Can the share be fair?

A study on the cost-benefit analysis of the redistribution of mitigation costs burden sharing regimes

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Summary

Mitigation of climate change is the biggest challenge of the 21st century. The Paris Agreement set 2ºC as the threshold not to cross. Intergraded Assessment Models have made estimations of the costs associated to climate change as well as those of mitigation. Considerable investments will have to be made to prevent extreme consequences and further destabilise our climate system. Most recent estimates have established 1,8ºC as the cost optimal temperature. The costs associated represent a global budget for mitigation. A fair mitigation of climate change where emitters are either held responsible through strong reduction as well as contribution to mitigation costs for regions with less means needs to be achieved. This research examined the effects of various burden sharing regimes on the distribution of mitigation costs and allowances. By looking at GDP per capita, historical emission, population shares and setting aims of emission convergence, this study examines different approaches to fairness. Whilst also confirming the importance of mitigation to minimise the costs of climate change, the cost benefit ratios calculated indicate the benefits of implementing these regimes as they can benefit regions from the global south by either providing them with higher allowances or/ and financing for mitigation. Principles of fairness need to be agreed upon by the international community to implement effective mechanisms for emission trading and financing of mitigation especially as the costs of adaptation still need to be included in research. The results of cost-benefit models need to be seen as an opportunity for policymakers to make choices to benefit all.

1.Introduction

The continuous increase of carbon emissions due to human activity is affecting ecosystems all over the planet as well as human societies (Dietz et al., 2021). Amongst the biggest consequences is the increase of temperature that leads to sea level rise, extreme weather events and potential losses of agricultural production which all come with economic costs that will keep increasing if no mitigation measures are put into place (Estrada & Botzen, 2021; Schinko et al., 2020).

This increase in emissions is linked to the development of economies that are mainly responsible for the warming of the planet such as Europe and the United States of America during the industrial evolution up till today (Hegerl et al., 2019) . In contrast, countries that developed later such as China, have lower historical emissions but have now become among the biggest emitters of greenhouse gases (GHG). Climate change will affect regions of the world unevenly where areas with low historical or current emissions will be hit hardest (Van Houtan et al., 2021). Events such as droughts and floodings will particularly take a toll on less economically developed region, as they face greater challenge to finance adaptation.

Whilst there is an understanding of a shared responsibility to reduce the emissions to fight climate change, the question of who will pay and who is to reduce their emissions remains debated. Policies related to the mitigation and adaptation of climate change are often presented as costly and not worth to be invested in or hindering economic development (Shishlov & Censkowsky, 2022). Yet the cost of inaction has been calculated as even greater. Furthermore, the attempts in international climate governance to financially support countries at risk have put in place a complicated system which has not been successful in establishing flows that provide the necessary support nor has there been established on a quantitative basis to what amount these financial means should be provided (Ringius et al., 2002). Establishing this is crucial in determining in what manner costs can be allocated in the best way to mitigate climate change in the most economically beneficial way.

Models to determine the costs of climate change have been developed to advise policy makers and present the reality that continuous increase of emissions will lead to economic damages and losses (IPCC, 2022). The shared socioeconomic pathways (SSPs) presented in the IPCC reports presents different possible futures that can occur considering population growth, economic and technological development as well as measures taken to mitigate and adapt to climate change. They are associated with the representative concentration pathways (RCPs) which focus on the emissions of GHG. Each level of emissions is coupled with the associated radiative forcing which can be translated to a certain increase in temperature.

To determine the impacts on an economic level other models were created to couple SSPs and radiative forcing under damages then quantified economically (Weyant, 2017). The estimation of costs of climate mitigation policies as well as the costs of damages have allowed researchers to explore the financial advantages as well as disadvantages that come with investing in climate mitigation or the possible costs that can be caused if investments are made later.

One of the main economic metrics to evaluate the impacts of climate change is the social costs of carbon (SSC) first determined in the United States on demand of the government (Kikstra et al., 2021). It represents the costs that are equivalent when emitting an additional ton of CO2. It is the cornerstone on which research on the costs of climate change has been built and modelled mainly after the use of it by William Nordhaus and the introduction of the one of the first costs-benefit models, the Dynamic Integrated Climate-Economy model (DICE) (Nordhaus & Boyer, 1999). Through this a first look into weighing the costs of climate mitigation against those of the damages caused by it and thus the benefits of investing in mitigation policies.

Although models have examined this through a global lens and regional lens, the costs of benefits against the costs of damages and have only been performed at a global scale (van der Wijst et al., 2023). A study conducted by Van der Wijst et al. (2023) determined that the most cost-efficient scenario would be to limit temperature increase to around 1,8 ºC. After establishing the link between temperature and carbon budget, questions of how to distribute the costs of emission reduction between the regions of the world in a fair way have been addressed but the weighing between the benefits and the costs remains answered.

Moreover, essential ethical questions regarding equity in damages and costs are raised when it comes to determining which countries or regions carry the responsibility for the sharpest reduction in emissions as well as for the payment of mitigation and adaptation costs for the countries that have not contributed to the current emission level but are the at the forefront of feeling the effects of climate change (Davidson, 2021). Hence, it is important to explore what the costs for each region will be as well as the benefits of investing in climate mitigation. Furthermore, this can help determine where the reduction in emission will be the least costly. The research presented in this report explores the regional differences in costs of mitigation and damage by answering the following research question and sub-questions.

How can the allocation of estimated costs for climate change mitigation be distributed among regions to ensure an equitable sharing of burdens, whilst preserving economic benefits?

- What are the regional differences in mitigation and damage costs?
- How can the use of burden sharing regimes alter the regional differences in mitigation costs and allowances?

- What ethical and practical considerations relate to the implementation of burden sharing regimes both on a societal level as well as in research?

First this report will introduce all the theoretical concepts that will be used and addressed in the research, including an introduction to integrated assessment models, burden sharing regimes, research that has so far been conducted on cost benefit analysis of climate mitigation. The methods will be presented including all the calculations that have been used to determine the new share of mitigation costs and allowances according to each burden sharing regime that has been selected to be included in this study. The results will then be presented and discussed to answer the different research questions. The study will explore how certain burden sharing regimes can have a considerable influence on a country whilst other regions would remain moderately affected if changes in the distribution of allowances and mitigation costs would be applied following the ones presented by the various BSRs.

This research will contribute to a large body of literature on the modelling of cost-benefit analysis of climate change mitigation and be highly relevant for policy makers particularly in the areas of international climate financing and mitigation that can have impacts on previously set agreements. The results can provide insights in how climate mitigation can be tackled as how allowances for emissions can be distributed whilst remaining under the 2ºC. This can then be translated into concrete measures such as different financial mechanisms for the implementation of mitigation measures and reviews of current emission trading practices such as cap-and-trade systems, carbon taxes and permits and Nationally Determined Contributions in the Paris Agreement (Bhatti et al., 2010; Glanemann et al., 2020).

2.Theoretical framework

This chapter will introduce the main concepts related to the research, including an introduction to integrated assessment models, the MIMOSA model, as well as the various burden sharing regimes that will provide the data for the research. Finally, the last section will look into previously conducted research on the topic of equity in fairness in integrated assessment modelling.

2.1 Integrated Assessment models

Integrated Assessment Models (IAMS), were developed in an attempt to quantify the impacts of the interactions of various systems, natural and social ones, focusing on future climate change projections. They are aimed at informing policy makers about potential impacts of mitigations measures. 2 types of IAM are distinguished by Weyant (2017), detailed process (DP) and the cost benefit ones (CB). The first type focuses on the representation and interactions between the earth system and humans to determine pathways to achieve a certain policy (Braunreiter et al. 2021). DPs take aways are that mitigation costs divert greatly in their range, present general principles to reduce mitigation costs, yet they do emphasise that many uncertainties remain. As the research uses a CB model for the analysis, more detail will be given about the specifics of this model.

CB models combine the damages on an economic perspective to determine the optimal mitigation policies from an economic perspective. CB models attempt to determine the optimal emissions trajectory by associating a price for the emissions themselves. They evaluate the consequences of lack of implementation of mitigation policies or policies that are not sufficient. The first CB model was introduced by William Nordhaus (1999), the model evaluated how emissions and temperature changes were impacted by climate policies. For this, emissions are matched to GHG gas concentrations and then temperature. The economic aspect comes in when the temperature is translated to, for example, a loss in GDP. By doing this, models can determine the costs of climate change associated to different temperature change and hence the avoided costs in lower temperature scenarios. This is also related to the US development of the social cost of carbon, where the damage related to the emission of one ton of carbon is quantified. In these models determining mitigation costs as well as the economic contribution in GDP in order to implement mitigation play a key role. Optimal and non-optimal policies differ in the difference between the cost of a ton of carbon emissions against the damage caused by the ton. The closer they are to each other the more welfare is maximised

Damage functions are used to quantify the damage caused by climate change, the input data is where the assumptions and considerations of the model play the biggest role (Burke et al., 2015; van der Wijst et al., 2023). Factors such as agriculture and forestry as well as energy use and sea level rise are considered.

Overall IAMs differ in their results due to different characteristics and their parameters, as explained by Krey (2014), system boundaries, the spatial and temporal dimensions and mathematical concepts differ for each model, despite having some overlap between certain models the results will always differ due to the assumptions made or the research questions that is to be answered. The temporal dimension as well as spatial resolution contribute to different result when determining carbon budgets and emission allowances. The chosen scale, grouping of countries per region, the time frame used for the model as well as the level of detail of the model are all elements of the temporal dimension and spatial resolution influencing the obtained results. The resolution of the models plays a major role in the computing of it, the more detailed and equations that need to be considered the longer the model will need to run and the more power it will need. Integration of regional, national, and global focuses remain challenging to be integrated contributing to wider margins of error. Finally, another element subject to variance is the role of technology and its development, as models using a faster developing technology as well as increased efficiency will provide different result than a model relying less on technology or estimating a slower development process.

2.1.1. MIMOSA

This research will make use of the MIMOSA model, developed by van der Wijst et al. (2021). The model looks at the most optimal way to achieve a certain climate target, the economic value of climate change induced damages is compared to the cost of implementing climate policies. It aims at balancing those two factors to determine which emission target is best to achieve to limit the damage at the lowest costs possible.

In the case of cost benefit scenarios, where temperature and carbon budget are not directly addressed, the carbon price was set by balancing the mitigation and damage costs which is then applied to find the corresponding temperature which similarly to the cost optimal runs aims at a 2ºC or lower temperature, the results were varying depending on the discounting rate and was overall yielding optimal temperatures between 1,1ºC and 3,5ºC.Under new conditions and with the use of the COACCH damage functions other cost optimal scenarios were determined. The damage functions were established under the COACCH project, an EU financed project contributing to the improvement and availability of data related to climate change impacts, their costs and policy for the use of communities on a European scale. The damage functions are based on the modelling of physical impacts then translated into economic ones (Van der Wijst et al., 2021). The parametrisation of the damage functions is derived from literature surveys, economic estimations, or expert opinion. The losses are translated from a quantification of associated consequences of climate change such as sea level rise, or temperature increase. They were then aggregated, and the cost of damages was included to put them into perspective with the ones of mitigation. The data used to answer the research questions was calculated using the COACCH damage functions implemented in the MIMOSA model (van der Wijst et al., 2023). The study of van der Wijst et al. (2023) estimates an optimal temperature of 1,8ºC as cost-optimal on a global scale, however the study does not consider the differences between regions and the extent to which each of them is expected to contribute through reductions of emissions or financial support to other regions. To answer the research questions, the model will first be adapted to calculate regional cost-benefit ratios, subsequently burden sharing regimes will be included in the model.

2.1.2 Current literature on cost-optimal temperature

The literature on the cost-optimal temperature developed over the past decades following the development of the cost-benefit models (Kikstra & Waidelich, 2023). The first studies using the DICE model to calculate the cost for the US of remaining under 2ºC came with a conclusion of higher induced costs of mitigation than the economic damage/ avoided damage (Glaneman et al. 2020). These results came out before a revaluation of the costs of damages was done and are considered to underestimate the costs of climate change. Glaneman et al (2020), using the Burke equations (source) and adapted the model to preserve the growth aspect of the model, in their work they consider that mitigation efforts are actively pursued in order to satisfy global welfare. In contrast with a BAU scenario, their results find that a 2ºC target is the optimal cost-benefit temperature rather than the 2,9ºC previously found with the DICE-2013 model. The model was also used to test different climate sensitivities where in each case the mitigation efforts contributed to are reduction in damages. Kikstra & Waidelich (2023) use their work along with other models showing how the changes in modelling over the past decades have resulted in decreasing cost-optimal temperatures. Compilling 14 different studies (including van der Wijst et al (2023), Glaneman et al. (2020)) they establish a decreasing trend in cost optimal temperatures parallel to the establishment of new agreements (Cancun, Paris). All studies indicate avoided damages ranging between 1.5-3.9 times higher than the costs of mitigation. Hoegh-Guldenberg et al. (2019) study the cost benefits of investments up till 2200 with investments in the energy sector till 2050 concluding the necessity of those investments to minimise the costs which with technological development would lead to an increase in temperature between 3 ºC and 4ºC. The studies have thus looked at the global temperature and the study of Gazotti et al. (2021), looked at potential regional distribution however most CB models used in their studies have a resolution of 6 to 16 regions which is too low to represent a realistic economic growth and wealth fragmentation.

Gazotti et al. (2021) take a further step as Glaneman et al (2021) do not consider regional heterogeneity by trying to include regional economic heterogeneity. By adapting the DICE model to 50 regions and including inequality aversion. With the RICE50+ model, they present that if countries were to react to climate change for their own national interest the emissions would lead to a 3C increase with carbon neutrality achieved by mid-century. More cooperative scenarios lead to a 2ºC increase similarly to the results of Glanemann et al. (2023) They also conclude that the current NDCs are closer to non-cooperative ranges than where India has an NDC 10% lower than the optimal self-interest one. They conclude the heterogeneity in the distribution of mitigation costs across the world with more than 20% of GDP loss for certain regions/countries). They do investigate equality settings for their model which alter the result exploring the consequences on income decrease to conclude on the 2ºC setting as being cost optimal restating the importance of international cooperation to achieve the goal.

Hänsel et al. (2020) similarly update the DICE model, establish the necessity for more stringent mitigation measures but the economic feasibility implied with staying within the Paris Agreement. Yet for this to be achieved they emphasises the necessity of a sharp increase of the carbon price along with a fast decarbonisation. Numerous studies have thus concluded the necessity of reaching for temperature goals around and mainly under 2ºC and it being the most cost effective one.

2.2 Burden sharing regimes

The different burden sharing regimes will be introduced to give an overview of their differences and their perspective on equity and how this could affect the result.

2.2.1 Grandfathering

The grandfathering approach affects the current distribution of regional allowances the least, it is based on the status quo of emissions that are in place, allowing the biggest polluters to retain their emission allowances (Knight, 2012). The equity is thus determined by sovereignty, as per it is often not considered as an equity scheme as it denies the right to development of regions with lower emissions, it is nonetheless included in this study to be compared with other burden sharing regimes and the case where no burden sharing regime would be implemented. The distribution of emissions in the Kyoto protocol was based on grandfathering principles due to its focus on developed countries/ Annex 1 for the limitations of emissions granting countries such as 110% of 1990 emissions for Australia.

2.2.2 Immediate per capita convergence

This regime places a higher emphasis on equality between humans where goods are considered to be equal in access to all (Sargl et al. 2016). It takes the population of a country and GDP per capita into account when determining the emission allowances. The emissions converge towards the same per capita emissions for all individuals. As it does consider historical emissions It follows the principles of the common but differentiated responsibility when additional mechanisms of financing are put into place. It however considers both developing countries and developed countries to be part of the emissions reduction’s efforts.

