



Net0Pathways through impRoved IAMs across Sectors, diMensions, and scAles

Deliverable 5.2

Report on improved representation of biophysical climate impacts, economic impacts, adaptation and maladaptation in IAMs

Deliverable 5.2
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1. Executive summary

This deliverable presents research on climate change impacts conducted within Tasks 5.2 and 5.3 of the PRISMA project. This research addresses the need to better represent and understand the biophysical and economic repercussions of current and future climate change on biophysical and socio-economic systems.

Climate impacts have traditionally not been considered within detailed integrated assessment models (IAM). Representing impacts enables models to explore equity considerations concerning climate impacts and adaptation needs as well as better represent interactions between various sectors. Research within task 5.2 expands on recent research efforts of climate impacts and adaptation representation in IAMs through model development. Specifically, it focuses on model and scenario improvements of climate impacts in the residential and water sectors, and explores the representation of (mal)adaptation and socioeconomic heterogeneities in different sectors. A first study explored how different climate change adaptation and mitigation futures are projected to shape vulnerability to heat, and energy demand and emissions for space cooling, using the IMAGE model (PBL). Within the water sector, one study assessed future climate change impacts on access to drinking water and sanitation services (IIASA). The last study focused on the risks of maladaptation stemming from the expansion of waste water treatment and desalination capacities (IIASA).

Complementing the biophysical modelling of climate impacts, Task 5.3 focuses on an economic evaluation of impacts. It aims to address the lack of comprehensive coverage of impact channels in all economic sectors and representation of their overall effect on economic growth in process-based IAMs. The first research aim is to assess climate change impacts on productivity. The representation of climate change impacts on productivity - going beyond labour productivity and incorporating the productivity of all production factors - in the IMACLIM-R World model was improved by developing two climate and climate impacts modules (ENPC/CNRS). A systematic literature review was also conducted to better understand climate change impacts on economic inequality (ENPC/CNRS). PBL has improved the economic impact representation in the IMAGE model by integrating GDP and labour productivity impacts as an optional model setting, using recent empirical labour productivity impact data. The second research aim is to implement damage functions into IAMs. First, a



macroeconomic damage function was implemented in IMACLIM to compare direct and total impacts from climate change (ENPC/CNRS). Second, the first comprehensive estimate of the social cost of carbon for ocean-based welfare was conducted by enhancing the RICE50+ IAM with climate change impacts on blue capital (CMCC). Third, a stochastic debt sustainability analysis was coupled in the RICE50+ to evaluate climate risks to sovereign debt and assess the effectiveness of adaptation investments and fiscal policies in mitigating these risks (CMCC). Fourth, a framework was created to decompose costs and benefits within the REMIND-MAGPIE IAM, to study the effect of fully integrating economic damages into climate policy scenarios (PIK). Finally, a scenario analysis was conducted to assess economic impacts arising from global net-zero emissions by 2050 using two macroeconomic models, E3mE and GEM-E3 (E3M).

The ongoing work in this deliverable has resulted in 11 manuscripts and publications, which have been added to this deliverable as separate chapters. To accommodate the reader, chapters in a paper format start with a summary of the respective manuscripts/papers. All other chapters provide a more concise description of the research involved.

Chapter title	Task	Contributor	Chapter format
Adaptation in the residential cooling demand sector	5.2	PBL	Paper with summary
Adaptation in the water demand sector	5.2	IIASA	Paper
Risk of maladaptation in the water sector	5.2	IIASA	Paper
Update of the representation of climate impacts in the IMACLIM-R World model	5.3	ENPC/CNRS	Summary
Climate change impacts on economic inequality	5.3	ENPC/CNRS	Summary (paper in Annex)



Comparing the direct impacts and the total impacts from climate change in IMACLIM	5.3	ENPC/CNRS	Summary (paper in Annex)
Incorporating Ocean-Based Climate Damages into the Social Cost of Carbon	5.3	CMCC	Paper with summary
Climate-Debt Dynamics: Integrating Climate Impacts and Adaptation into Sovereign Debt Sustainability Analysis	5.3	CMCC	Summary
Decomposing costs and benefits of climate change in integrated scenarios	5.3	PIK	Summary
Comparing Economic Impacts of Net-Zero Transition with Climate Damage Uncertainties	5.3	E3M	Summary (paper in annex)
Integrating GDP- and Labour productivity impacts in IMAGE	5.3	PBL	Summary



