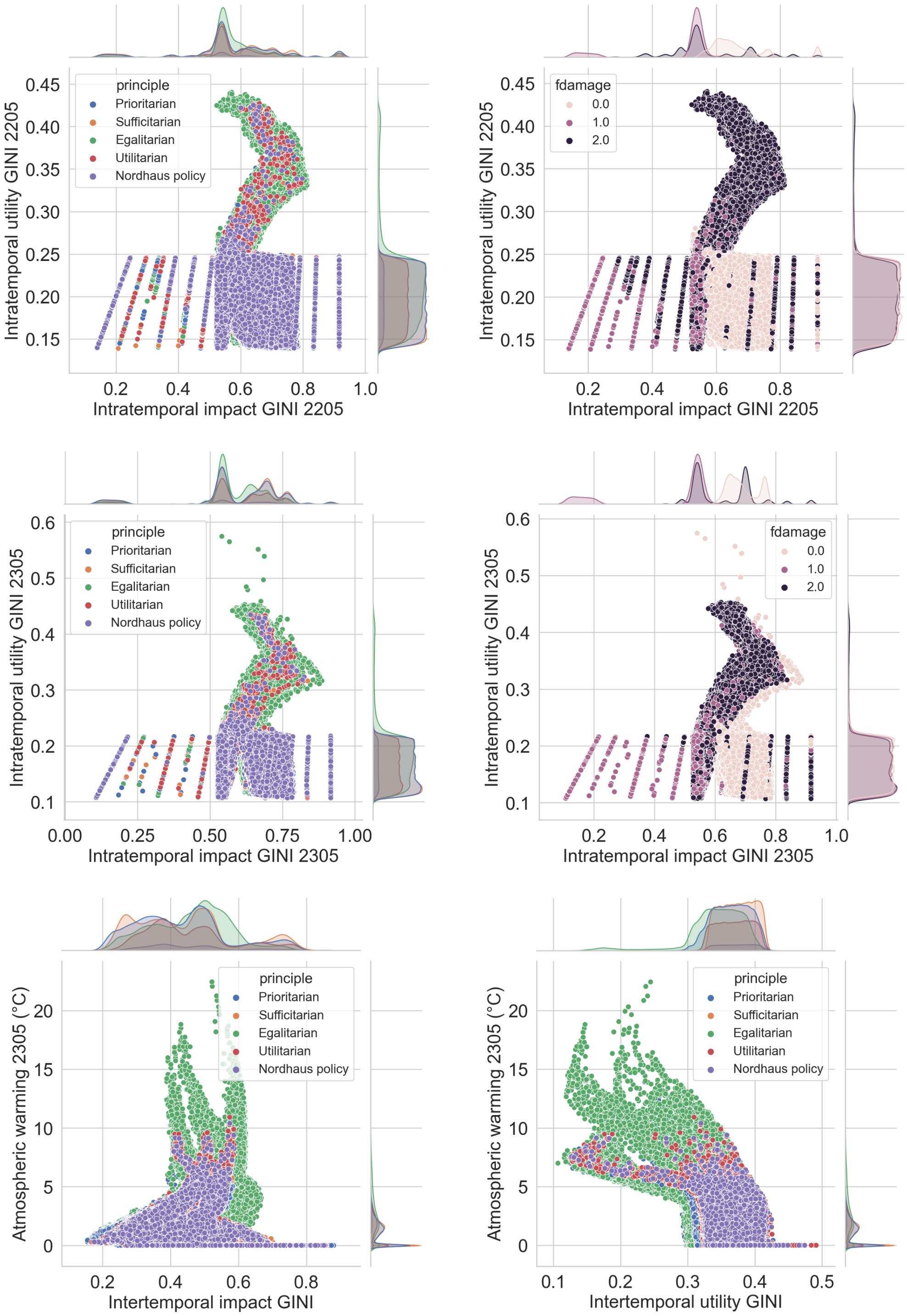


Figure H.3: Long term uncertainty outcomes Egalitarian objectives

Utilitarian violin plots long term outcomes

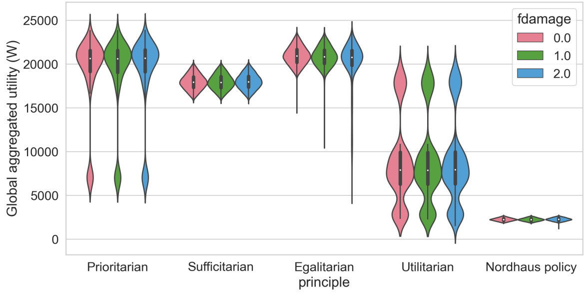


Figure H.4: Influence of damage function on aggregated Utility

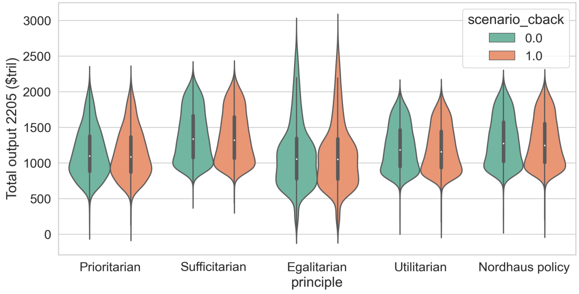


Figure H.5: Influence of backstop price on total output

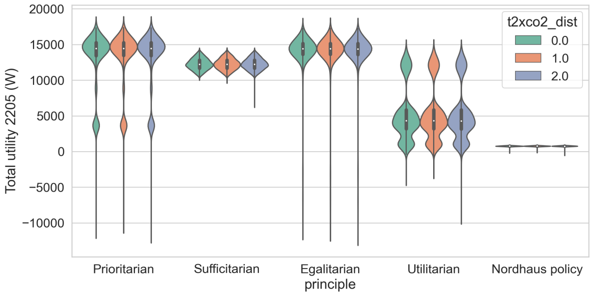


Figure H.6: Influence of temperature distribution on Utility

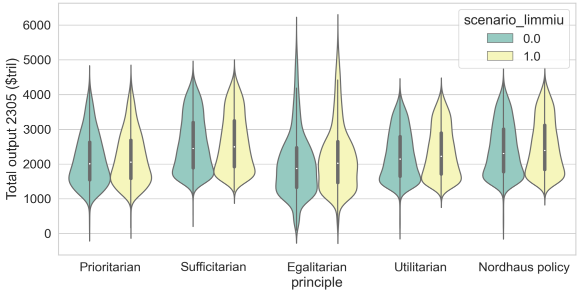


Figure H.7: Influence of negative emission on total output

Prioritarian violin plot long term outcomes

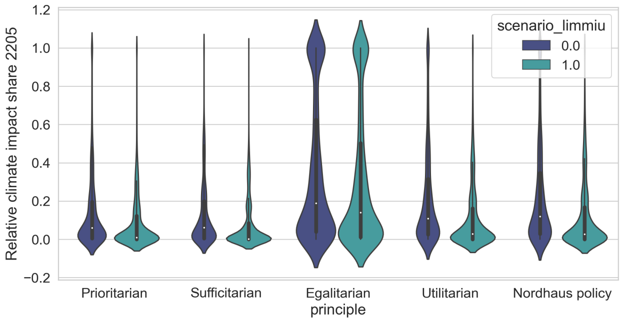


Figure H.8: Influence of damage function on relative climate impact

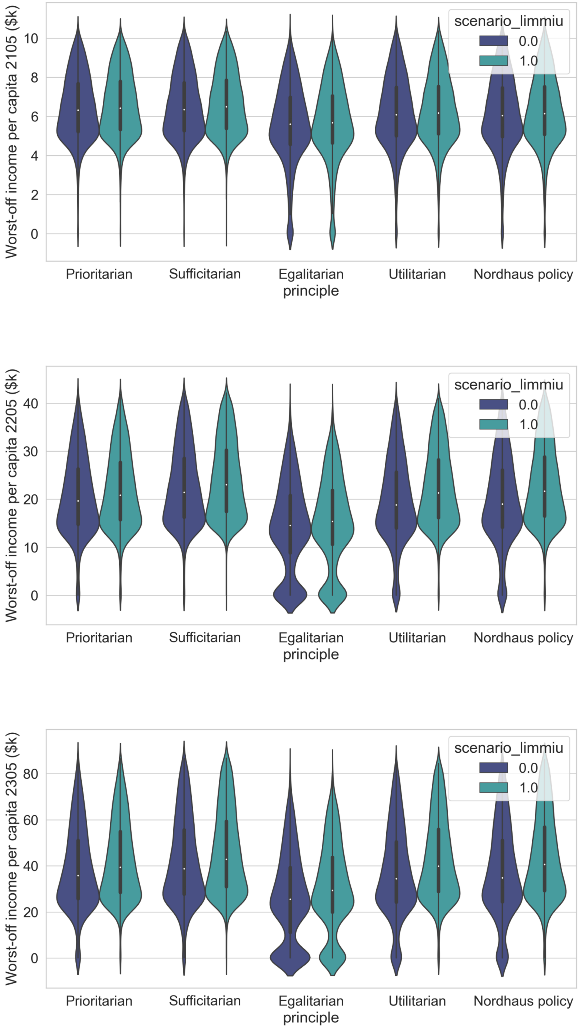


Figure H.9: Influence of damage function on relative climate impact

I LONG TERM UNCERTAINTY ANALYSIS: ROBUSTNESS HEAT MAPS

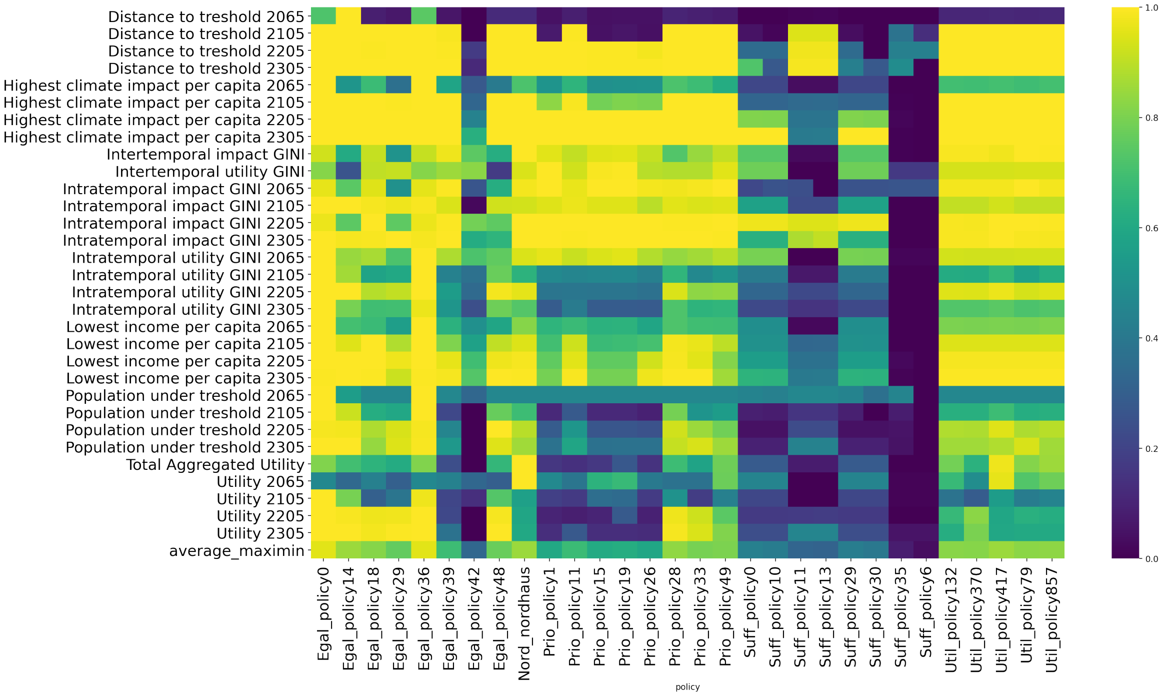


Figure I.1: Heat map maximum regret long term uncertainty analysis

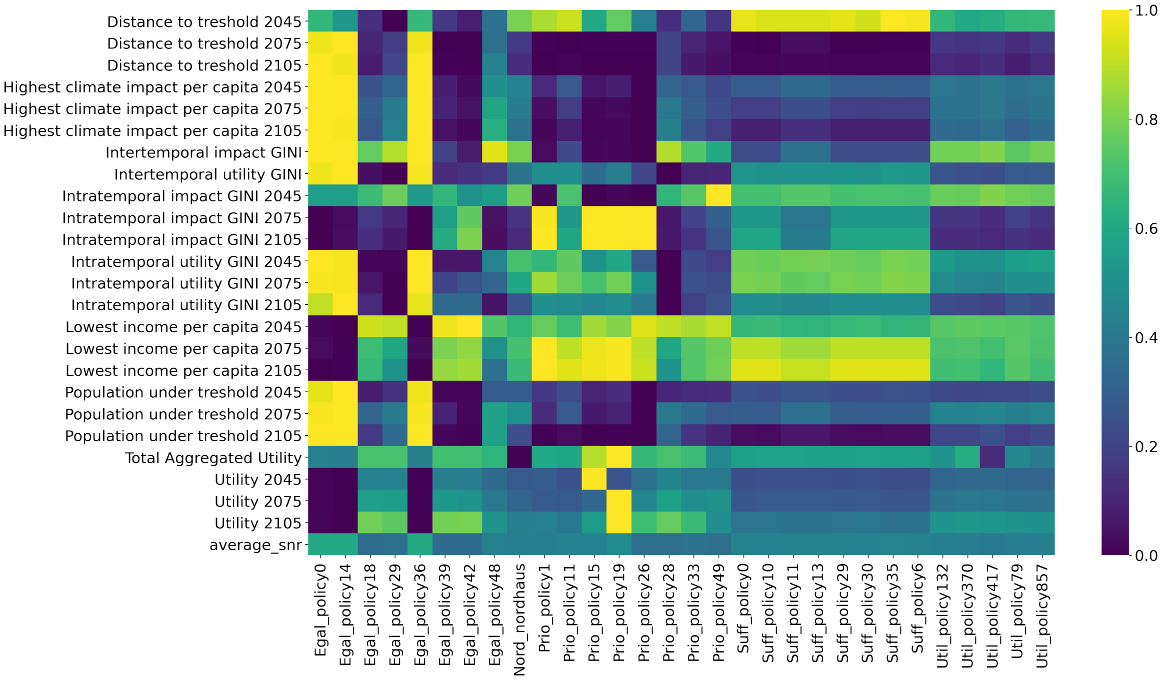


Figure I.2: Heat map signal to noise ratio long term uncertainty analysis

J WORST CASE ANALYSIS

Composition of climate uncertainties

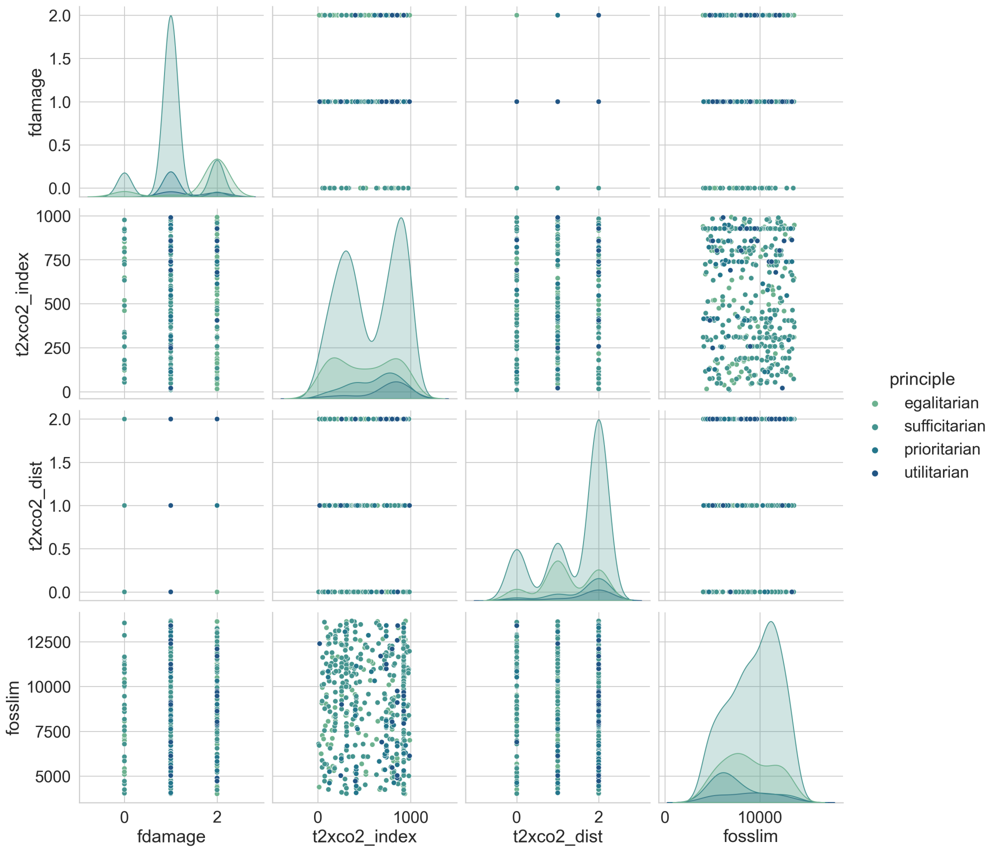


Figure J.1: Overview worst-case input climate uncertainties

Composition of socioeconomic uncertainties

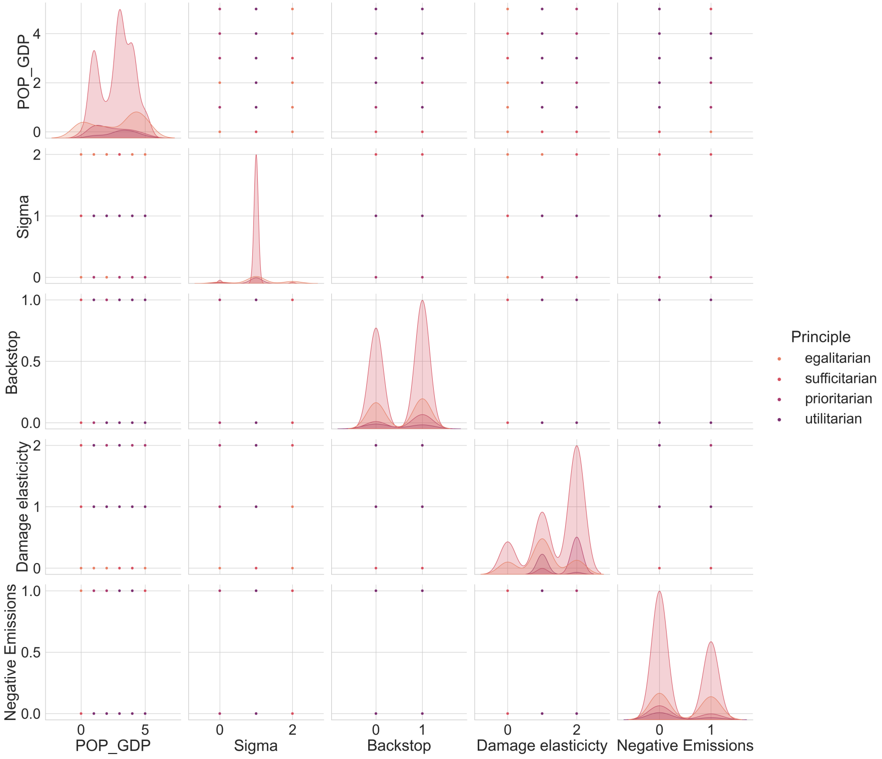