2.2.3 Per capita convergence

This regime combines the GF and IEPC regimes, the allowances tend to be smaller than the ones for the ECPC. The emission allowance converge overtime towards equal per capita at a set time, after which the allocation is dependent on the population share (van den Berg et al., 2020).

2.2.4 Ability to Pay

The regime considers the burden to be the responsibility of the ones able to pay for the mitigation costs, regardless of historical or current emissions. This is thus open to interpretation as it can be implemented according to a country's GDP or GDP per capita (Davidson 2021). The responsibility for reduction is thus country dependent unless the regime is applied cooperatively and globally in which case support for less wealthy countries can be organised. This regime also implies that countries which have tried to justify their rights to emit and develop such as China would have to make the same or bigger reduction efforts as countries that have historically emitted and contributed to climate change to a greater scale (Anderson et al. 2017).

2.2.5 Greenhouse development rights

This regime aims at redistributing the emission depending on the capability of region to finance climate mitigation and the responsibility they have due to past emissions. This approach was designed by Baer et al (2014), the theory takes a different approach than the other burden sharing regimes addressed in this research as it calculates its own index and quantifies responsibility and capability. GDP per capita is included in the index but is not the main criteria as a development thresholds is determined by the authors that links back to the capability component of the index. The authors also based their ideas on the principles of common but differentiated responsibility prescribed in the UNFCC. The responsibility is not only seen on a country level but an individual one as a higher income is correlated with bigger per capita emissions. Hence individuals with higher incomes in all countries carry more responsibility for the reduction of emissions than lower income ones.

2.3 Emissions and equity in current research

Research has already looked into the cost-benefit feasibility of remaining under 2ºC. Using the DICE model Glanemann et al. (2020), examine the cost benefit aspect of the climate agreement estimating that 2ºC under the conditions presented in the Paris Agreement would achieve a cost optimal results from a global perspective. Yet similarly to the other models the regional aspect is not included. In Pan et al. (2023) where both equity and efficiency are addressed through several burden sharing regimes including the ones discussed in this research were evaluated with the potential trade-offs of safety in light of considered dangerous emissions. Using the carbon Gini coefficient, they investigate the inequalities in emission distributions. Their research reflects on the current distribution of emissions, through the comparison with global abatement costs. They determine where equity and efficiency cross each other showing room to improve the equity efficiency allocation. The study also underlines the importance of support to help countries that are the furthest from the frontier the possibilities to invest more to help the global targets for the reduction, mainly when comparing the mitigation efforts that need to be achieved when considering a 1,5C scenario rather than a 2ºC one. In other words, achieving the national allocation does not help improving equity and efficiency, hence the need to consider reallocation.

Furthermore, as hypothesized in this research, investments and financial flows towards regions where the return for investment in emission reduction is higher contributes to the lowering of the overall marginal costs. Van den Berg et al. (2020) compare various burden sharing regimes on national allowances as well as pathways based on carbon budgets by examining the influence of changing certain parameters such as historical emissions, changes in the distribution between capability and responsibility. The study concludes on the disparities between the different burden sharing approaches on the allowances and pathways. Whilst allocations are not meant to return a negative number, negative allocations were given for bigger polluters under certain parameters of burden sharing regimes.

Another study by Pachauri et al (2022) investigates the financial flows that need to occur in order to achieve climate targets, looking into responsibility and capability it explores the finances invested into mitigation as well as north south flows concluding the importance of increasing financial contributions to developing countries in order to achieve targets set by the Paris Agreement. There is increasing understanding that the major emitters and wealthiest countries will have to contribute significantly in their reduction goals as well as the financing of mitigation to achieve the goals set in the Paris Agreement and the underlying mechanisms that need to be put in place. Those studies have not investigated the results of specific cost benefit analysis models which enable to compare the cost of mitigation effort but also the economically avoided damages and compare them, this study will allow a first glance into the possibilities to fill those gaps

3. Methodology

This chapter will introduce the methodology used to answer the different questions presented previously. As the study builds upon previous work conducted with the MIMOSA model, the runs of the model will provide the data that will be used in the different experiments conducted in this research. The abbreviations mentioned in multiple equations are presented in table 1. abbreviations specific to one equation are mentioned under it.

Table 1: Abbreviations used in the equations

Abbreviation	**Full form**
e	euler's number
t	time steps (representing each year)
R	social discount rate (3%) pure rate of time preference + economic growth
r	regions
bsr	burden sharing regime
a	regional allowance
E	global emissions
A	global emission allowance
i	region
pop	regional population
POP	global population
BAU	global baseline emissions
gdp	regional gdp
GDP	global gdp

3.1 The Cost Benefit ratios of Climate change mitigation

The MIMOMA model determined 1,8C as the cost optimal temperature to limit dangerous warming whilst optimising investment in mitigation. The global and regional outputs of the scenario will be used for the research. Alike other IAMs, the regional distribution was done without considerations for equality, responsibility and only in a least-cost manner.

Regional estimates of damage and mitigation costs are thus established under which all regions contribute to reaching 1,8 C. To calculate the benefits a region will get out of investing in mitigation, it is crucial to estimate how much damage will be avoided by implementing mitigation measures, these are the benefits a region will obtain.

The model runs from 2020 to 2150, with 5-year intervals marking each time step used to track the changes in damage and mitigation costs as well as the regional allowance. The resulting data will be synthesized by calculating the Net Present Value (NPV). The NPV considers variation over time of the costs of mitigation as well as the changes in the costs caused by climate change (damage costs of climate change). As the purpose is to make a cost benefit analysis, the benefits related to the implementation of climate change mitigation are determined in the NPV calculated as presented in equation 1:

$$(1) \quad NPVBenefits = \sum_t e^{-Rt} \, Avoided\ Damages_t$$

Where:

$Avoided\ Damages$ = Damage costs baseline scenario- damage costs mitigation scenario

To calculate the Cost Benefit Ratio the avoided damages, need to be compared with the mitigation costs. The NPV of the costs of mitigation that are needed to achieve the 1,8 ºC target are subsequently calculated. This can in turn be used to implement carbon taxes on a larger scale. The NPV of mitigation costs is calculated as follows:

$$(2)\quad NPVmitigation = \sum_t e^{-Rt}\, costsM_t$$

Where:

$costs\ M_t$ = damage costs at a time step t

A social discount rate of 3% is applied as a consideration for changing valuation of costs and economic development. As explained in van der Wijst et al. (2023), a 3% discount rate stems from a pure rate of time preference of 1% a year combined with the assumption of an average economic growth of 2% a year. The pure rate of time is an indication of the valuation between the present and the future, or how important the future is valued, here what the investments made in present time will be valued monetarily in the future, thus the future being valued less than the present (Drupp et al., 2018) The social discount rate is taken from previously conducted studies, including the work of van der Wijst et al. (2023) presented as a medium discount rate yielding better results in line with the Paris Agreement targets in the case of the mimosa model.

The calculation of the NPV allows to determine the benefits of investing in climate change mitigation when it is compared to the cost of avoided damages (or what is saved by investing in climate mitigation). The comparison is done by calculating the Cost Benefit Ratio as presented below.

$$(3)\quad CBR = \frac{NPV\ Benefits}{NPV\ Mitigation}$$

The CBR will be calculated for every region, showing which regions have greater benefits in comparison to the costs of mitigation. Hence this will also indicate which regions can invest more as their CBR will be greater and can expect to get more out of their investment.

After obtaining the results of the CBR, burden sharing regimes will be implemented to determine the consequences for the different regions in terms of shifts in contribution to mitigation. This will be used to answer the second sub question.

3.2 Splitting the pie of climate mitigation costs

Now that the Cost Benefit Ratio has been determined, the question remains of the responsibility of contribution to the investment and reduction of climate change. The mitigation costs per region will be adapted per time step, each region will bear a percentage of the costs that need to be carried globally to achieve the necessary target set by the initial scenario of achieving 1,8 ºC.

First the total costs of mitigation (global costs) will be calculated as the sum of the cost for every time step.

$$(4)\ \ Global\ costs = \ \textstyle\sum_r \ Mitigation\ costs_{rt}$$

Then, the percentage of what each region will contribute to the climate mitigation investment will be determined according to each burden sharing regime that will be analysed. The burden sharing regimes were previously introduced theoretically in section 2.2 Each of them will help determine the share each region should contribute to the mitigation of climate change by redistributing emission allowances and the corresponding mitigation costs.

To determine the share of each region the work is based on the paper by van der Berg et al. (2020). The equations presented allow for the calculation of the new emissions shares, depending on the variables that are accounted for by each burden sharing regime. Thus, every region receives a new emission allowance for each time step. This is then compared with the emissions projected in the 1,8 scenario by calculating the new costs for each region and comparing them with the mitigation costs of the baseline scenarios as previously presented with the NPV and the CBR.

First the Emission allowance gap is calculated as follows:

$$(5)\quad EAG = Mitigation\ emissions - regional\ allowance_{bsr}$$

This will give the difference between the 1,8 scenario where the allowances are not redistributed and the emissions under the chosen burden sharing regime. Then an emission reduction is calculated to determine how the allowance of a certain burden sharing regime compares to the baseline scenario. The change in emissions (EAG) is then translated to monetary terms by multiplying with the average global price of mitigation as:

$$(6)\quad \mathrm{GER} = mitigation_{baseline} - regional\ allowance_{bsr}$$

To determine the changes in costs between the 1,8 scenario and each burden sharing regime the Mitigation Cost Gap is determined.

$$(7)\quad MCG = EAG.\frac{TMC}{GER}$$

TMC= total mitigation costs

GER= total global emission reduction

The MCG will then allow to calculate the new mitigation costs, as it is the new difference between the mitigation costs of a chosen burden sharing regime and the costs in the 1,8 C scenario.

$$(8) \quad Mitigation\ costs_{bsr} = Mitigation\ costs - MCG_{bsr}$$

The costs for each region are thus presented under the new distribution for the chosen burden sharing regime. A negative value will indicate that the region will have to finance mitigation efforts elsewhere whilst a positive value will indicate the region is to receive financial support. More than determining the shares it is crucial to determine whether these methods for splitting the costs would still result in a positive outcome for every region. Hence, after redistributing the emission shares and determining which countries will have to pay the costs for others, the NPVs and CBRs were calculated.

$$(9) \quad NPV_{bsr} = \sum_t e^{-Rt}\, costsM_{t,bsr}$$

$$(10) \qquad CBR_{bsr} = \frac{NPV\ Benefits}{NPV_{bsr}}$$

The comparison made allows to determine what burden sharing regime would still provide the biggest benefits for all at a minimum costs for better mitigation.

3.2.1 Grandfathering

This regime assumes the same chair of emissions at each time step, thus if a country is allocated 10% of the share in 2020, in 2150 it will retain 10% of the global carbon budget. The regional allocation is calculated as follows

$$(11) \qquad a_{i,t}GF = \frac{e_{i,t=2010}}{E_{t=2010}}.A_t$$

Where:

e= regional emissions

3.2.2 Immediate per Capita Convergence

$$(12) \qquad a_t IEPC = \frac{pop_t}{POP_t}.A_t$$

3.2.3 Ability to Pay

Step 1: reduction before correction

$$(13) \qquad ra_{i,t}AP = \sqrt[3]{\frac{gdp_{i,t}}{pop_{i,t}} / \frac{GDP_t}{POP_t}} \cdot \frac{BAU_t - A_t}{BAU_t} \cdot bau_t$$

Step 2: determining the correction factor:

$$(14) \qquad corr_{ra_t} = \frac{\sum_i^N ra_{i,t}AP}{BAU_t - A_t}$$

Step 3: Allowances

$$(15) \qquad a_{i,t}AP = bau_{i,t} - \frac{ra_{i,t}AP}{corr\_ra_t}$$

3.2.4 Per Capita Convergence

$$(16) \qquad a_{i,t}PCC = A_t.(MIN\left(\frac{t-2010}{tconv-2010}, 1\right).\frac{pop_{i,t}}{POP_t} + MAX\left(1 - \frac{t-2010}{tconv-2010}, 0\right).\frac{e_{i,t=2010}}{E_{t=2010}}$$

Where:

tconv = the year of convergence

e= regional emissions

3.2.5 Greenhouse development rights

First, the Responsibility and capability index for the years 2020 and 2030 needed to be calculated this was done with the help of the online calculator provided by the climate and equity reference project. The calculator allows to choose the share between the capability and responsibility as well as the chosen year for the accounting of historical emissions. Hence the parameters of the calculator were set to 0,5 split of capability and responsibility. An example of the calculator can be found in Appendix __. The index itself and the methods to quantify responsibility and capability were developed by Kemp-Benedict et al. (2018).

Capacity is reflected by the income of the population, an income threshold of $7500 per capita with the above income being included in the capacity, hence two countries with the same population but where the income is higher will have a greater capability. Responsibility is set similarly where income above the development threshold is considered as contributing to the emissions, here the calculations are cumulative, hence the responsibility of each year adds up to the previous one.

The parameters to calculate the index were set similarly to the one's used by van de Berg et al. (2020), with an equal share of responsibility (0.5) and capability (0.5).Each country obtains an index (percentage of the global RCI, summed up to 1), the countries were then grouped in the regions used in the MIMOSA model. The RCI's were both calculated for 2020 and 2030, the calculator did not offer the possibly to calculate the index beyond 2030.

The RCI was then applied as prescribed by van den Berg et al. (2020) to determine the new regional shares

For t<2030

$$(17) \qquad a_{i,t}GDR = bau_{i,t} - (BAU_t - A_t).rci_{i,t}$$

Where:

rci: responsibility and capability index

For t>2030

$$(18) \quad a_{i,t}GDR = ((\frac{2100-t}{70}).bau_{i,t}) - (BAU_t - A_t).rci_{i,2030} + ((\frac{t-2030}{70}).a_{i,t}AP)$$

In the case of van den Berg et al. a convergence towards the ability to pay after 2030 was assumed and was applied in this study. As the index calculation were per country the results were grouped by regions that are used in the MIMOSA model. As a few countries were not included in either the index calculator or corresponding to one of the regions of the MIMOSA model the RCI had to be slightly corrected to have a total index of 1.

4.Results

This chapter will present the results of the research to answer the different research questions. All the burden sharing regimes are presented as well as the original cost-optimal mitigation scenario. Table 2 presents the grouping of countries of the IMAGE regions used in this study.

Table 2: Grouping of IMAGE regions and their abbreviations

Region	Abbreviation	Countries
Brazil	BRA	Brazil
Canada	CAN	Canada
Central Europe	CEU	Albania, Bosnia Herzegovina, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, The former Yugoslav Republic of Macedonia, Montenegro, Poland, Serbia, Slovakia, Slovenia, Cyprus, Romania, Kosovo
China	CHN	China; China, Hong Kong Special Administrative Region; China, Macao Special Administrative Region; Mongolia; Taiwan
Eastern Africa	EAF	Burundi; Comoros; Djibouti; Eritrea; Ethiopia; Kenya; Madagascar; Mauritius; Réunion; Rwanda; Somalia; Somalia; Sudan; South Sudan; Uganda; Seychelles
India	INDIA	India
Indonesia	INDO	Timor-Leste, Indonesia, Papua New Guinea
Japan	JAP	Japan
Korea	KOR	Democratic People`s Republic of Korea; Republic of Korea
Middle East	ME	Bahrain; Iran (Islamic Republic of); Iraq; Israel; Jordan; Kuwait; Lebanon; Oman; Qatar; Saudi Arabia; Syrian Arab Republic; United Arab Emirates; Yemen
Mexico	MEX	Mexico
Northern Africa	NAF	Algeria; Egypt; Libyan Arab Jamahiriya; Morocco; Tunisia; Western Sahara
Oceania	OCE	American Samoa; Kiribati; Micronesia, Federated States of; Palau; Tonga; Australia; New Zealand; Fiji; French Polynesia; New Caledonia; Samoa; Solomon Islands; Vanuatu
Rest of central America	RCAM	Antigua and Barbuda; Bahamas; Barbados; Belize; Bermuda; Costa Rica; Cuba; Dominican Republic; El Salvador; Guadeloupe; Guatemala; Haiti; Honduras; Jamaica; Martinique; Netherlands Antilles; Nicaragua; Panama; Trinidad and Tobago; Aruba; Dominica; Grenada; Saint Kitts and Nevis; Saint Lucia; Saint Vincent and the Grenadines; Virgin Islands (US); Puerto Rico
Rest of Southern Africa	RSAF	Angola; Botswana; Lesotho; Malawi; Mozambique; Namibia; Swaziland; United Republic of Tanzania; Zambia; Zimbabwe; Mayotte
Rest of Southern America	RSAM	Argentina; Bolivia (Plurinational State of); Chile; Colombia; Ecuador; Guyana; Paraguay; Peru; Suriname; Uruguay; Venezuela (Bolivarian Republic of); French Guiana
Rest of South Asia	RSAS	Afghanistan; Bangladesh; Bhutan; Maldives; Nepal; Pakistan; Sri Lanka
Russia	RUS	Armenia; Azerbaijan; Georgia; Russian Federation

South Africa	SAF	South Africa
South East Asia	SEAS	Cambodia; Lao People`s Democratic Republic; Viet Nam; Guam; Brunei Darussalam; Malaysia; Myanmar; Philippines; Singapore; Thailand
Stan countries	STAN	Kazakhstan; Kyrgyzstan; Tajikistan; Turkmenistan; Uzbekistan
Turkey	TUR	Turkey
Ukraine	UKR	Belarus; Republic of Moldova; Ukraine
United States of America	USA	United States of America
West Africa	WAF	Benin; Burkina Faso; Cameroon; Cape Verde; Central African Republic; Chad; Congo; Democratic Republic of the Congo; Côte d`Ivoire; Gabon; Gambia; Ghana; Guinea; Guinea-Bissau; Liberia; Mali; Mauritania; Niger; Nigeria; Senegal; Sierra Leone; Togo; Equatorial Guinea; Sao Tome and Principe
Western Europe	WEU	Austria; Belgium; Denmark; Greenland; Finland; France; Germany; Greece; Iceland; Ireland; Italy; Luxembourg; Malta; Netherlands; Norway; Portugal; Spain; Sweden; Switzerland; United Kingdom of Great Britain and Northern Ireland

4.1 the costs benefit ratios on a regional level

The CBR indicates the benefit a country yields relative to the costs they make. When the CBR is higher than 1, the region receives higher benefits from investing in climate change mitigation due to the avoided damages than the costs necessary to invest in it. The CBR on a global level until 2100 is 3.673463 and for 2150 reaches 9.554703. The differences between regions are reflected in the CBR for each region for both the period 2020-2100 and 2020-2150.

For the remaining of the 21st century the results show that only the East Africa (EAF) region would be better off if a burden sharing regime would be implemented, in the case of that region the IEPC regime. Meaning all the other 25 regions would be less advantaged and yield less benefits from the application of a BSR. Regions that have a CBR falling under 1 show the associated BSR presents greater disadvantages to them, under the AP regime 5 regions have a CBR< 1, other BSRs have up to 4 regions where the CBR is under 1 as presented in table 3. Another important observation is the difference in CBRs for each region. The EAF cost-benefit varies greatly between the different BSRs, from 10 to almost 40 whilst regions such as Russia (RUS), the Middle East (ME), Ukraine (UKR) and China, including some neighbouring countries (CHN) have slighter difference between them as is shown in figure 1

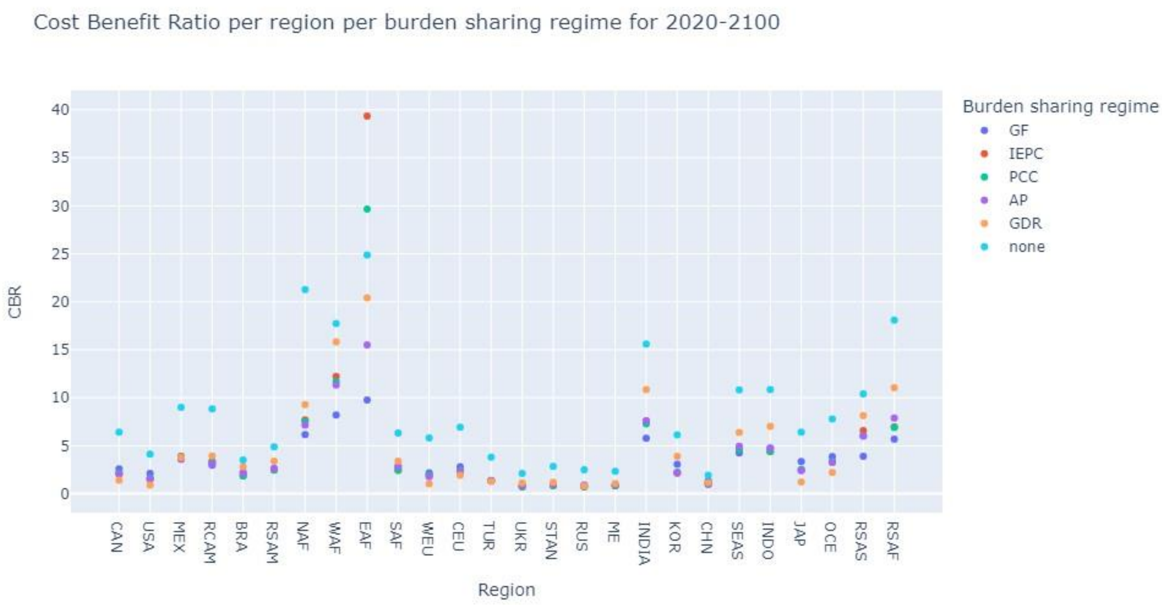

Figure 1: The cost benefit ratio for all 26 image regions for the period from 2020 to 2100: Each burden sharing regime is represented and compared with the CBR when no burden sharing regime is applied.

Table 3: Regions for which the CBR falls under 1 under a certain BSR for up till 2100

BSR	Region
GF	UKR, STAN, RUS, ME
IEPC	UKR, STAN, RUS, ME, CHN
PCC	UKR, STAN,RUS,ME
AP	UKR, STAN,RUS,ME,CHN
GDR	GDR,USA,RUS

The results of the CBR indicate significant differences when only looking to the end of the century or expanding the results until 2150 (figure 1). Although the MIMOSA model has greater uncertainties in the results for the period after 2100, it is relevant to look at the trends and how they differ compared to 2100.

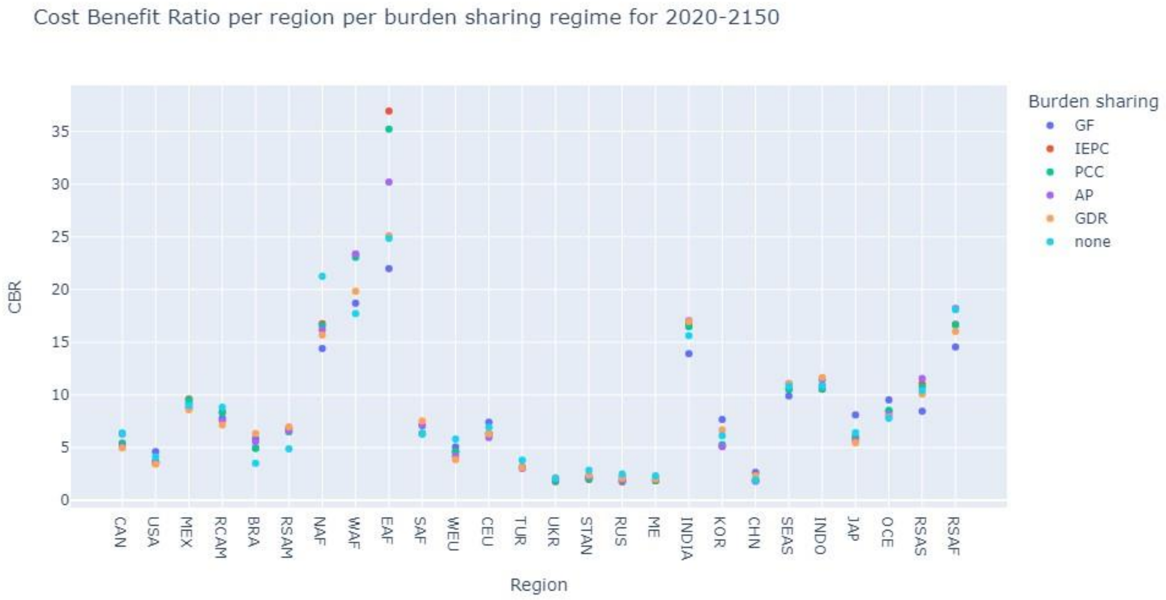

Figure 1 : The cost benefit ratio for all 26 image regions for the period from 2020 to 2150: Each burden sharing regime is represented and compared with the CBR when no burden sharing regime is applied.

The CBRs change when expanding the results to 2150, first for all burden sharing regimes and regions the CBR is higher than 1 indicating all regions having bigger benefits than costs regardless of in which way the mitigation costs are split between them. Moreover there is greater variety in which burden sharing regime results in the highest CBR as presented in table 4. Nonetheless 10 regions remain with their highest CBR when no changes in allowances and hence mitigation costs occur. Yet the differences between the implementation of a BSR or not for those regions results in rather minimal difference when compared to the ranges in BSR for region such as EAF.

Table 4: highest CBR for each region for the period 2020-21

BSR	Regions
GF	CHN,JAP, KOR, OCE, USA
IEPC	EAF, MEX
PCC	none
AP	INDIA, RSAF, WAF,
GDR	BRA, INDO,RSAM, SAF,UKR
none	CAN,CEU,ME,NAF,RCAM,RUS,SEAS,STAN,TUR,WEU

The GDR gives the lowest CBR for 23 regions when ignoring the scenario where no BSR is applied and would thus be a BSR that would be rather costly for the same benefits when only looking in terms of economic aspects.

Overall, the CBR indicates that despite the aim many of the BSRs have to split the costs more equally by taking into consideration population, GDP, or historical emission, economically when applied to the results of an integrated assessment model, a lot of uncertainty remains as to whether this would allow for a better spreading of the cost. Yet the CBR only presents part of the effects BSR have for regions. The results are interesting as in the shorter-term certain regions which appear to have less benefits financially when looking at the CBR could be the ones that will benefit from higher allowances for carbon emissions.

4.2 Emission allowances

For clarity purposes the detailed figures will be presented by selections of regions, all references to other regions discussed will be complemented by the corresponding Appendix that can be found at the end of the report.

The fundamental approach of the burden sharing regimes is to redistribute the emissions in a fair way depending on their definition of fairness. First, the results are presented for some of the biggest historical emitters. The United States of America (USA) has the highest emission allowances under the GF, despite slowly progressing towards 0, the rate of reduction is slower and with a higher starting allowance. The region would receive a higher allowance under this regime than if no regime would even be applied. As show in figure 2, The USA, Western Europe (WEU, including the UK) and Japan (JAP) all have negative emissions under the GDR regime. For the same regions the allowances appear to increase again after reaching their most negative value in 2040 or 2050.

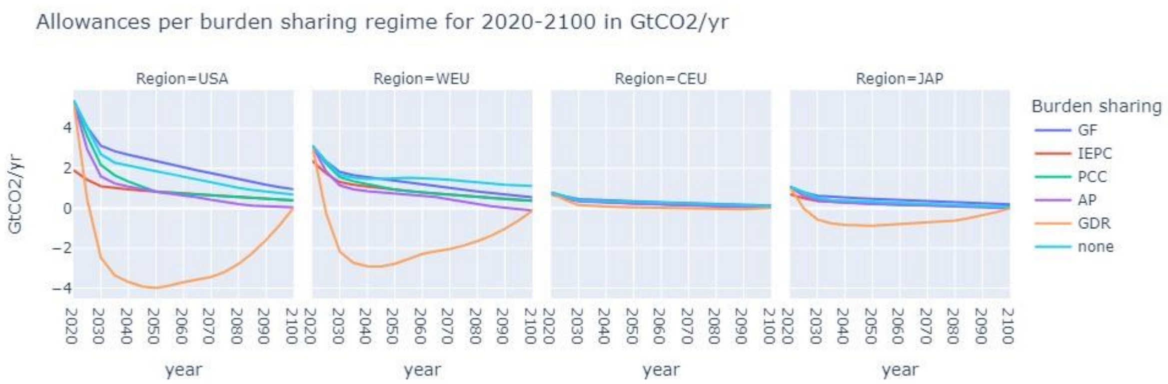

Figure 2: allowances of CAN, the European Union including the United Kingdom and Japan for 2020-2100

The results for the African continent present interesting variances, as presented in figure 3 South Africa (SAF) is a country by itself whilst the other regions represent a group of countries.

Results of the AP BSR are particularly interesting in the case of Western Africa (WAF) and the rest of southern Africa (RSAF) as an increase in emission allowances after 2060 could occur, assuming that regions will grow financially as the allocation is dependent on financial means of a region to pay for their emissions and associated mitigation costs.

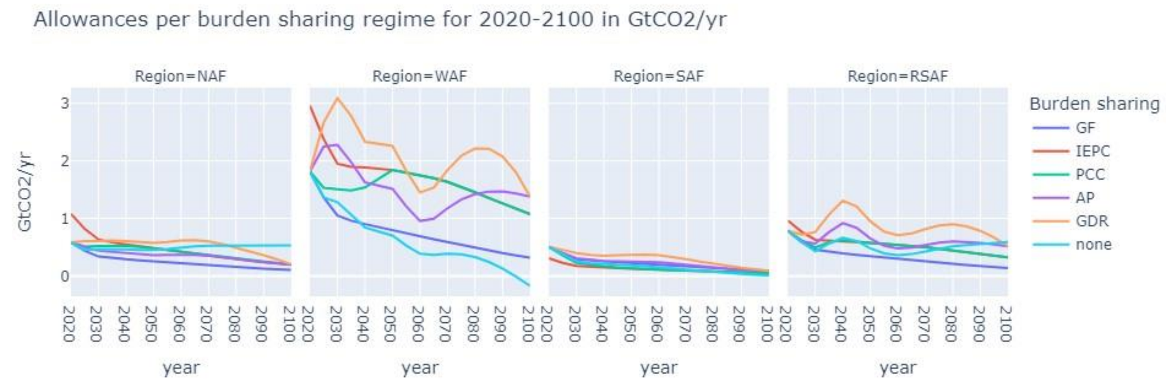

Figure 3: allowances for the African continent per burden sharing regime per for 2020-2100

WAF is the region where the greatest difference occurs between the BSRs, the other regions follow similar trends of emissions allocations between the BSRs. It is in this selection also the only region for which by the end of the century any reallocation of burdens and emissions is better than when no distribution of allowances occurs. Overall, the African continent would benefit the most from the GDR allowances scheme. Alike the biggest emitters all emissions evolve towards zero emissions allowance.