Figure J.2: Overview worst-case input socio-economic uncertainties

Utilitarian outcomes

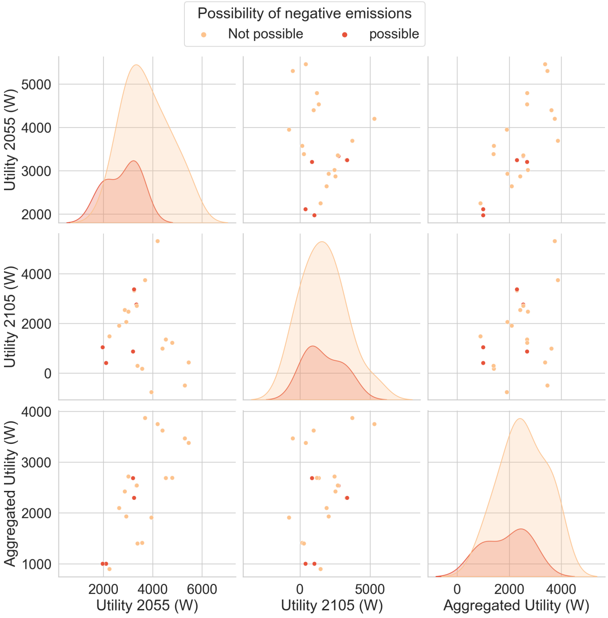


Figure J.3: Overview worst-case outcomes Utilitarian principle

Egalitarian outcomes

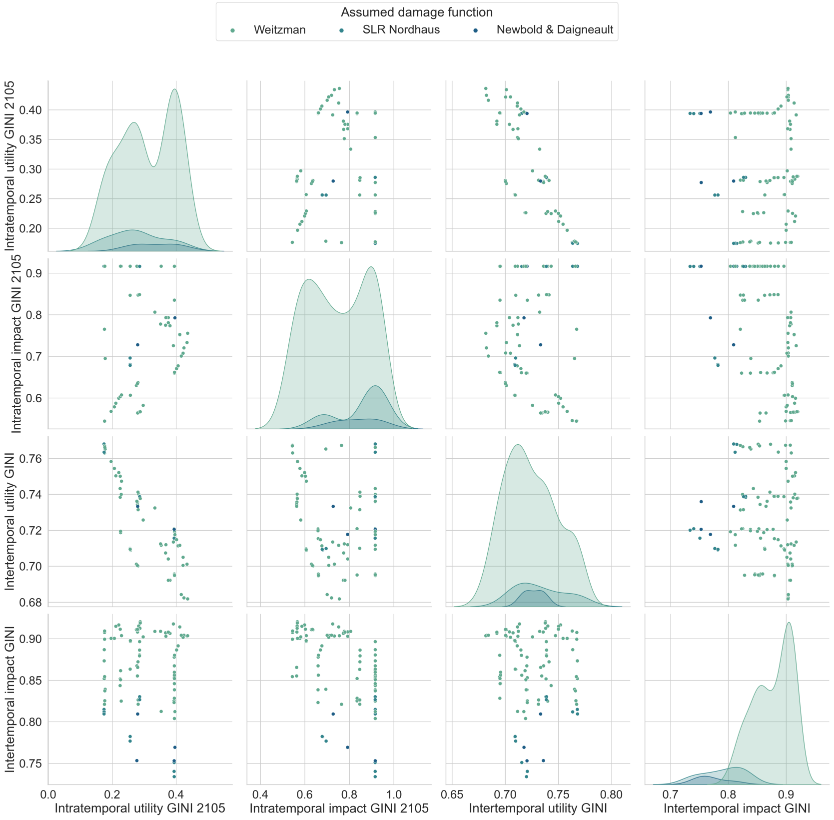


Figure J.4: Overview worst-case outcomes Egalitarian principle

Prioritarian outcomes

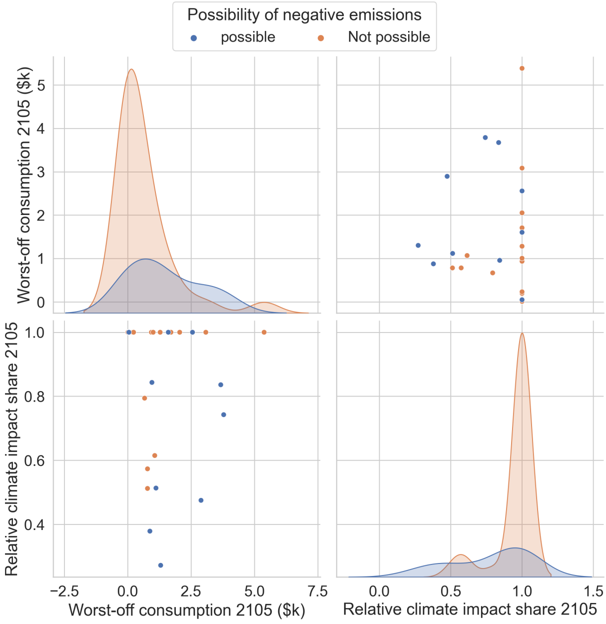


Figure J.5: Overview worst-case outcomes worst-off income and negative emissions

K SCENARIO DISCOVERY

Silhouette width analysis

The figure below shows the silhouette width score of four objectives of the clustering of 15000 simulation runs under the Sufficitarian (policy 30) strategy. The silhouette width is a guide for the number of clusters that are appropriate to cluster a group of time series. This metric is based on the individual silhouette score of each observation in a cluster. The individual silhouette score is the similarity of an observation to its co-members in the cluster. The total average silhouette width is the average of the average silhouette width of each cluster. Generally, a higher value of the silhouette score is preferred [Lingeswaran, 2019]. But the final call, how many clusters to take, can only be made through visual inspection. This because some clusters are more valuable to be shown than others, which is not reflected in the silhouette width score.