For the BRICS regions (BRICS states as well as neighbouring states or administrative territories) represented in figure 4, results vary. China, Taiwan, Hong Kong and Mongolia (CHN) are faced with the sharpest decrease in emissions as a region. India (INDIA) in contrast to the other regions is granted an increase as it sees a continuous increase in the allowed emissions under the GDR. Although the differences are smaller for BRA than INDIA and CHINA, the region would benefit from a bigger allowance under all BSRs.

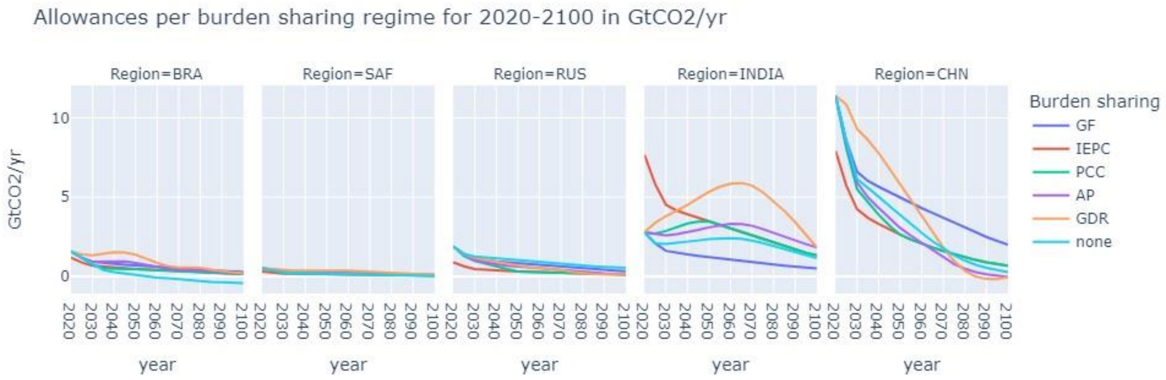

Figure 4: allowance for the BRICS states per burden sharing regime per for 2020-2100

The remaining regions are presented in Appendix A. Their allocations are stable and do not vary considerably from each other, similarly to the regions presented here their allocation decrease towards zero GT/CO2. Whilst these results introduce a first look into what regions would be entitled to regarding emissions, the regions are considerably different when taking into their demographic specificities. Looking into the results per capita can provide further insight in the difference between BSRs for each region, the results are included in Appendix A. The sum of the allowances are presented in figure 5. It once more shows how the different burden sharing regimes can have considerable influence. The allowance for some regions differ greatly whilst for others like MEX they are remain close to each other.

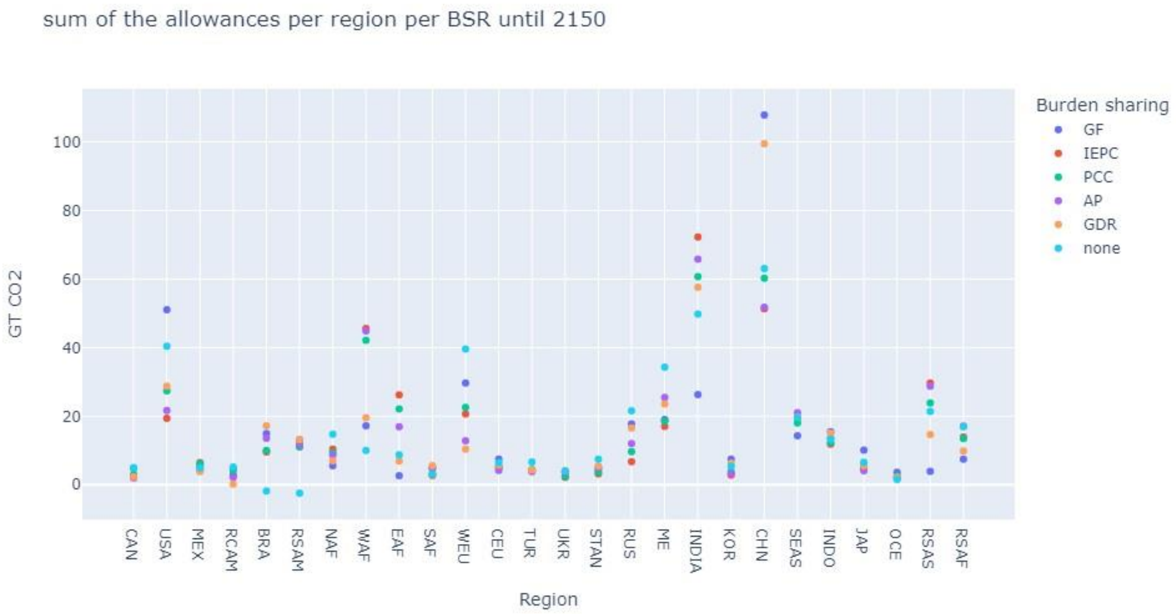

Figure 5: Sum of the allowances per BSR

When the results are presented per capita (presented in Appendix B) the difference between the burden sharing regimes is emphasized.

4.3. Mitigation costs

4.3.1 Evolution over time

Regions such as the USA, Western Europe (WEU), Centra Europe (CEU) and Japan (JAP) all see their cost increasing over the century as shown in figure 6. The GDR increase is sharper and faster although a reduction in the costs is noticeable for all the regions towards the second half of the century. When the results are expanded to 2150 the GDR sees a reverse trend after 2100 where the costs sharply decrease (Appendix A). The other BSRs decrease slightly and stabilize after.

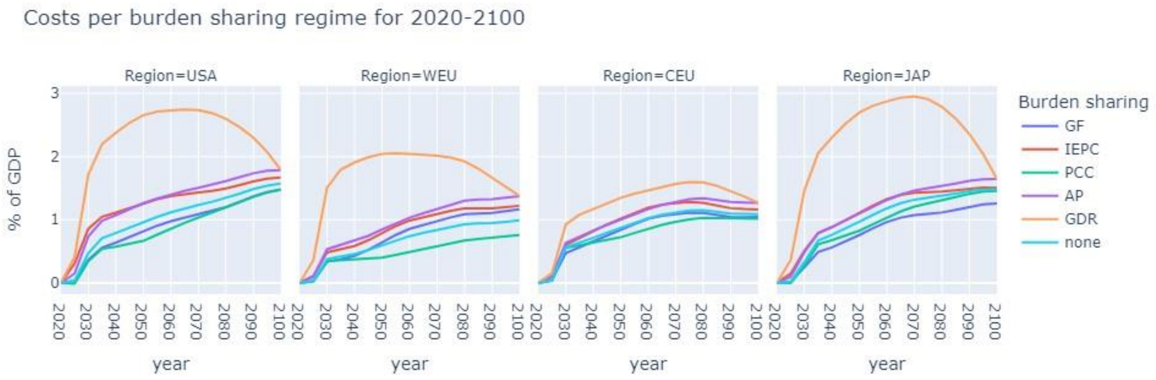

Figure 6: the mitigation costs of USA,WEU,CEU and JAP for 2020-2100

For the BRICS regions the results differ greatly between regions and BSRs. The GDR regime results in the lowest costs for Brazil (BRA), SAF, INDIA as shown in figure 7. RUS differs the most from the other regions as the PCC regime presents the least costs whilst it is one of the highest for BRA, SAF and INDIA. The costs remain the lowest for CHN and the highest for BRA when comparing it to the other BRICS regions.

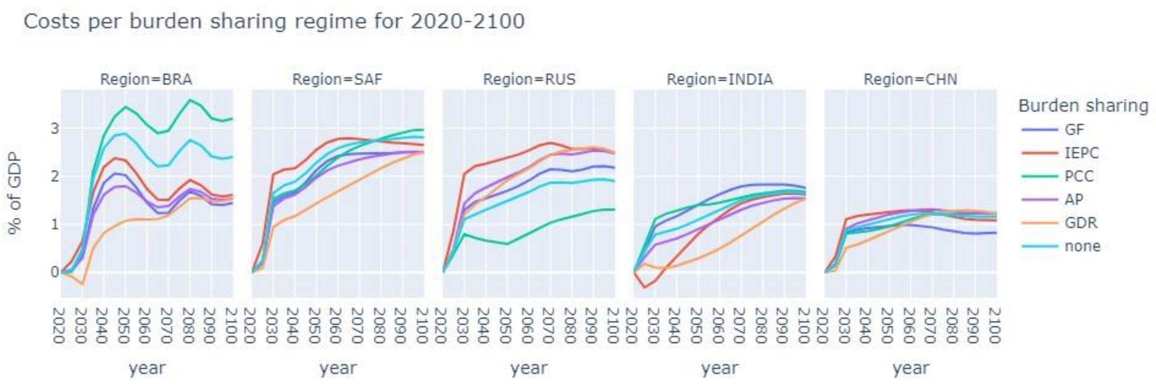

Figure 7: the mitigation costs of the BRICS region for 2020-2100

For all the regions, the implementation of a BSR would reduce their mitigation rather than having no BSR in place, yet for certain regions some of the BSR induce higher costs such as the PCC for BRA. For RUS only one BSR remains more favourable in terms of costs When expanding the results to 2150, the costs decrease for all regions and all BSRs except for INDIA and the GDR for which the cost increase further. RUS and CHN see a sharp decrease in the mitigation costs under the GDR regime.

The African continent experiences different trends for the different regions as shown in figure 8. The NAF experience a steady increase in costs where the AP regime is the more costly, the WAF and RSAF see a sharp increase in their costs until 2030 and 2040 respectively followed by a drop, the regime with the least costs increases or later increase is the GDR. When looking into the start of the 22nd century the trends remain similar with an increase of the costs of the GDR for all the regions. Taking only into account the last 20 years the SAF region would have the highest cost if no regime would be implemented. Once more looking to the sum of the costs provides additional necessary information to determine which BSR is the most financially advantageous for each region.

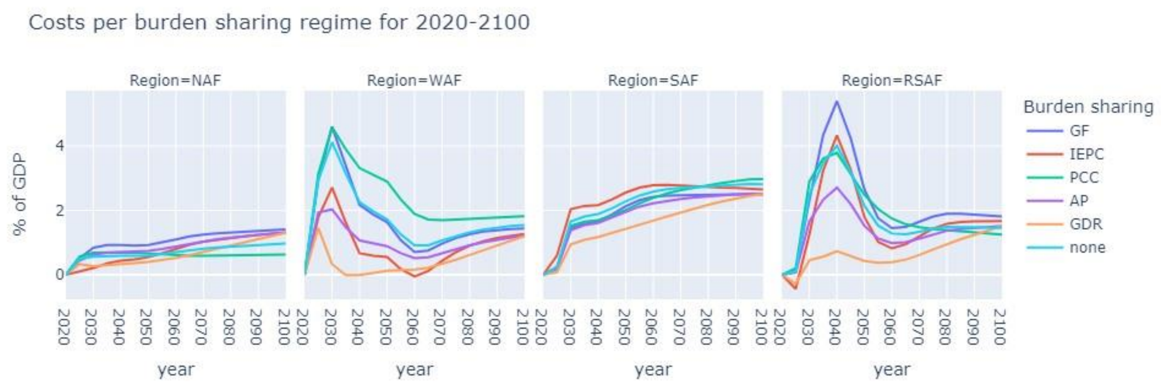

Figure 8: Costs per BSR of the African continent for 2020-2100

4.3.2 total mitigation costs

Figure 9 and figure 10 present the total costs in Trillions of USD and percentage of GDP. Interestingly regions such as SAF with overall low costs would regardless of which BSR, is one of the regions with the highest contributions in percentage of GDP, a similar trend is noticeable with RUS, UKR and the STAN region (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan, Uzbekistan). The EAF, when looking at the IEPC regime would need to dedicate in total, according to the MIMOSA calculations only 0.36% of their GDP by the end of 2100, on the other hand Brazil would have to dedicate close to 3% of their GDP, as presented in figure 9 if the PCC regime would be implemented.

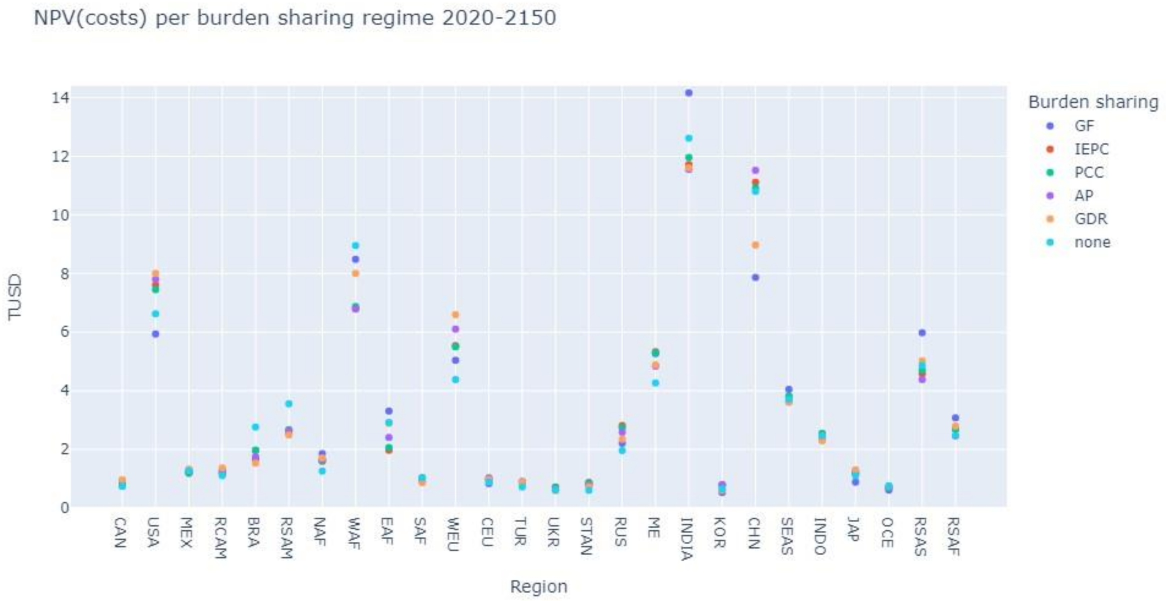

Figure 9: total mitigation costs per BSR until 2150 in in Trillions of USD

When looking into the sum of the costs the results indicate quite some variations in which BSR is advantageous. NAF, RCAM, RCAF, SEAS, INDIA , RASF would have the highest costs in percentage of GDP if allocation principle would be applied. Only the WAF would have the highest cost with no implementation of BSRs. CAN,JAP,OCE,WEU,CEU would have the highest cost under the GDR regime. BRA has the highest costs in percentage of GDP overall with the costs under the PCC regime reaching 2,9% of GDP in total. All the burden sharing regimes seem to provide financial advantages to the regions, as none of the regions would be financially better off if no BSR is applied. When looking into the further results until 2150, overall, the share of costs in percentage fog GDP decreases as the highest costs would be for BRA with 2,5 % of GDP allocated to mitigation. The PCC regime comes with the lowest costs for CAN, USA, RCAM, NAF, WEU, CEU, TUR, UKR, RUS, ME and RSAF.

Finally when summing the global costs of mitigation for each BSR by 2150 are presented in figure 10

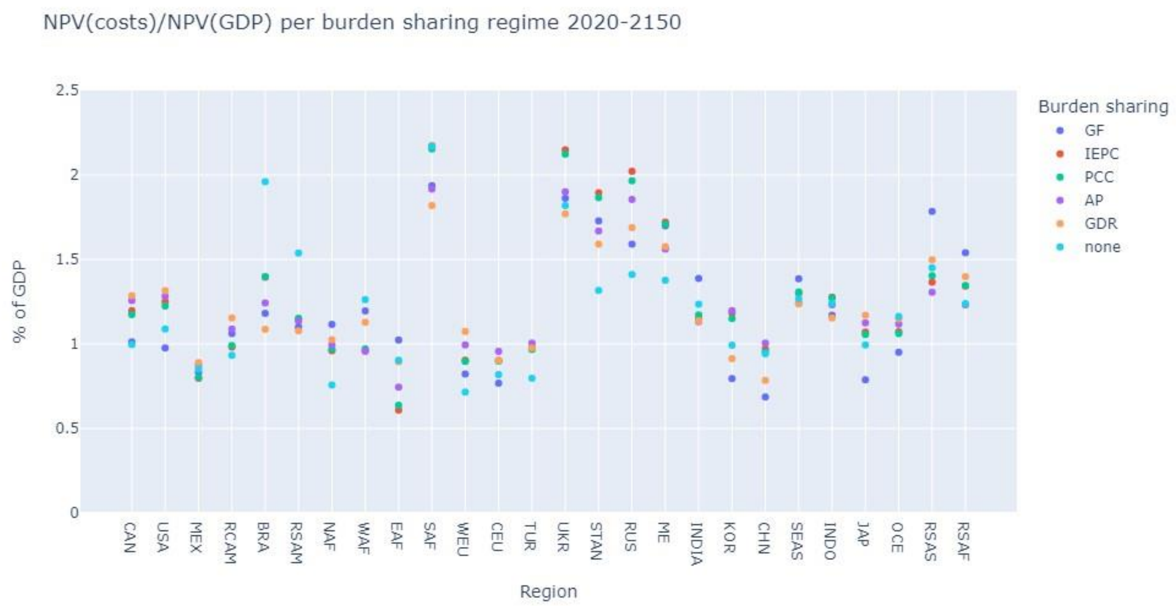

Figure 10: Costs in percentage of GDP for 2020-2150

4.3.3 Mitigation Cost Gap

The total mitigation cost gap presented in figure 11., shows what each region can be expected to receive contribute to in financial transfers/ support of other regions. The regions that a positive MCG are the ones providing financial support. The variance between the regions and BSRs appears surprising as the USA under the GF would be a beneficiary of financial aid whilst INDIA would be the biggest dispenser of financial aid. Overall under all BSRs WEU is one of the biggest contributors in term of their MCG.

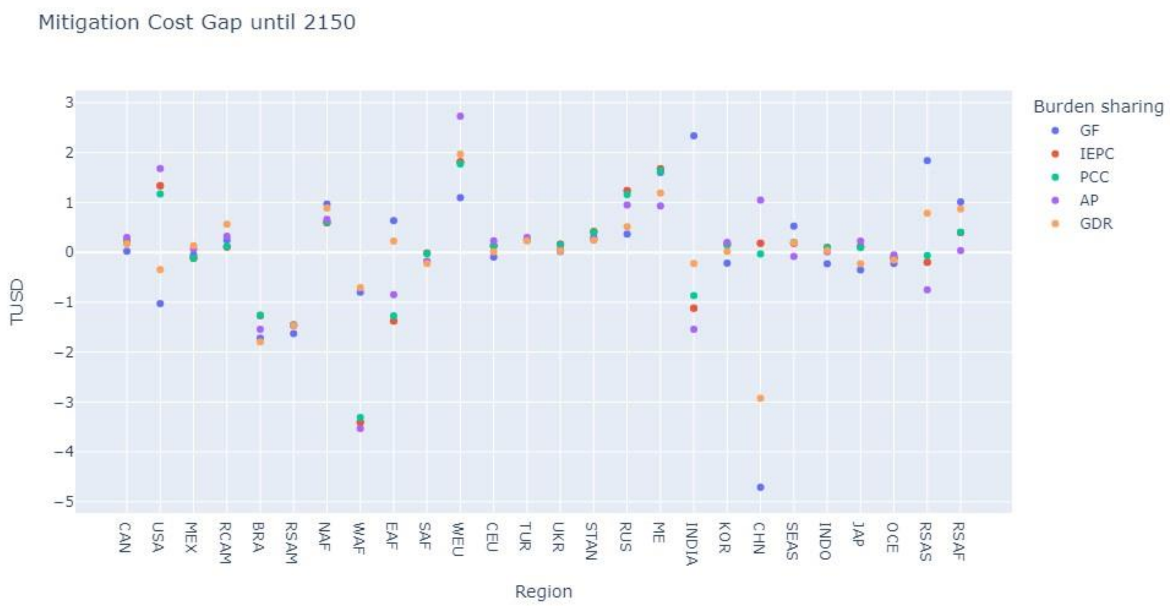

Figure 11: Mitigation Cost Gap until 2150

4.4 the full picture

To have an accurate description of the influence a certain BSR could have, it is important to get the full picture of the allowances and the costs both per capita and for the full region and compare it with the CBR.

Table 5 represents which BSR provides the highest score and the lowest for each category. An optimal combination for each region, would be the lowest costs in % of GDP, the highest CBR with the highest allowance and the lowest MCG. The combination between highest allowance and lowest costs thus implies lesser mitigation efforts which results in lower costs, most regions fall within the pattern also with the highest allowance except for western Africa (WAF) for which the lowest costs are with the AP regime and the highest allowance IEPC. The EAF satisfies the maximum outcome mentioned previously as the IEPC scores the best in every category. Unexpectedly the highest costs correspond to the lowest CBR. The most variation comes in the MCG.

Table 5: Each region with the corresponding best BSR and worst BSR for each category, Costs, BSR, MCG and allowance.

Region	costs %=GDP		CBR		MCG		allowance	
	min	max	min	max	min	max	min	max
CAN	GF	GDR	GDR	GF	PCC	GDR	AP	GF
USA	GF	GDR	GDR	GF	GDR	GF	IEPC	GF
MEX	IEPC	GDR	GDR	IEPC	GDR	GF	GDR	IEPC
RCAM	IEPC	GDR	GDR	IEPC	AP	GF	GDR	IEPC
BRA	GDR	PCC	PCC	GDR	GF	IEPC	IEPC	GDR
RSAM	GDR	PCC	PCC	GDR	GF	GDR	PCC	GDR
NAF	IEPC	GF	GF	IEPC	IEPC	GDR	GF	IEPC
WAF	AP	GF	GF	AP	GDR	GF	GF	IEPC
EAF	IEPC	GF	GF	IEPC	IEPC	GDR	GF	IEPC
SAF	GDR	IEPC	IEPC	GDR	IEPC	GDR	IEPC	GDR
WEU	GF	GDR	GDR	GF	AP	IEPC	GDR	GF
CEU	GF	AP	AP	GF	GF	GDR	AP	GF
TUR	PCC	AP	AP	PCC	GDR	GF	AP	PCC
UKR	GDR	IEPC	IEPC	GDR	GF	GDR	IEPC	GDR
STAN	GDR	IEPC	IEPC	GDR	GF	GDR	IEPC	GDR
RUS	GF	IEPC	IEPC	GF	PCC	GDR	IEPC	GF
ME	AP	IEPC	IEPC	AP	GF	GDR	IEPC	AP
INDIA	AP	GF	GF	AP	IEPC	GF	GF	IEPC
KOR	GF	AP	AP	GF	IEPC	GDR	IEPC	GF
CHN	GF	AP	AP	GF	GF	GDR	IEPC	GF
SEAS	GDR	GF	GF	GDR	IEPC	GDR	GF	AP
INDO	GDR	IEPC	IEPC	GDR	GDR	PCC	IEPC	GF
JAP	GF	GDR	GDR	GF	IEPC	GDR	AP	GF
OCE	GF	GDR	GDR	GF	GDR	GF	AP	GF
RSAS	AP	GF	GF	AP	GF	GDR	GF	IEPC
RSAF	AP	GF	GF	AP	GDR	GF	GF	AP

As a final comparison the costs per BSR are presented in figure 12 with in comparison to the avoided damages, indicating no matter if a certain BSR is implemented all regions are better off. All the results of the research were presented, the result need to be put in the further context of the research to answer the different research questions which will be addressed in the next chapter.

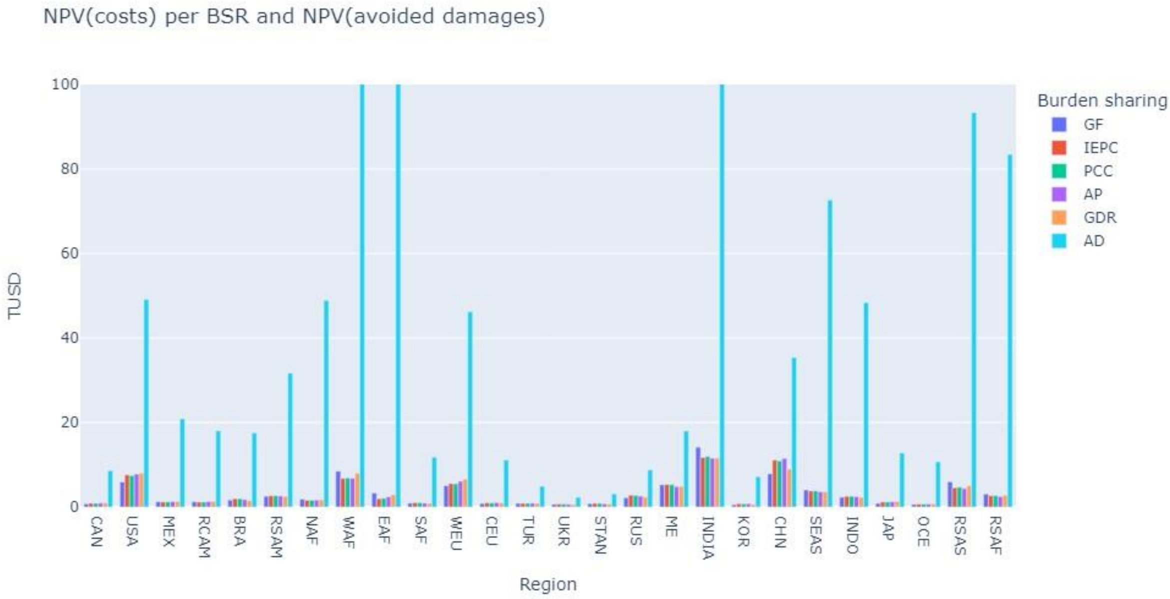

Figure 12. Costs per BSR and avoided damages. The avoided damages are represented in light blue.

5.Discussion

This chapter will reflect on the findings of the study and put them in perspective with the literature on the subject. It will look into the importance of looking at long term perspective, the potential changes that are needed in the financial system as well as the limitations of the research.

5.1 CBR

The CBR results reflect the necessity to have a long-term approach to climate mitigation and it's financing. A significant difference is observed between the periods running till 2100 and up to 2150 For the 21st century the results show how many regions are disadvantaged by the implementation of a BSR, with regions where the CBRs of BSR are lower than in the case where no regime is applied. These results are interesting as the burden sharing regimes are designed to benefit countries which have less means for investing in mitigation or provide them with the allowance, they are entitled to according to the fairness definition of the regime.

The CBRs running till 2150 provide a different outlook where the burden sharing regimes result in higher CBRs. This is reflected with the global CBR for 2100 in their study reaches 3.9 for a 3% discount rate, in this study under the same discount rate, a global CBR of 3,67 is calculated for 2100 and reaches 9,55 for 2150. The efforts before 2100 will provide further benefits in the second half of the century as even with strong mitigation, further heating and damages will occur beyond 2100 increasing the damage costs (Lyon et al., 2022). The global and regional difference after 2100 can thus be explained by the increasing damage costs beyond 2100 despite achieving close to 0 or net zero emissions. The change in CBR between 2100 and 2150 shows the importance of the long-term approach that needs to be taken when considering future costs of climate change and remaining under the 2ºC.

The Paris Agreement under the UNFCCC, as the agreement to remain under 2ºC, frames the discussion on financial flows between global North and Global South. Using the BSRs can help reduce the burden for regions which will be more affected by climate change by using them to determine the nationally determined contributions (NDCs). The CBR can inform the parties of potential pathways to take whilst remaining within the limits of the agreement and reaching the cost-optimal temperature of 1,8C. Pathways of emissions are important to consider as certain regions will face sharper decrease in emissions to remain within their allocations. An effective carbon market can help remaining within the global budget as countries with lower emissions can sell their remaining national budget and invest the earnings in mitigation (Yang et al., 2021). Climate finance systems can be helped by the various burden sharing regimes to determine, from an equity and burden sharing perspective, what countries and regions are responsible for carrying the costs rather than focusing on specific metrics or indicators defining a developed or developing country.

The Paris Agreement aimed at mobilising $100 billion per year for developing countries for 2020. The Climate Policy Initiative (CPI, 2021) which tracks the private and public investments and financial flows established that mitigation is one of the sectors where the funds are the most invested in (reaching $571 billion in 2019/2020), the total amount of climate financing, including mitigation, adaptation would need to reach around $4,35 trillion by 2030. The mechanisms to satisfy this would need to be binding as the financing ranges from creation of debt, equity, and grants for projects in areas ranging from transport, water and waste to energy systems funded by both private and public sector, including intermediates. The climate finance markets have become increasingly complicated due to the variety in actors, guidelines, and various mechanisms (Bowen et al., 2017; Shishlov & Censkowsky, 2022). Having an efficient way of trading carbon or invest will be key to achieve the goals.

5.2 Allowances

In all the regions the emissions gradually evolved towards zero, an important element to consider is although a decrease in emissions is expected from all regions, the emission allowances of certain BSR remain more favourable than others. Some regions see their emissions decreasing more gradually is some BSRs than others, spread across a longer period and can even return to an increase later.

In van den Berg et al. (2020) the allowances have similar trends to the ones in this study with greater allowances for regions such as China and India as well as the negative budgets for Japan, the US and zero budgets for European nations or in the case of MIMOSA regions. In their work Pan et al. (2023)focus on tradeoffs between equity and efficiency, the emissions of most regions are to reach net zero by 2050 in the case of this study, where only emissions are looked at and not strictly net zero. For most of the regions similar trends are visible for plateaus and short peaks in emissions for global south regions before declining towards 0.

There is an emphasis on the necessity to reduce towards net zero this century, varying between 2050 and 2070 when looking at CO2 emissions (Braunreiter et al., 2021; Chen et al., 2021; Krey, 2014; Williges et al., 2022). Burden sharing regimes thus offer options to achieve global allowances by distributing them. The allowances do not reach 0 in the study due to sharp decrease occurring at first. One of the sectors where emissions can be reduced the most is the energy sector. In their work on the energy transition under the Paris Agreement using effort sharing regimes, Chen et al. (2021) determine that Latin America and the African continent have higher potentials for bioenergy which would contribute to lowering emissions and remaining within allowances, hence this opens the possibility for smaller carbon budgets in those regions contributing to a more cost effective reduction in emissions or providing the option for higher allowances in other regions.

Developed regions such as Europe and more particularly western Europe have higher mitigation costs not only due to historical emissions but their reliance on fossil fuels requiring more financial means for transitions and larger scale reductions (Abbass et al., 2022). Energy being a high emission sector, it is important to consider this aspect in allowances distribution and if choosing a certain BSR. Thus, the allowances are an indication of how much should be reduced to achieve the goals, by investing in the right sectors where the costs will provide the biggest reduction and significant efforts can be made to remain within the allowances.