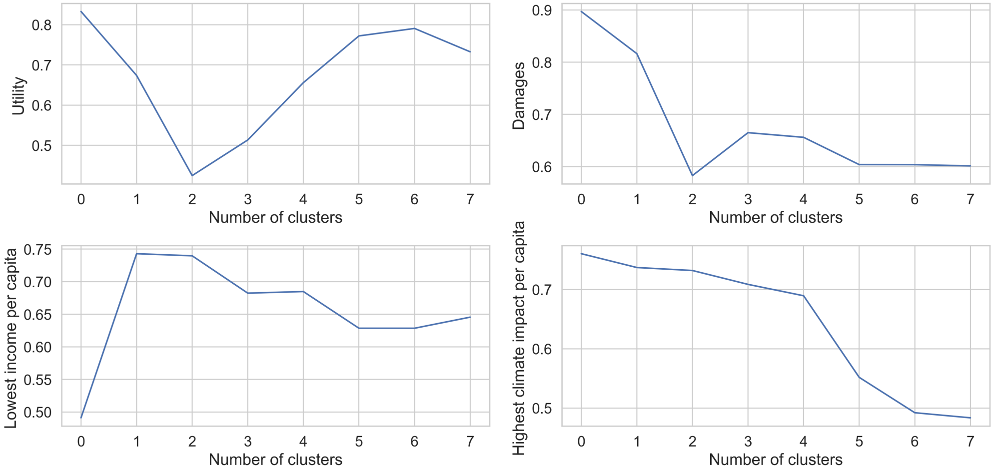
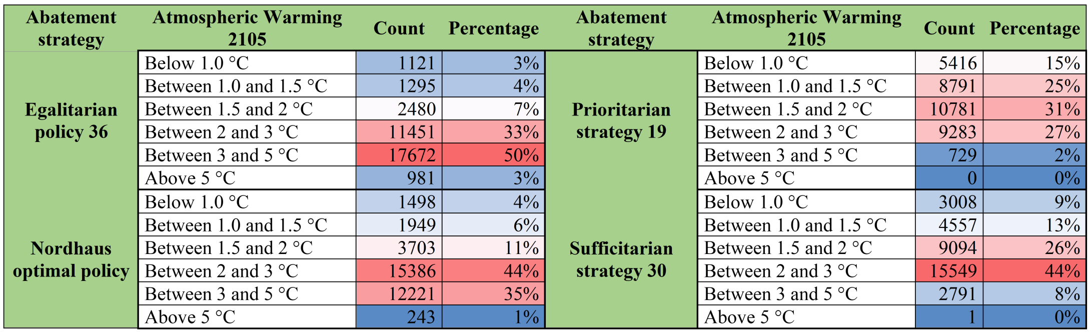


Figure K.1: Silhouette scores of Sufficitarian clusters for four objectives

Frequency table of emission pathways per temperature outcome 2105



Abatement strategy	Atmospheric Warming 2105	Count	Percentage	Abatement strategy	Atmospheric Warming 2105	Count	Percentage
Egalitarian policy 36	Below 1.0 °C	1121	3%	Prioritarian strategy 19	Below 1.0 °C	5416	15%
	Between 1.0 and 1.5 °C	1295	4%		Between 1.0 and 1.5 °C	8791	25%
	Between 1.5 and 2 °C	2480	7%		Between 1.5 and 2 °C	10781	31%
	Between 2 and 3 °C	11451	33%		Between 2 and 3 °C	9283	27%
	Between 3 and 5 °C	17672	50%		Between 3 and 5 °C	729	2%
	Above 5 °C	981	3%		Above 5 °C	0	0%
Nordhaus optimal policy	Below 1.0 °C	1498	4%	Sufficitarian strategy 30	Below 1.0 °C	3008	9%
	Between 1.0 and 1.5 °C	1949	6%		Between 1.0 and 1.5 °C	4557	13%
	Between 1.5 and 2 °C	3703	11%		Between 1.5 and 2 °C	9094	26%
	Between 2 and 3 °C	15386	44%		Between 2 and 3 °C	15549	44%
	Between 3 and 5 °C	12221	35%		Between 3 and 5 °C	2791	8%
	Above 5 °C	243	1%		Above 5 °C	1	0%

Figure K.2: Frequency table **figure 11.4** emission pathways across scenarios

Development of atmospheric warming per economic SSP scenario

The figure below shows the average atmospheric warming development for the most robust strategy per principle and the Nordhaus policy for each economic SSP scenario.