5.3 Mitigation costs and MCG

The mitigation costs presented are put in perspective with the mitigation costs gap which indicates which part of the costs will either be covered by another region, or which financial aid part will be transferred to others. Each BSR implies a reduction of the burden for certain regions, and an increase for others. A concern for the regions supplying the financial funding is the potential negative impact on their GDP as well as sovereignty (Abbass et al., 2022; Bauer et al., 2020)In a study conducted by Bowen et al.(2017)where equal costs are applied to all (in the same share of percentage of GDP) with different degrees of policy implementation (less to more stringent) an increase in costs did not affect the growth rate but it did not reduce the inequalities between regions in the share of costs. When testing their models to determine the financial flows across the world they establish that by 2050, between $400 billion up to $2 trillion would be transferred to other countries which reaches $6 trillion at the highest for 2100. In the results of this study the financial flows would range from $4.8 trillion in case of the PCC to $13 trillion for the GDR by 2150. the USA, Western Europe and Japan would be the main contributors of financial flows towards other countries from 2020 on with China, either on the receiving end of financial support or providing financial aid (depending on the BSR), the same pattern can be observed for India.

As addressed in Pachauri et al. (2022), mitigation costs and MCGs show the necessity to change international financial flows to achieve the targets in a fair manner. Mostly research emphasizes the need for a global trading system for emission and (Luderer et al., 2012; Pan et al., 2023; Robiou du Pont et al., 2017)The challenge coming from this is the determination of a global social cost of carbon while the regional distribution can be determined using the burden sharing regimes. In the case of the MIMOSA model the cost is set globally however to further address the equity challenges in allowance distributions regional social costs of carbon have been suggested to be applied. Others considers the application of a global social costs of carbon to go against cost beneficial efforts of equity (Davidson, 2021; De Cian et al., 2016; Kikstra et al., 2021). Careful considerations need to be taken as well as methods need to be implemented to determine the just price of carbon based on burden sharing principles (Bowen et al. 2017). Rules for the use of financial flows or emission trading schemes need to be established. They also raise concerns on potential decrease of energy supply investment should policies focus too much on efficiency. In their scenario, where the costs of mitigation are equalized for all, with stringent climate policies, after a 2020 peak a loss in income is noticeable across the globe without impacting growth rates substantially. The mitigation costs remain unevenly distributed reinforcing the necessity for redistribution of costs. The cap-and-trade systems thus comes back the selling of emission permits. Bigger (historical) emitters are the biggest buyers of those emissions. The middle east is set to have higher mitigation costs as they are energy exporters. In all the tested models an increase in financial flows is noticed.

The question of willingness remains. The implementation of burden sharing regimes depends on the cooperation of countries and the eventual losses they would accept to make (Kesternich et al., 2021)can take a lot of time to satisfy the different parties. Polluters pay principle is favoured by developed countries more than by developing ones. In their study, Kesternich et al, (2021) the Ability to pay rule appears to be more harmoniously accepted than a polluters pay principle. The Grandfathering approach is not preferred schemes such as the Convergence per Capita find greater support amongst developed countries but is discarded as an option for developing ones. When comparing with the CBR results obtained with the MIMOSA model for a majority of the countries are not significantly affected as the PCC amongst the best regimes for them.

As the effects of climate change will continue to affect all regions, investing on the long term is the safer option if contrasted with the benefits obtained, as well as well as avoiding further costs associated to adaptation. It is thus important that efforts are made to determine the willingness of the implementation of burden sharing approaches to achieve the aforementioned result in an equitable way.

Limitations

First the model used (MIMOSA) has uncertainties due to the nature of the damages functions and the estimates made by it in the avoided damages and their economic valuation. The data was analysed under specific set conditions of the model, changing the parameters of the model would have yield different results on the allocations and costs which then impact the CBR and MCG. The results and calculations of the data were done with the regions of the IMAGE model which are also used in the MIMOSA model. For more accuracy in the results the resolution should be adapted to national level, as this would allow for further detail in emission allowances, mitigation costs and the CBRs. This can be relevant for regions such as the European Union where cap and trade systems are already in place and could provide alternatives to policy makers for the regulations and mechanisms currently in place. The results presented remain within the range of findings of broader literature, yet this does emphasize the need for further research on a regional level of cost-benefits of climate mitigation.

The GDR index was only calculated for the year 2020 and 2030, it was thus not updated after and the 2030 index was subsequently used for all the other time steps until 2150. In addition, some of the countries of the IMAGE regions and the index do not overlap, the index used in the research is not complete and had to be scaled. Calculating the index for each time step in the study can be a solution to remedy this limitation. This can also explain why developed regions show surprising results where their allowances increase and end up on the receiving end of financial aid. Furthermore, only one specific setting of the GDR index was used, further research can be conducted using other development thresholds higher or lower than $7500 as well as another starting year for the accounting of historical emissions. To understand the effects of the GDR regime on allowance and cost benefit all the settings could be investigated. Nonetheless, the GDR is an interesting approach with highlights the importance of taking historical emissions into account as well the changing economic situation of a region. Regimes like the GDR are important to reflect the inequalities between regions.

The distribution of the allowances was done following the development of equations by van den Berg et al (2020), other researchers have implemented the regimes differently such as Pan et al (2023) and Robiou du Pont et al (2017), leading to different results in terms of financial transfers as well as cost-benefit ratios. It is important to further compare the results and methodologies applied if recommendations are to be made to policymakers.

When looking into costs associated with climate change, particularly with financial flows across the world, regions that are less financially developed and more susceptible to climate change will not only require financial assistance for mitigation but also for adaptation. As adaptation costs have not been included in the studies published till this day, further development of models will need to incorporate this to further improve the estimates of total costs related to climate change. As explained by Kikstra & Waidelich (2023), underline the importance of improving current models which so far do not include consequences of health, biodiversity loss extreme weather events resulting in estimates likely to be lower than reality. The result of this study help look into the problematics of distribution of costs with further integration of variables and costs bigger steps can be made to support the international community and inform them on the various options that can be chosen from for the regulation of carbon markets and climate financing to remain within the Paris Agreement.

6. Conclusion

The aims of this study were to look into ways in which mitigation costs could be distributed more evenly and determine the cost-benefits of such redistribution. The literature has established that remaining within the limits of warming agreed upon in the Paris Agreement is crucial. Climate mitigation financing is a core challenge of a world approach of reduction of CO_2 emissions under the idea of shared but differentiated responsibility. Cost benefit models were developed over the previous decades to determine the economic advantages of mitigation and the importance of remaining under the 2ºC. On a global scale, various models have established the cost-optimal temperatures between 1,8 ºC for the most recent studies. However, the studies have not gone far on the question of distributing the costs to achieve the 2ºC across the different regions.

This research has given an introduction on Integrated assessment models and their functioning to introduce the work so far done in the field of equity in mitigation costs as well as to introduce the MIMOSA model used in this study. Using multiple burden sharing regimes, where GDP per capita, population, historical emissions were considered, a redistribution of costs and allowances was made.

The main findings of the research conclude the importance of a long-term approach as the costs of climate change will continue to rise despite the decrease in emissions. The various burden sharing regimes applied in this study offer different pathways for the 26 regions to address current inequalities in mitigation between global north and global south. BSRs with a focus on the current status quo such as the Grandfathering approach are more beneficial to current big emitters whilst the Immediate per capita convergence and per capita convergence slowly converge towards the same allocation per capita for all. The Greenhouse development rights, emphasises the importance of financial flows and strong reduction in emissions from historical emitters. Looking until 2150, the implementation of a burden sharing regimes has greater economic consequences on developing regions where the cost-benefit ratios differed significantly compared to developed ones. The results thus help answer the following research question and sub questions. How does the allocation of climate change mitigation costs, using different burden sharing regimes affect Cost-benefit ratios of regions?

- What are the regional differences in mitigation and damage costs?

Through this study and with support of additional literature it is highlighted that the costs for each region can differ greatly as the avoided damages are significantly higher. The results of the model show the importance of strong mitigation in order to reduce the emissions towards zero as fast as possible. Shortly addressed are the potentials of reduction of certain regions due to their high renewable energy potential. Investing in regions where the costs of reduction are lower can contribute to reaching the goals of the Paris Agreement at lower costs.

- How can the use of burden sharing regimes alter the regional differences in mitigation costs and allowances?

The regimes applied in this study have an influence on all the aspects investigated, the Cost-benefit ratio, mitigation costs, allowances, and mitigation costs gap. Striving for CBR close to each other can be a manner to reduce the inequality. As presented in the results section, the mitigation costs can vary greatly between the regions, with no implementation of a BSR the costs are significantly higher than the benefits, for 2150 all regions benefit from the implementation of a burden sharing regimes. Due to the various equity principles the burden sharing regimes are based upon, regions are either responsible for past emissions leading to a higher burden or are granted higher allowances to develop economically.

The distribution of allowances of the various burden sharing regimes can help determine optimal Nationally determined contributions as presented in the Paris Agreement as well as potential financing pathways

- What considerations relate to the implementation of burden sharing regimes both on a societal level as well as in research?

First, the results show how different approaches to fairness can have an impact the distribution of the burden. This needs to be considered when climate agreements are implemented, particularly when questions of financing are discussed. Through the Kyoto Protocol and the Paris agreement, mechanisms of trade and efforts reduction were introduced with the goal of reducing the burden for regions that fill face higher consequences of climate change but not being the ones contributing to it. Carbon markets, through permits, cap and trade systems are part of the efforts which can allow for a better distribution of the burdens. The results of this study underline the need for further investments in climate mitigation, the different burden sharing regimes and mitigation cost gap show hoe depending on the chosen approach the financial flows can vary.

Although the study did not cover other burden sharing regimes and tested the results of one model. It highlights the importance of continuing the research to explore the burden sharing regimes and their impact on cost-benefit ratios to determine a fairer approach towards mitigation. Furthermore, the research only covers mitigation costs. To improve the accuracy the distribution of costs and the burden, more models and studies need to include the costs of adaptation, as well as a further range of damage costs such as health and loss of biodiversity ad the total costs remain underestimated.

To conclude, the costs of mitigation are considerably lower than the damages if no action is undertaken. Climate change affects regions across the world in different ways with regions that have contributed less to emissions having to pay the highest price. Burden sharing regimes as studied in this research can help support those regions but this will first require a global approach to determining and fairness and some concessions from regions which have the means to help achieving climate targets in a cost-efficient and fair way.

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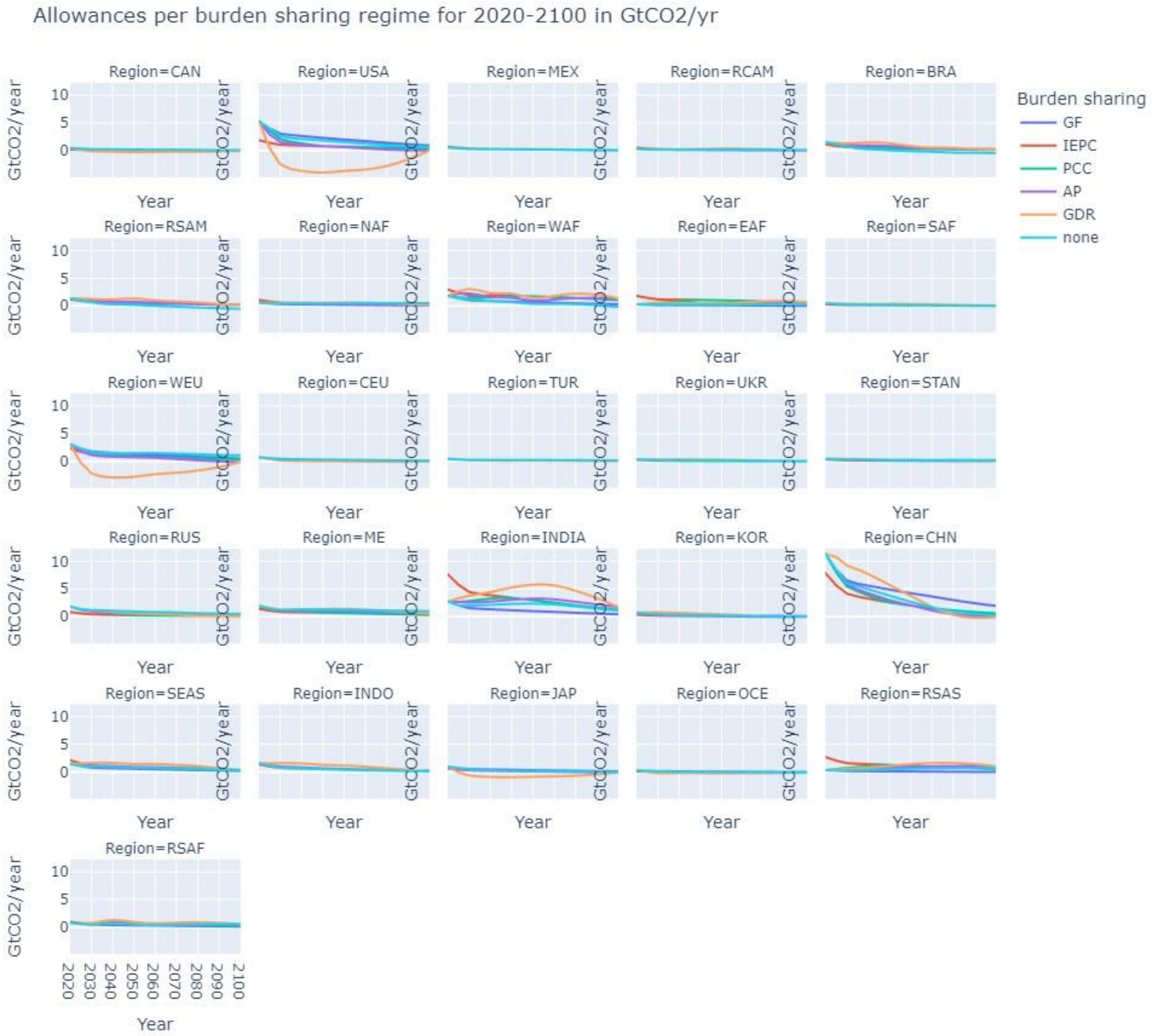
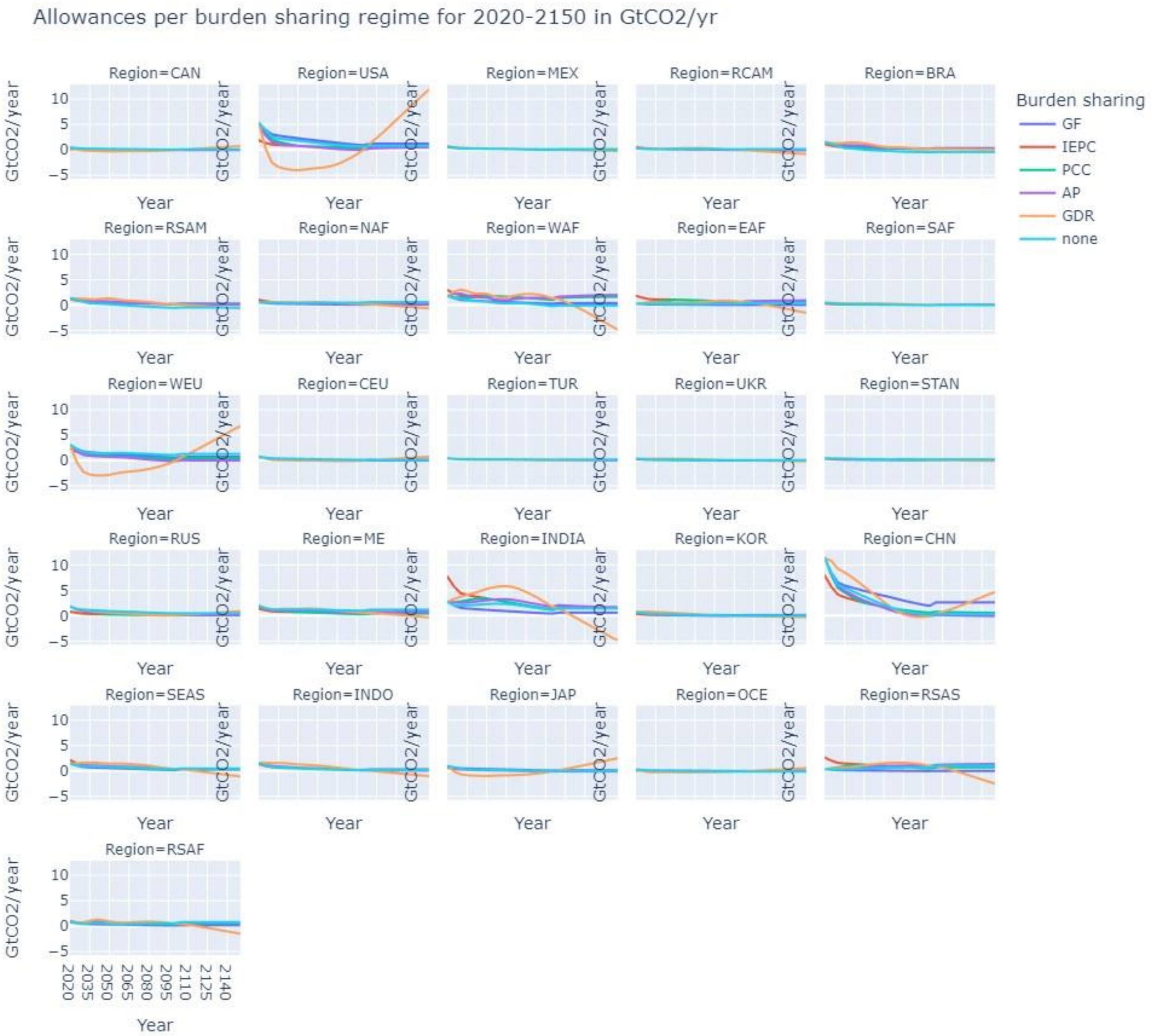
Appendix A- allowances per BSR