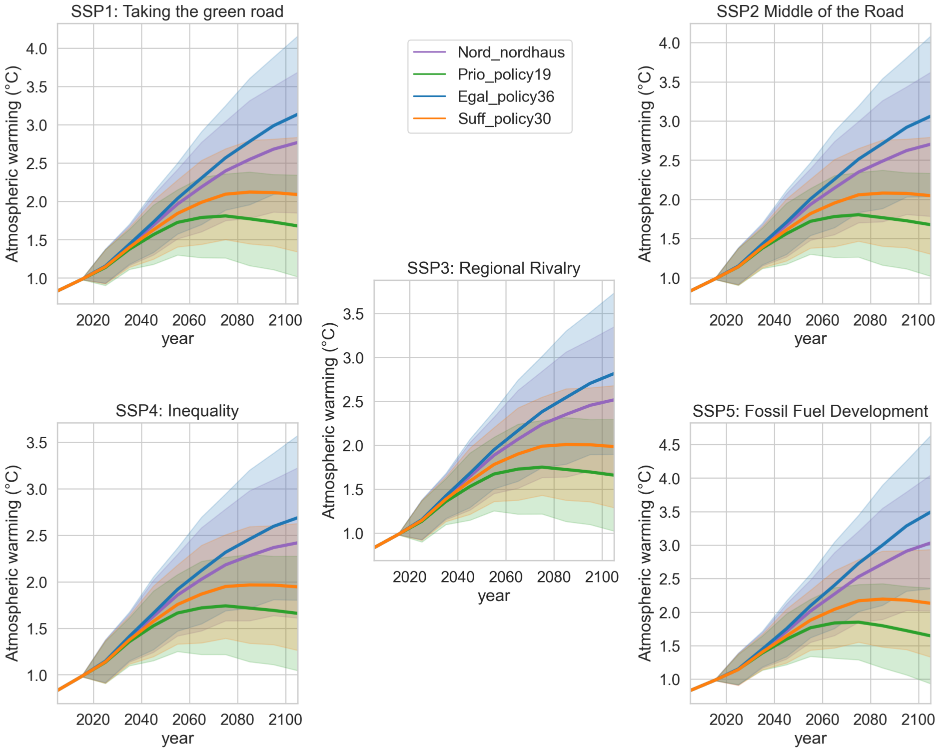


Figure K.3: Overview of temperature development most robust policy per economic scenario

Average atmospheric warming and CO_2 abatement pathway per principle

The figure below shows the average temperature and CO_2 emission pathway for the most robust strategy per principle and the Nordhaus policy.

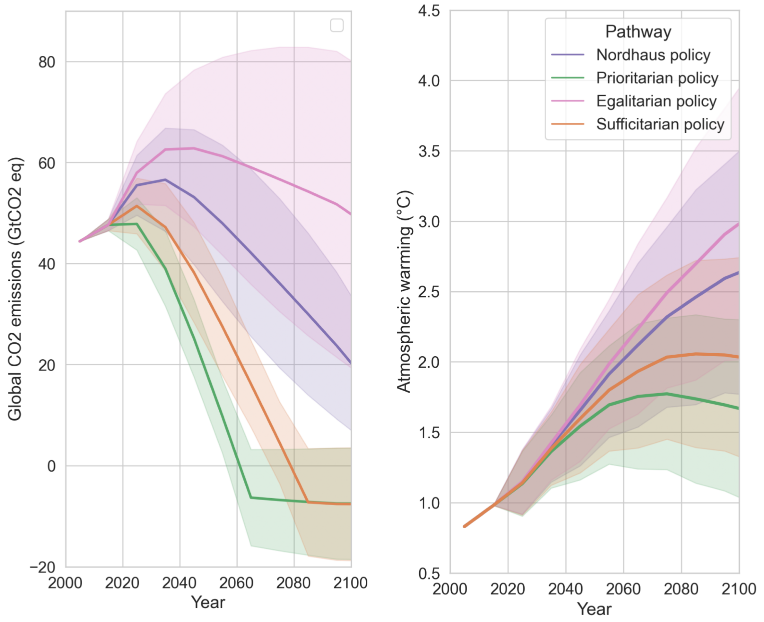
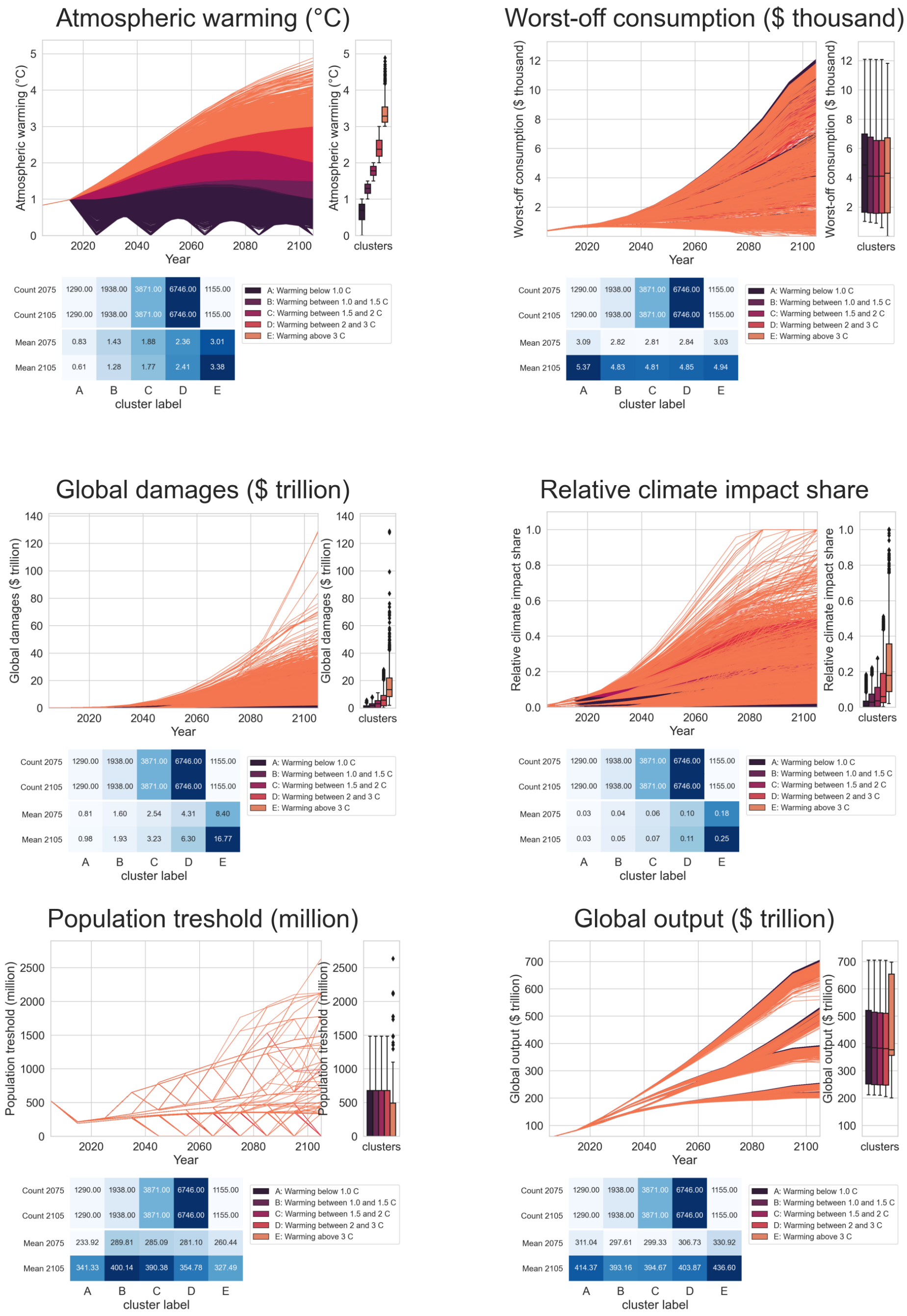


Figure K.4: Average temperature and emission pathway for most robust strategies

Agglomerative clustering results

The next three graphs show the result of the agglomerative cluster. All timeseries have been clustered into 5 clusters using the CID distance as a similarity measure. Agglomerative clustsering witht the complete linkage criterium has been used to form the clusters. Every graph has been clustered independently. Thus the clusters are not consistent between any of the graph. The clusters show groups of behaviour within the uncertainty analysis.

Agglomerative clustering results Sufficitarian policy 30



Atmospheric warming (°C)

	A	B	C	D	E
Count 2075	1290.00	1938.00	3871.00	6746.00	1155.00
Count 2105	1290.00	1938.00	3871.00	6746.00	1155.00
Mean 2075	0.83	1.43	1.88	2.36	3.01
Mean 2105	0.61	1.28	1.77	2.41	3.38

Worst-off consumption ($ thousand)

	A	B	C	D	E
Count 2075	1290.00	1938.00	3871.00	6746.00	1155.00
Count 2105	1290.00	1938.00	3871.00	6746.00	1155.00
Mean 2075	3.09	2.82	2.81	2.84	3.03
Mean 2105	5.37	4.83	4.81	4.85	4.94

Global damages ($ trillion)

	A	B	C	D	E
Count 2075	1290.00	1938.00	3871.00	6746.00	1155.00
Count 2105	1290.00	1938.00	3871.00	6746.00	1155.00
Mean 2075	0.81	1.60	2.54	4.31	8.40
Mean 2105	0.98	1.93	3.23	6.30	16.77

Relative climate impact share

	A	B	C	D	E
Count 2075	1290.00	1938.00	3871.00	6746.00	1155.00
Count 2105	1290.00	1938.00	3871.00	6746.00	1155.00
Mean 2075	0.03	0.04	0.06	0.10	0.18
Mean 2105	0.03	0.05	0.07	0.11	0.25

Population treshold (million)

	A	B	C	D	E
Count 2075	1290.00	1938.00	3871.00	6746.00	1155.00
Count 2105	1290.00	1938.00	3871.00	6746.00	1155.00
Mean 2075	233.92	289.81	285.09	281.10	260.44
Mean 2105	341.33	400.14	390.38	354.78	327.49

Global output ($ trillion)

	A	B	C	D	E
Count 2075	1290.00	1938.00	3871.00	6746.00	1155.00
Count 2105	1290.00	1938.00	3871.00	6746.00	1155.00
Mean 2075	311.04	297.61	299.33	306.73	330.92
Mean 2105	414.37	393.16	394.67	403.87	436.60

Figure K.5: Overview of outcomes agglomerative clustering Sufficitarian policy 30

Agglomerative clustering results Prioritarian policy 19

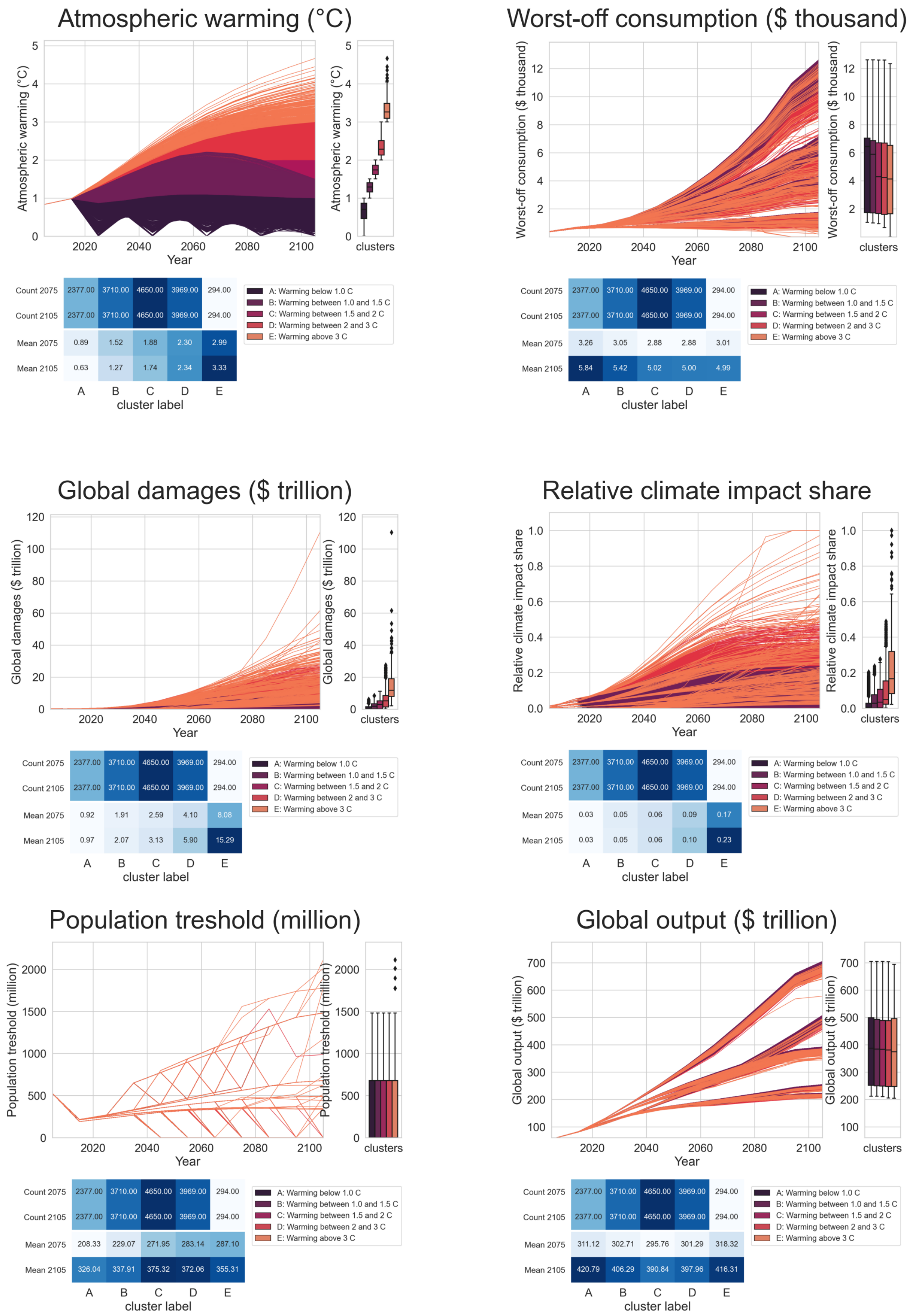


Figure K.6: Overview of outcomes agglomerative clustering Prioritarian policy 19

Agglomerative clustering results Nordhaus policy

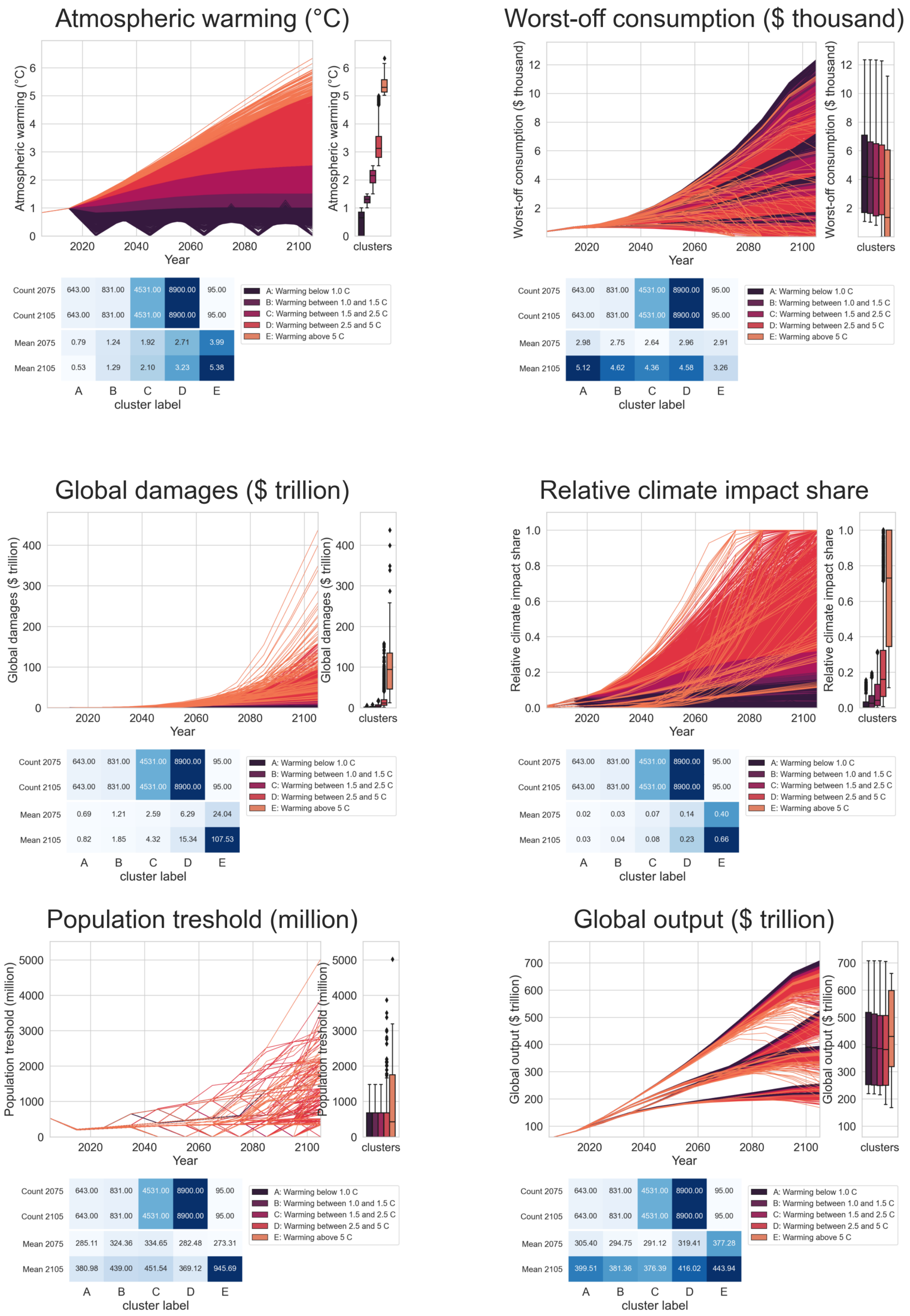


Figure K.7: Overview of outcomes agglomerative clustering Nordhaus policy

Clustering based on temperature outcomes 2105

The next figures show additional clustering figures of the development of the most important principle specific objectives. The developments have been clustered on temperature outcome in 2105. There are 5 clusters that have been used regarding temperature outcomes. **Most robust Sufficitarian policy compared with Nordhaus policy**