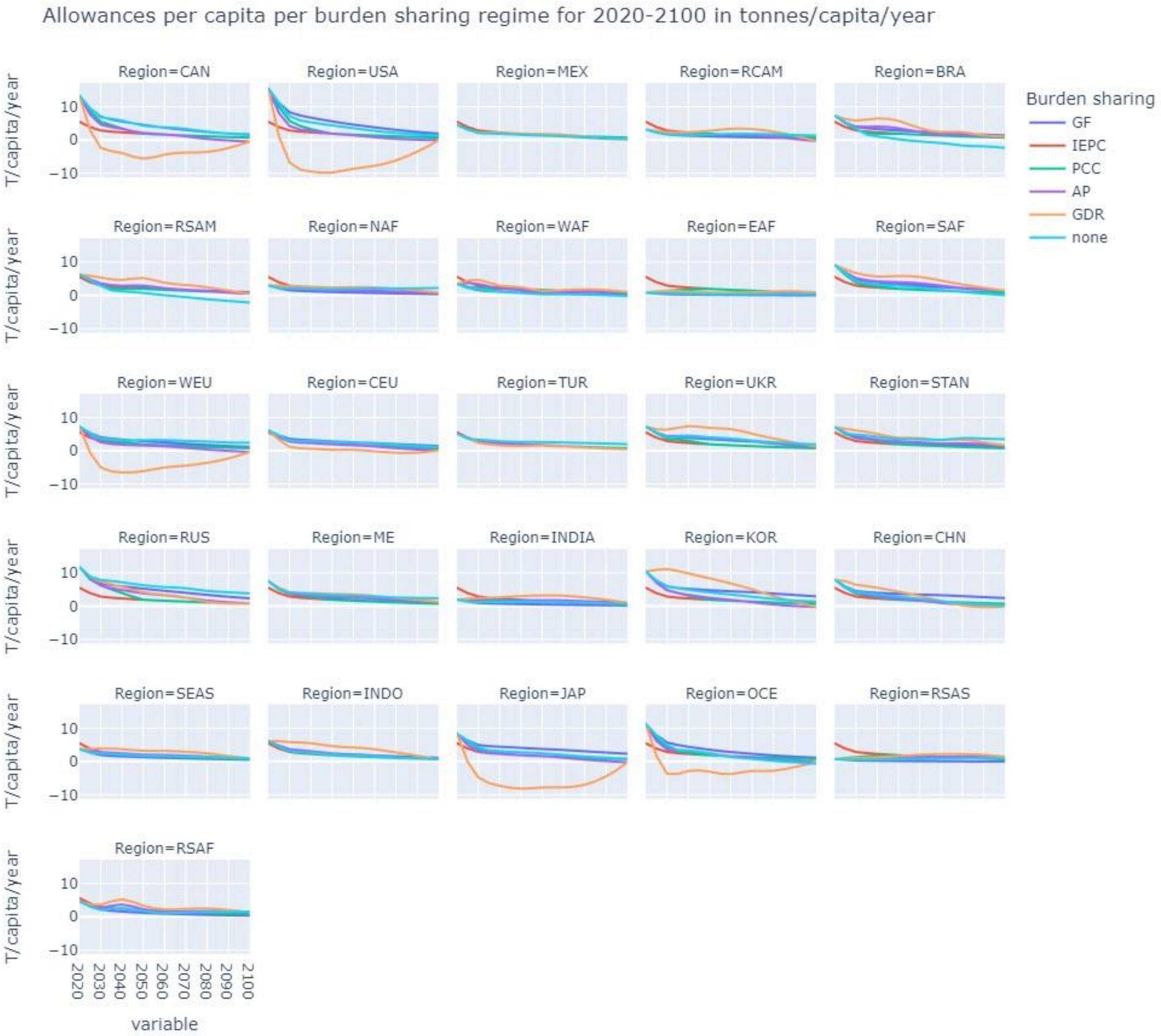


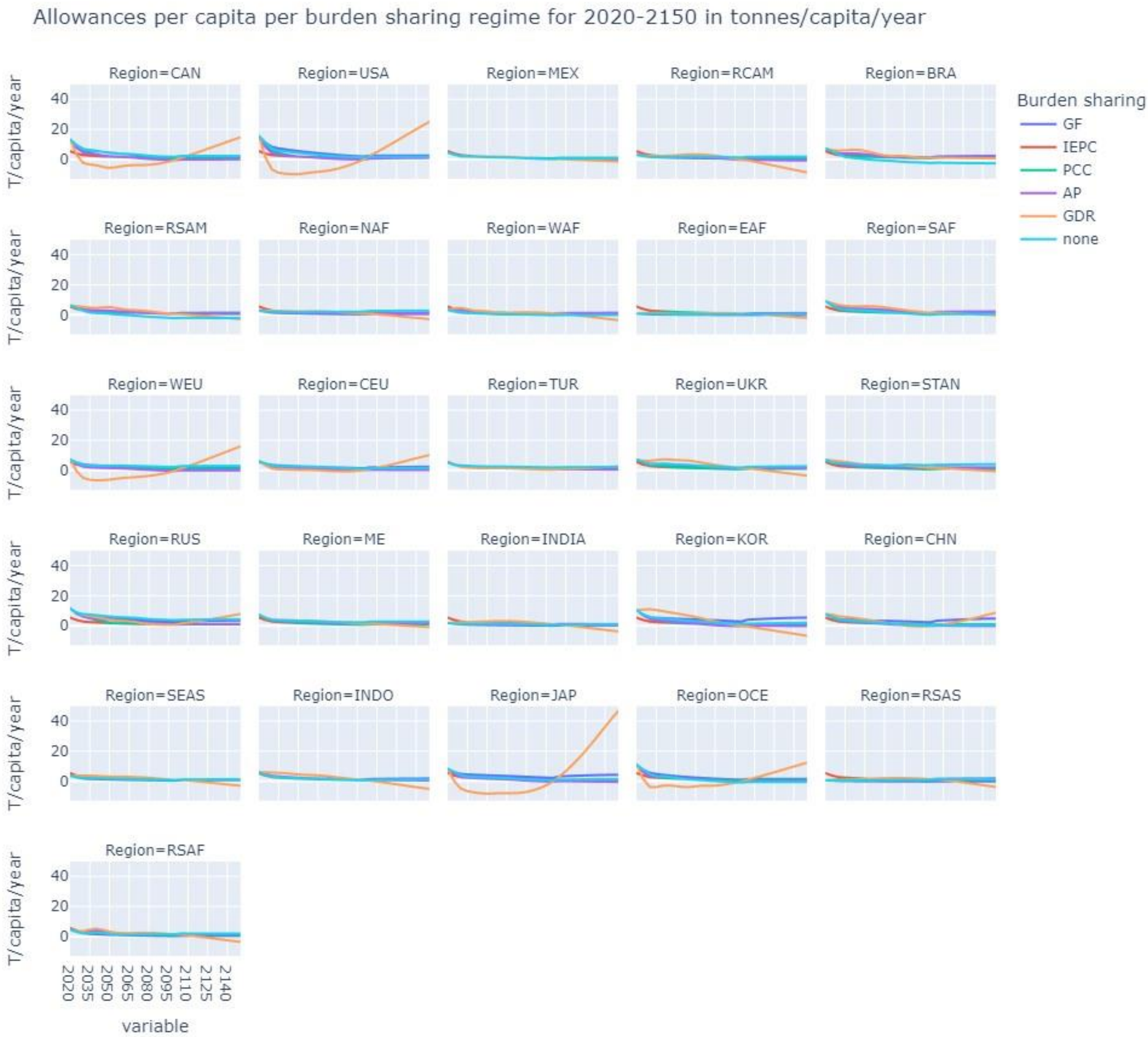
All the allowances per year per burden sharing regime, including a comparison with the Business as usual scenario where no mitigation efforts are implemented



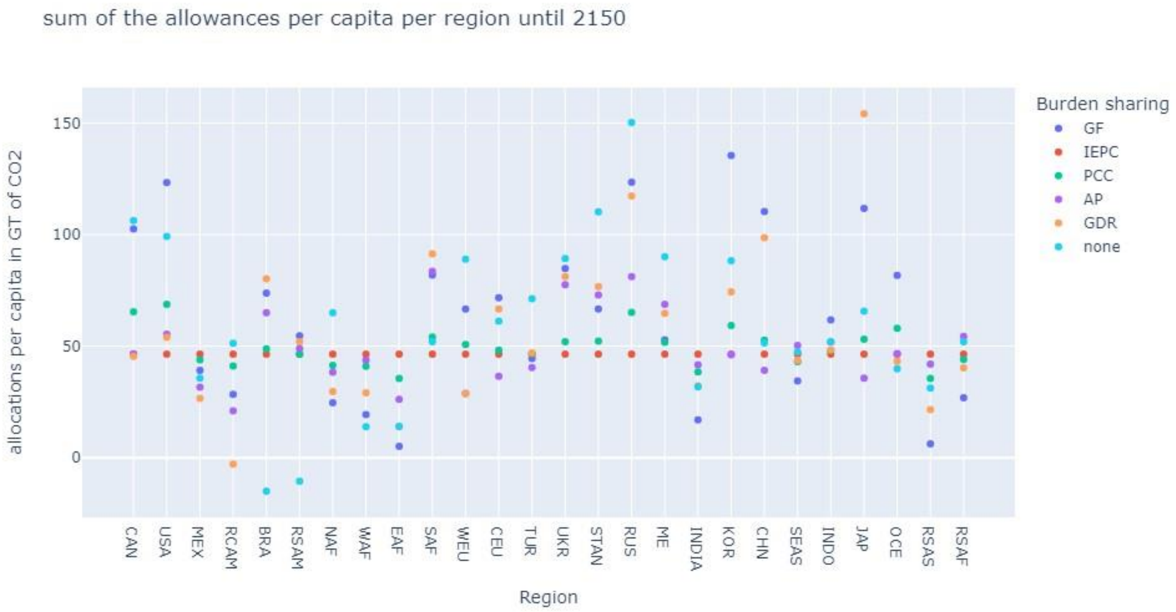
All the allowances per year per burden sharing regime, including a comparison with the Business as usual scenario where no mitigation efforts are implemented

Appendix B- allowances per BSR per capita

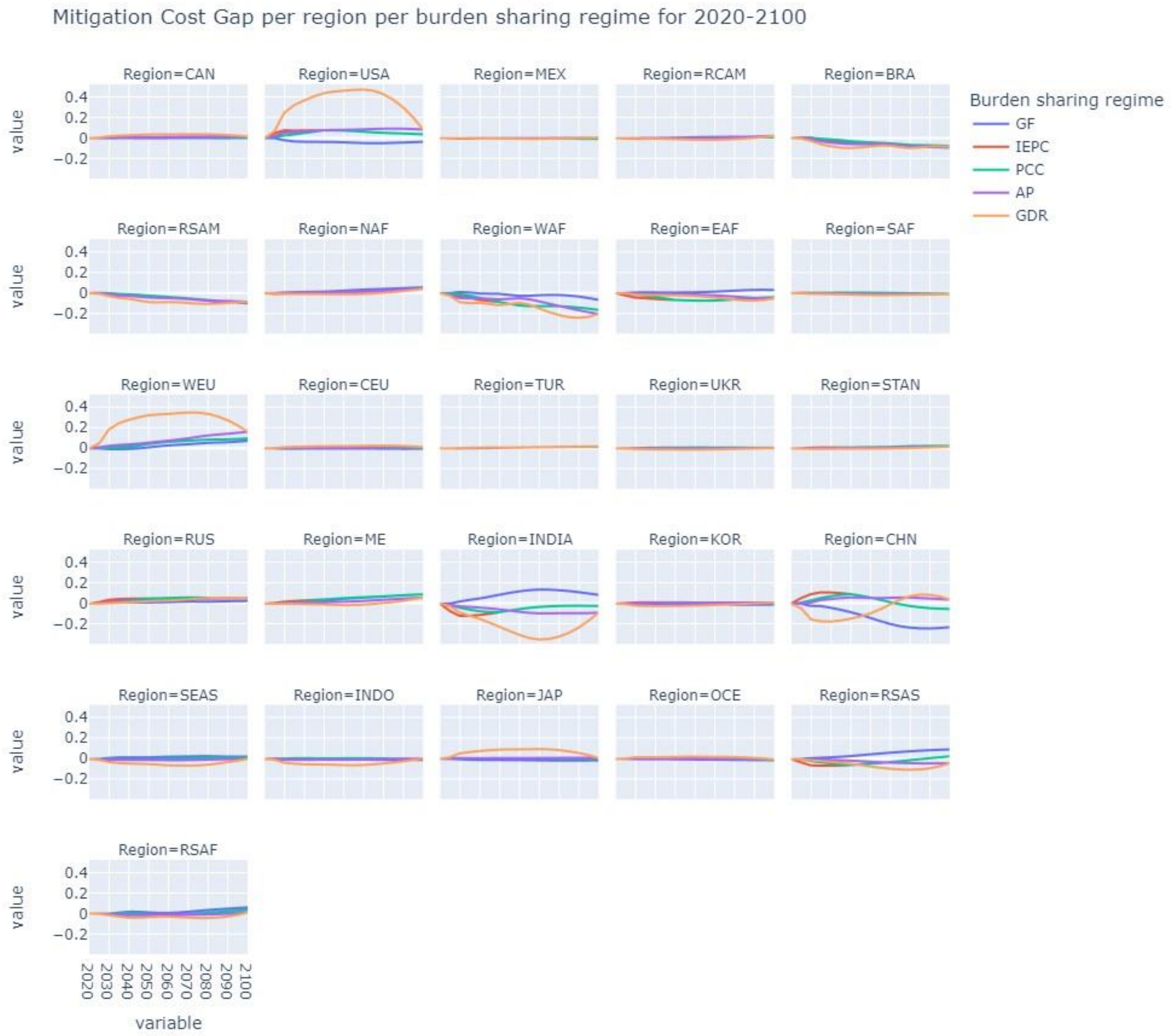




Allowances per capita per burden sharing regime for 2020-2150 in tonnes/capita/year
Region=CAN
Region=USA
Region=MEX
Region=RCAM
Region=BRA
Region=RSAM
Region=NAF
Region=WAF
Region=EAF
Region=SAF
Region=WEU
Region=CEU
Region=TUR
Region=UKR
Region=STAN
Region=RUS
Region=ME
Region=INDIA
Region=KOR
Region=CHN
Region=SEAS
Region=INDO
Region=JAP
Region=OCE
Region=RSAS
Region=RSAF
T/capita/year
40
20
0
2020
2035
2050
2065
2080
2095
2110
2125
2140
variable
Burden sharing
GF
IEPC
PCC
AP
GDR
none