Temperature development

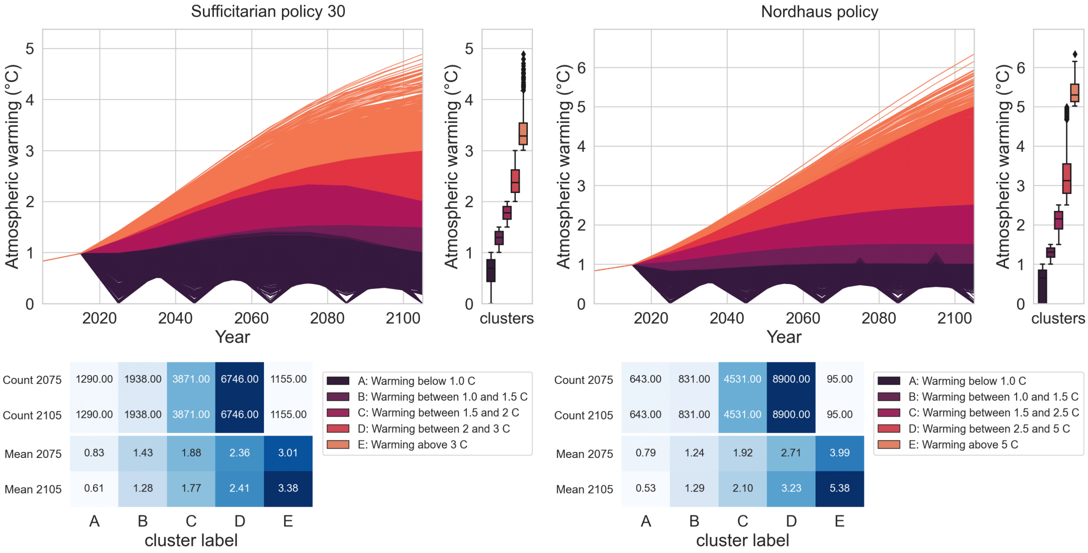


Figure K.8: Sufficitarian p36 and Nordhaus policy temperature pathways

Global emission development

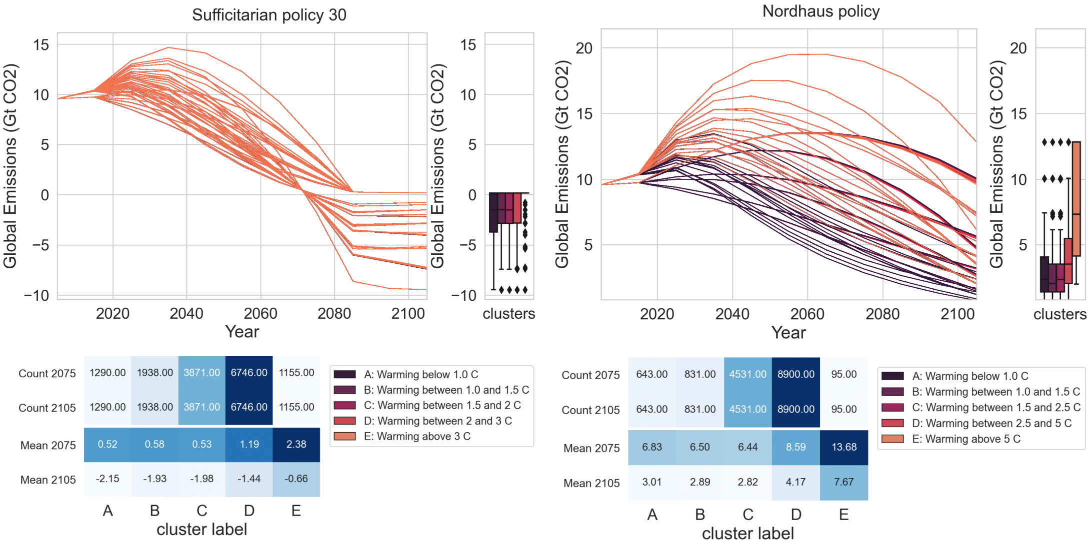


Figure K.9: Sufficitarian p36 and Nordhaus policy emission pathways

Population under threshold

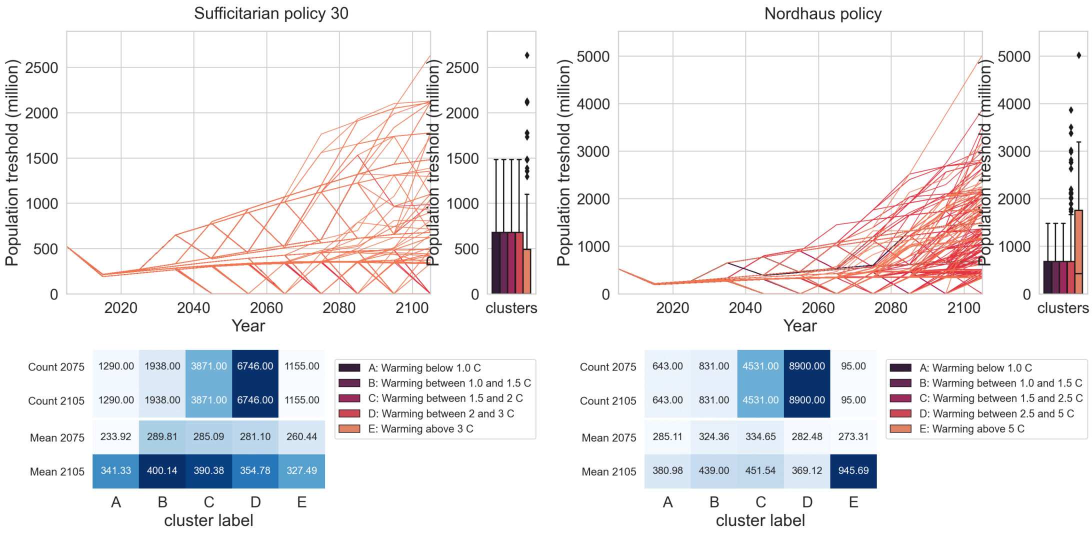


Figure K.10: Sufficitarian p36 and Nordhaus policy population under threshold pathways

Most robust Prioritarian policy compared with Nordhaus policy

Temperature development

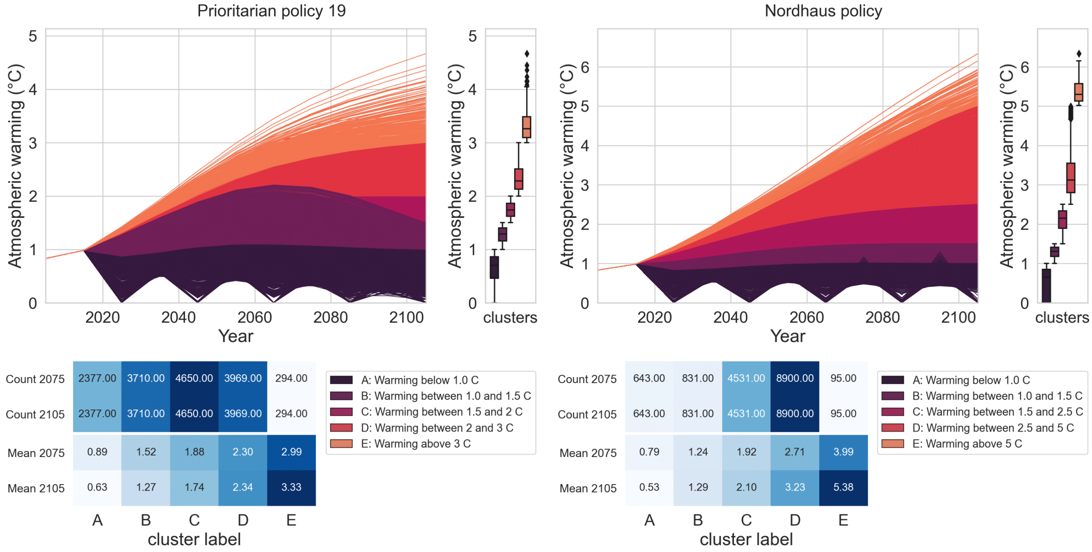
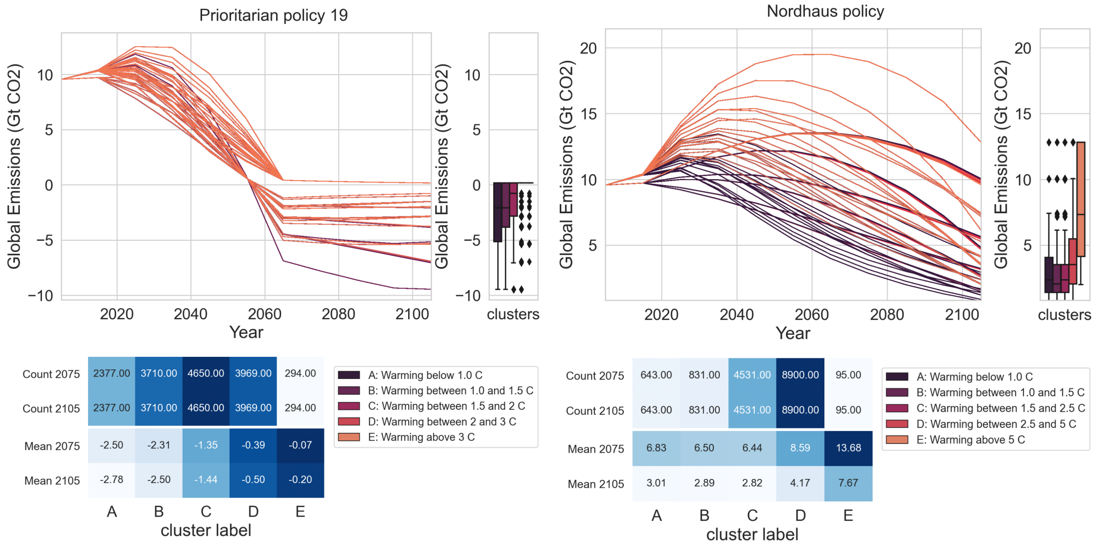


Figure K.11: Prioritarian p19 and Nordhaus policy temperature pathways

Global emission development

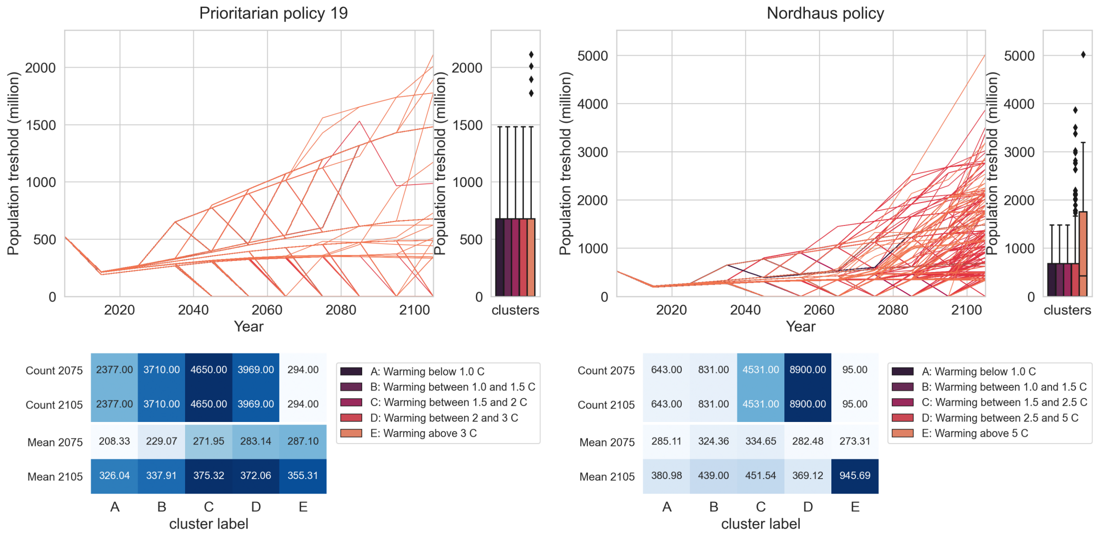


	A	B	C	D	E
Count 2075	2377.00	3710.00	4650.00	3969.00	294.00
Count 2105	2377.00	3710.00	4650.00	3969.00	294.00
Mean 2075	-2.50	-2.31	-1.35	-0.39	-0.07
Mean 2105	-2.78	-2.50	-1.44	-0.50	-0.20

	A	B	C	D	E
Count 2075	643.00	831.00	4531.00	8900.00	95.00
Count 2105	643.00	831.00	4531.00	8900.00	95.00
Mean 2075	6.83	6.50	6.44	8.59	13.68
Mean 2105	3.01	2.89	2.82	4.17	7.67

Figure K.12: Prioritarian p19 and Nordhaus policy emission pathways

Population below threshold



	A	B	C	D	E
Count 2075	2377.00	3710.00	4650.00	3969.00	294.00
Count 2105	2377.00	3710.00	4650.00	3969.00	294.00
Mean 2075	208.33	229.07	271.95	283.14	287.10
Mean 2105	326.04	337.91	375.32	372.06	355.31

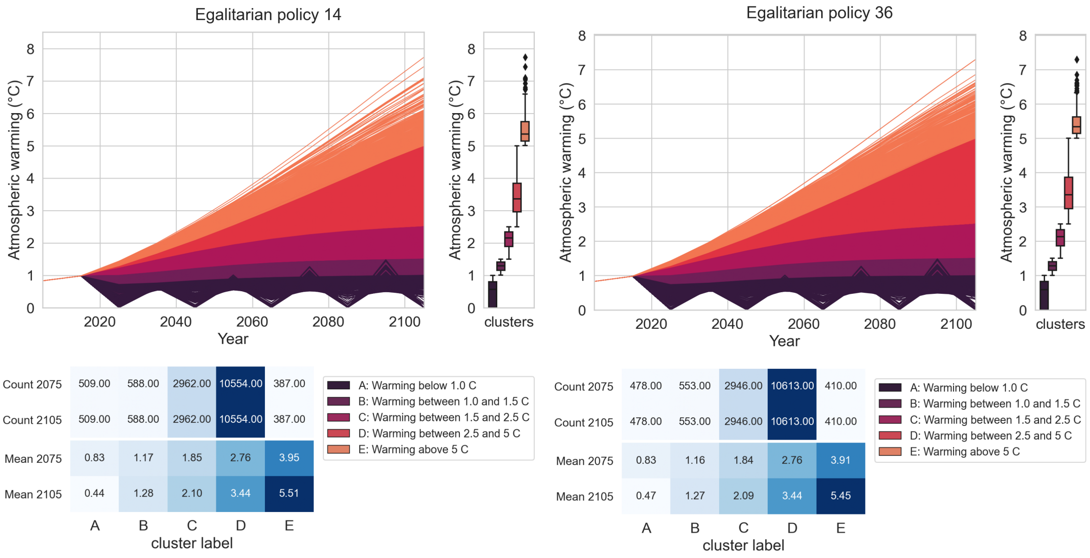
	A	B	C	D	E
Count 2075	643.00	831.00	4531.00	8900.00	95.00
Count 2105	643.00	831.00	4531.00	8900.00	95.00
Mean 2075	285.11	324.36	334.65	282.48	273.31
Mean 2105	380.98	439.00	451.54	369.12	945.69

Figure K.13: Prioritarian p19 and Nordhaus policy population below treshold

Egalitarian comparison policy 42 & policy 14

This section shows clustering plots of two Egalitarian policies. Namely the fast abatement policy 42 and slow abatement policy 14. Policy 42 is the most robust generated Egalitarian policy of this analysis.

Atmospheric warming development

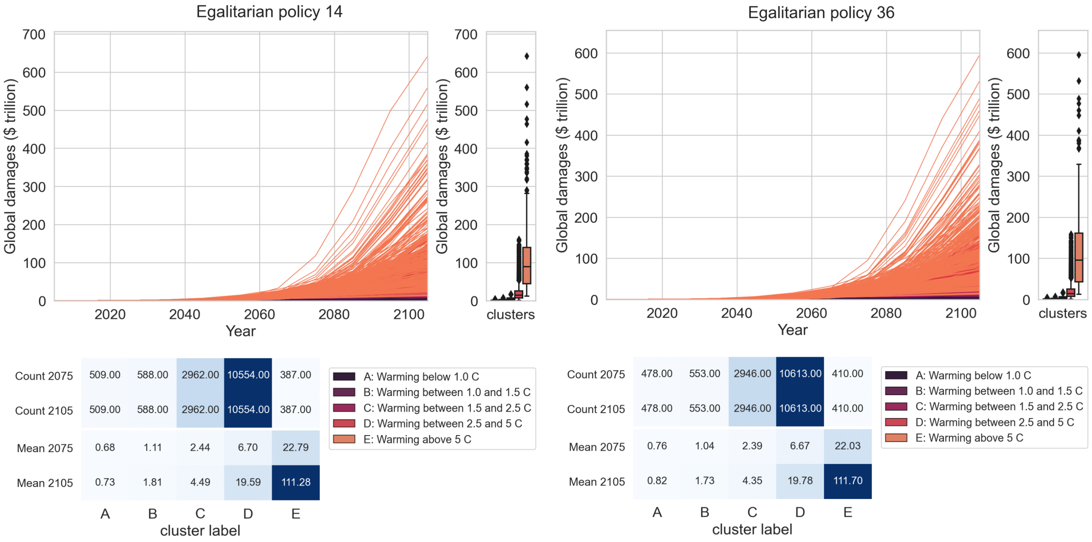


	A	B	C	D	E
Count 2075	509.00	588.00	2962.00	10554.00	387.00
Count 2105	509.00	588.00	2962.00	10554.00	387.00
Mean 2075	0.83	1.17	1.85	2.76	3.95
Mean 2105	0.44	1.28	2.10	3.44	5.51

	A	B	C	D	E
Count 2075	478.00	553.00	2946.00	10613.00	410.00
Count 2105	478.00	553.00	2946.00	10613.00	410.00
Mean 2075	0.83	1.16	1.84	2.76	3.91
Mean 2105	0.47	1.27	2.09	3.44	5.45

Figure K.14: Egalitarian p14 and p42 atmospheric warming development

Global damages

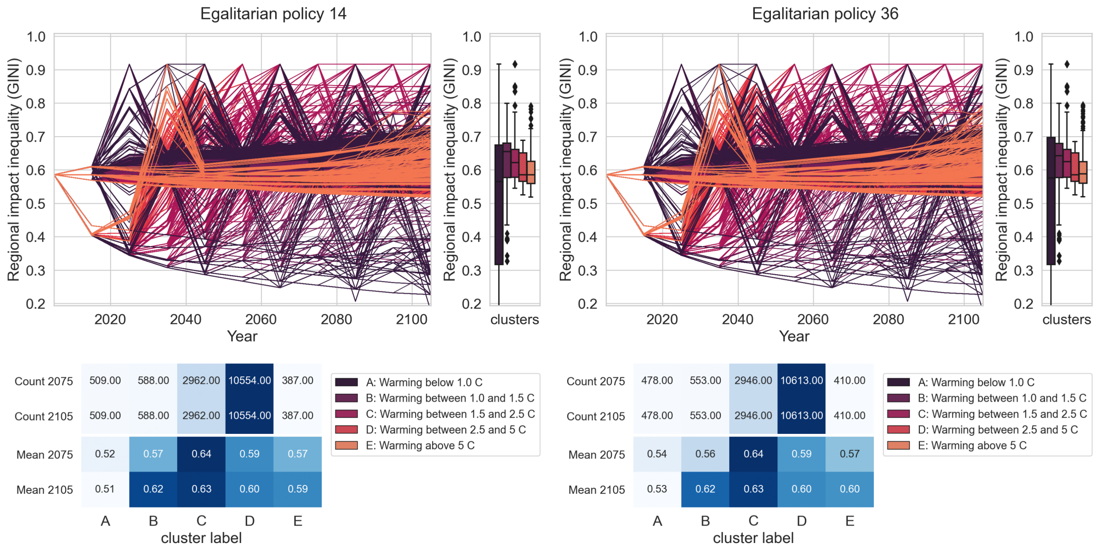


	A	B	C	D	E
Count 2075	509.00	588.00	2962.00	10554.00	387.00
Count 2105	509.00	588.00	2962.00	10554.00	387.00
Mean 2075	0.68	1.11	2.44	6.70	22.79
Mean 2105	0.73	1.81	4.49	19.59	111.28

	A	B	C	D	E
Count 2075	478.00	553.00	2946.00	10613.00	410.00
Count 2105	478.00	553.00	2946.00	10613.00	410.00
Mean 2075	0.76	1.04	2.39	6.67	22.03
Mean 2105	0.82	1.73	4.35	19.78	111.70

Figure K.15: Egalitarian p14 and p42 impact GINI global damages

Regional impact inequality development



Egalitarian policy 14

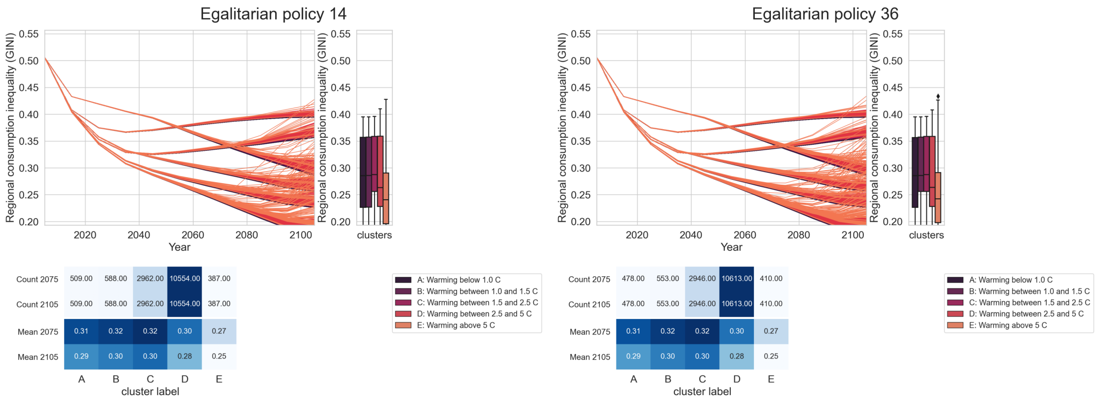
	A	B	C	D	E
Count 2075	509.00	588.00	2962.00	10554.00	387.00
Count 2105	509.00	588.00	2962.00	10554.00	387.00
Mean 2075	0.52	0.57	0.64	0.59	0.57
Mean 2105	0.51	0.62	0.63	0.60	0.59