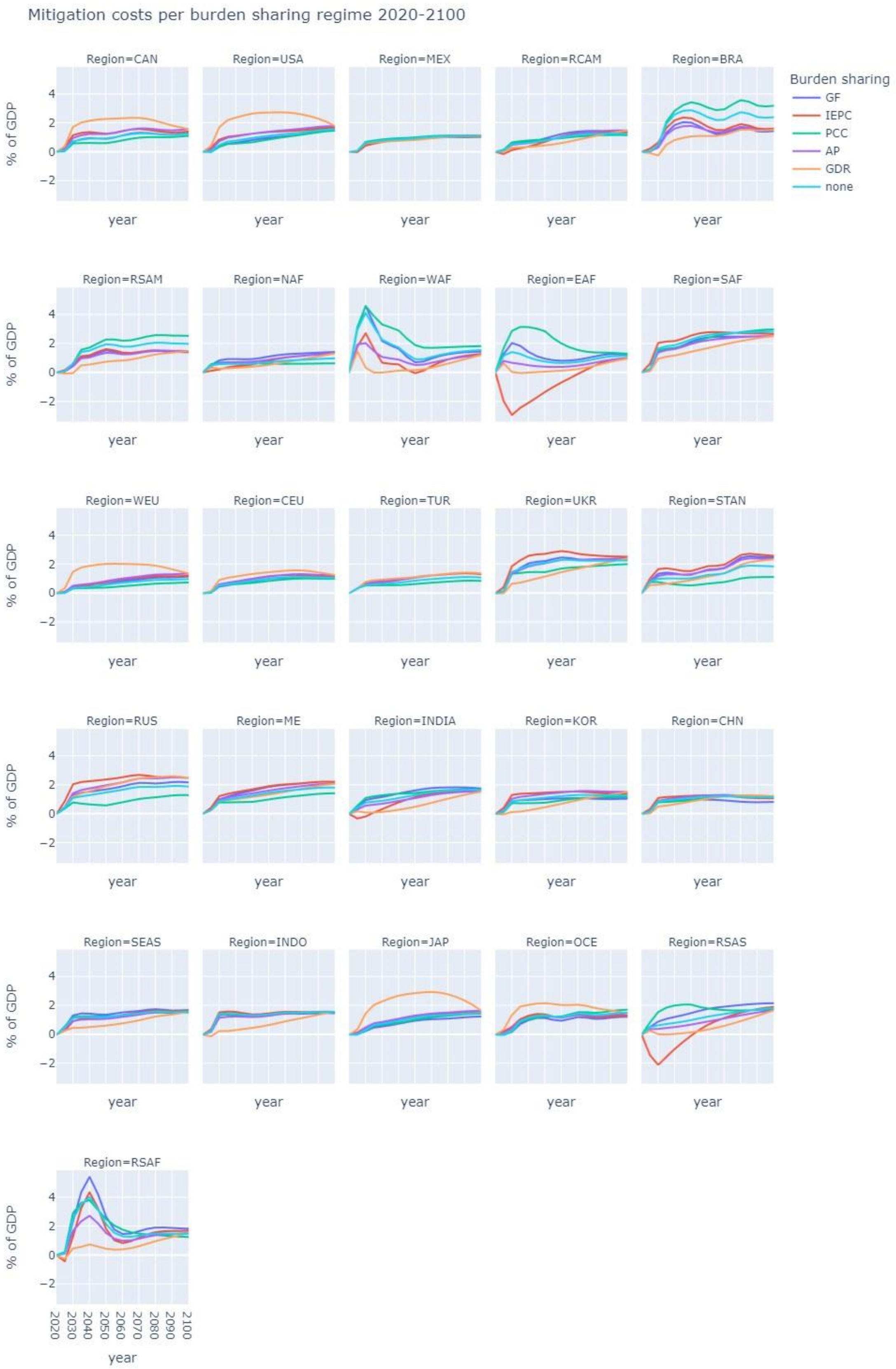

sum of the allowances per capita per region until 2150
allocations per capita in GT of CO2
150
100
50
0
CAN
USA
MEX
RCAM
BRA
RSAM
NAF
WAF
EAF
SAF
WEU
CEU
TUR
UKR
STAN
RUS
ME
INDIA
KOR
CHN
SEAS
INDO
JAP
OCE
RSAS
RSAF
Region
Burden sharing
GF
IEPC
PCC
AP
GDR
none

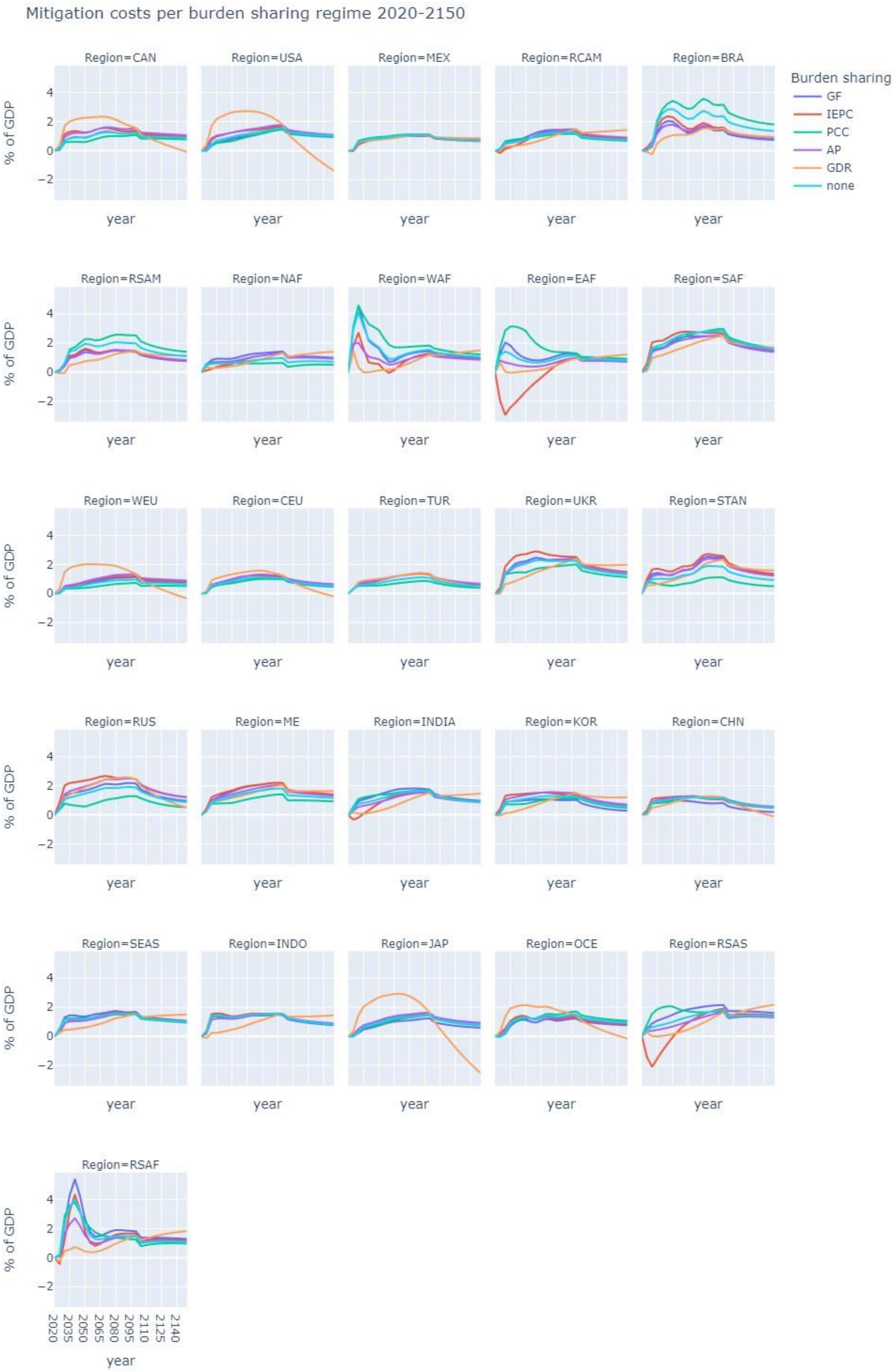
Appendix C – MCG per BSR

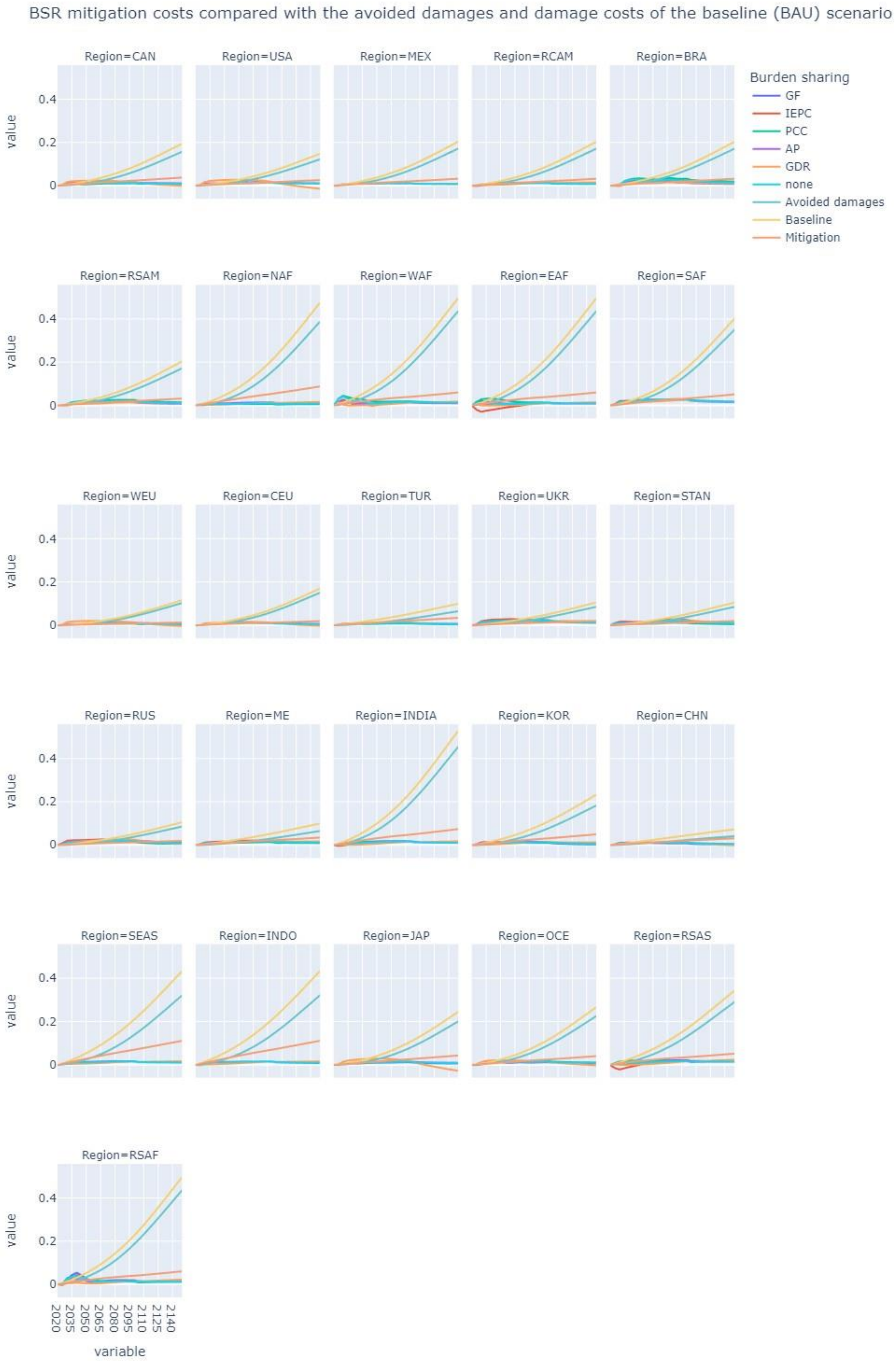


Mitigation Cost Gap per region per burden sharing regime for 2020-2150
Region=CAN
Region=USA
Region=MEX
Region=RCAM
Region=BRA
Region=RSAM
Region=NAF
Region=WAF
Region=EAF
Region=SAF
Region=WEU
Region=CEU
Region=TUR
Region=UKR
Region=STAN
Region=RUS
Region=ME
Region=INDIA
Region=KOR
Region=CHN
Region=SEAS
Region=INDO
Region=JAP
Region=OCE
Region=RSAS
Region=RSAF
value
variable
Burden sharing regime
GF
IEPC
PCC
AP
GDR

Appendix D -Mitigation Costs per BSR




Mitigation costs per burden sharing regime 2020-2150
Region=CAN
Region=USA
Region=MEX
Region=RCAM
Region=BRA
Region=RSAM
Region=NAF
Region=WAF
Region=EAF
Region=SAF
Region=WEU
Region=CEU
Region=TUR
Region=UKR
Region=STAN
Region=RUS
Region=ME
Region=INDIA
Region=KOR
Region=CHN
Region=SEAS
Region=INDO
Region=JAP
Region=OCE
Region=RSAS
Region=RSAF
% of GDP
4
2
0
−2
year
2020
2035
2050
2065
2080
2095
2110
2125
2140
Burden sharing
GF
IEPC
PCC
AP
GDR
none


BSR mitigation costs compared with the avoided damages and damage costs of the baseline (BAU) scenario
Region=CAN
Region=USA
Region=MEX
Region=RCAM
Region=BRA
Region=RSAM
Region=NAF
Region=WAF
Region=EAF
Region=SAF
Region=WEU
Region=CEU
Region=TUR
Region=UKR
Region=STAN
Region=RUS
Region=ME
Region=INDIA
Region=KOR
Region=CHN
Region=SEAS
Region=INDO
Region=JAP
Region=OCE
Region=RSAS
Region=RSAF
Burden sharing
GF
IEPC
PCC
AP
GDR
none
Avoided damages
Baseline
Mitigation
value
0
0.2
0.4
2020
2035
2050
2065
2080
2095
2110
2125
2140
variable

All the results are indicated in percentage of GDP for the period 2020-2150, the results are also compared with the damage costs in percentage of GDP of initial scenario of 1,8C

Appendix E – Repository

https://github.com/JuliettevdBrule/Master-thesis-.git