Egalitarian policy 36

	A	B	C	D	E
Count 2075	478.00	553.00	2946.00	10613.00	410.00
Count 2105	478.00	553.00	2946.00	10613.00	410.00
Mean 2075	0.54	0.56	0.64	0.59	0.57
Mean 2105	0.53	0.62	0.63	0.60	0.60

Figure K.16: Egalitarian p14 and p42 impact GINI

Regional consumption inequality development



Egalitarian policy 14

	A	B	C	D	E
Count 2075	509.00	588.00	2962.00	10554.00	387.00
Count 2105	509.00	588.00	2962.00	10554.00	387.00
Mean 2075	0.31	0.32	0.32	0.30	0.27
Mean 2105	0.29	0.30	0.30	0.28	0.25

Egalitarian policy 36

	A	B	C	D	E
Count 2075	478.00	553.00	2946.00	10613.00	410.00
Count 2105	478.00	553.00	2946.00	10613.00	410.00
Mean 2075	0.31	0.32	0.32	0.30	0.27
Mean 2105	0.29	0.30	0.30	0.28	0.25

Figure K.17: Egalitarian p14 and p42 consumption GINI

L INTERGENERATIONAL TRADEOFFS

Prioritarian tradeoffs

Short term worst-off consumption tradeoffs

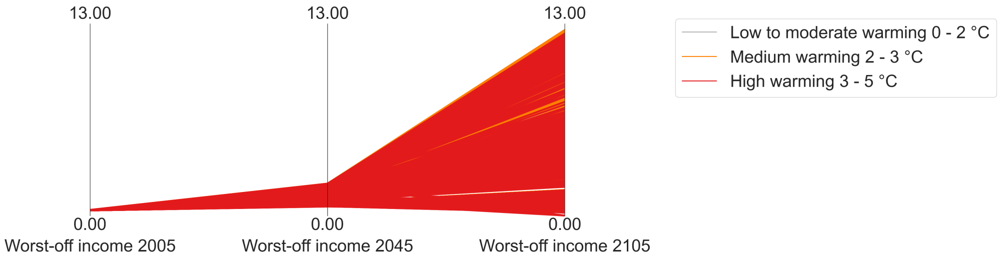


Figure L.1: Short term tradeoffs worst-off income class under Prioritarian policy 19

Long term term worst-off consumption tradeoffs

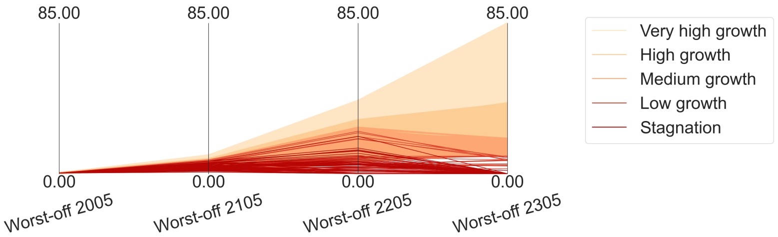


Figure L.2: Long term tradeoffs worst-off income class under Prioritarian policy 19

Short term worst-off relative impact tradeoffs

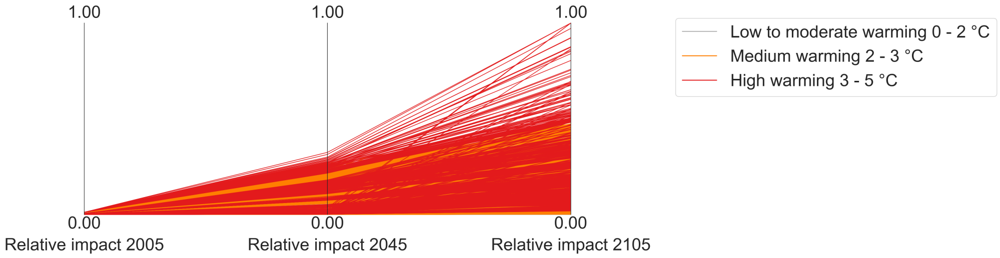


Figure L.3: Short term tradeoffs relative climate impact under Prioritarian policy 19

Long term term worst-off relative impact tradeoffs

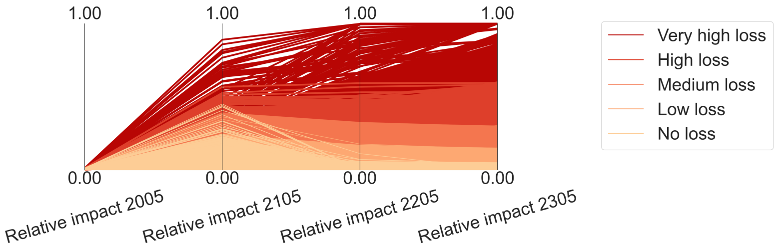


Figure L.4: Long term tradeoffs relative climate impact under Prioritarian policy 19

Egalitarian tradeoffs

Long term trade off inequality in consumption between regions

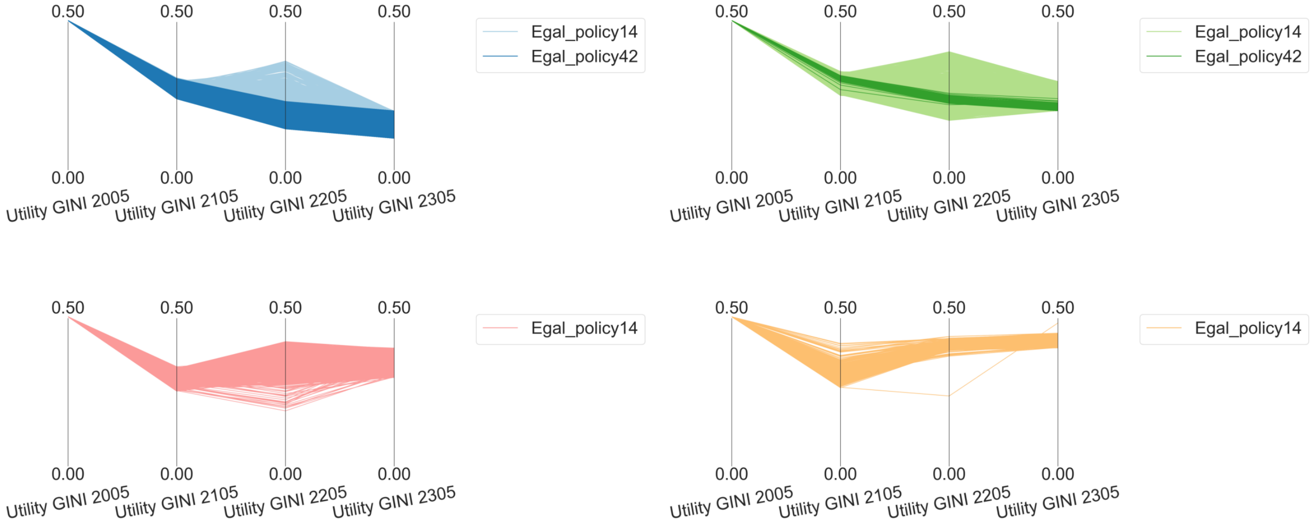


Figure L.5: Long term tradeoffs spatial consumption inequality Egalitarian policy 14 and 42

Long term trade-off inequality in impact between regions

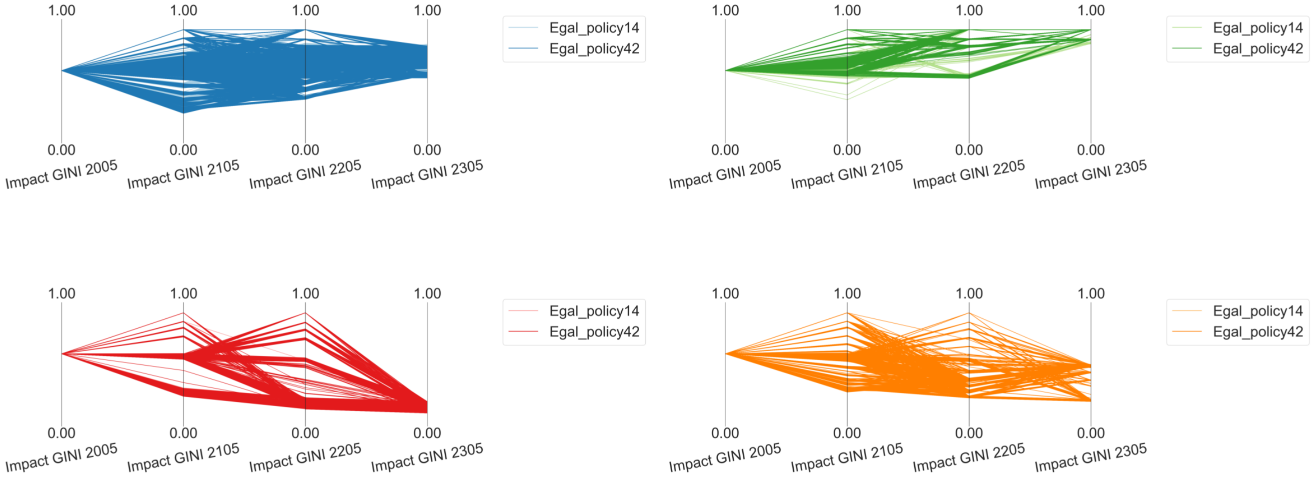


Figure L.6: Long term tradeoffs spatial impact inequality Egalitarian policy 14 and 42

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