2. Climate impacts, adaptation and maladaptation

1.2. Adaptation in the residential cooling demand sector

Summary

This research contributes to an improved representation of adaptation in the IMAGE IAM, in terms of residential space cooling as a strategy to cope with heat. While previous modelling studies have investigated vulnerability to heat – referring to the population exposed to heat but lacking cooling access, few studies have assessed intra-regional inequalities in cooling access and vulnerability to heat. This study fills this gap and adds other important novelties, including multiple cooling methods. This allows us to assess the impact of adaptation - in terms of energy and emissions - and combined adaptation/mitigation strategies such as increased cooling appliance energy-efficiency, passive cooling, such as green roofs, behavioural change, and improved urban layouts. We find that 3.6 billion people worldwide are currently vulnerable to heat. While expected economic development allows many households to gain access to cooling appliances, this progress is strongly offset by a growing population and exacerbated by climate change. 3.4 billion people are projected to remain vulnerable by 2100 in our *Baseline* scenario, mostly within Central and South America, Africa and South Asia, due to high rates of heat exposure and expected income inequality preventing a large share of the population from fulfilling their cooling needs. Providing cooling access to all vulnerable populations is projected to raise cooling energy demand by 156% in 2050 and 76% in 2100. However, this increase can be avoided when combined with both policies to limit global mean temperature change to well-below 2°C and an integrated approach incorporating energy-efficient cooling technologies, passive cooling, behavioural change, and improved urban planning. This study suggests that providing global access to residential space cooling can be achieved while meeting climate change policy goals, provided targeted policy action.

Introduction

Growing household incomes have been a major driver of demand for residential space cooling worldwide. Global energy demand for space cooling tripled between 1990 and 2016, growing faster than for any other energy service in the building sector (International Energy



Agency 2018). Rising ambient temperatures due to climate change are now increasingly contributing to this rising demand. Without cooling, people are more likely to suffer from heat-related physical and mental health impacts, from thermal discomfort to increased morbidity and mortality (Ebi et al. 2021; Turek-Hankins et al. 2021). One of the most widespread cooling strategies is air conditioning (AC), due to its high effectiveness (Jay et al. 2021). Given expected climate and income trends, future growth in residential AC could further drive-up energy demand, requiring increases in electricity generation capacity and complicating the decarbonisation of the electricity system, leading to overall increases in greenhouse gas (GHG) emissions. Conversely, climate policy could possibly limit cooling accessibility by discouraging high AC energy use or through higher fossil fuel-based electricity prices. Moreover, cooling is not affordable to all and ensuring global access to cooling will be a considerable challenge given high capital and operational costs (Jay et al. 2021). These issues highlight potential trade-offs between adapting to and mitigating higher temperatures (Isaac and Van Vuuren 2009; Van Ruijven et al. 2019; Vigié et al. 2021; Colelli et al. 2023).

Previous studies have investigated future AC uptake and associated cooling energy demand (Isaac and Van Vuuren 2009; Mastrucci et al. 2021). Within this field, a growing body of work explores the so-called-cooling gap – referring to the population exposed to heat but lacking cooling access, i.e., the population vulnerable to heat – and the implications of fulfilling unmet cooling needs. The cooling gap has been studied under current (Mastrucci et al. 2019) and future climatic and socio-economic conditions (Andrijevic et al. 2021; Pavanello et al. 2021; Mastrucci et al. 2022; Falchetta et al. 2024). However, few assessments to date have explored potential intra-regional inequalities in cooling access and vulnerability to heat on a global scale (Falchetta et al. 2024). As income is a known limiting factor to AC adoption (Pavanello et al. 2021), considering heterogeneity in income levels within regions is essential to gather more granular insights on vulnerability to heat. Additionally, existing estimates on the energy needed to provide universal cooling access (Mastrucci et al. 2019; Byers et al. 2024) can be improved by explicitly incorporating context-specific characteristics driving cooling needs and energy use, such as localised climate conditions and building attributes. Finally, accounting for a wider range of adaptation strategies beyond AC is crucial to investigate potential pathways towards lowering the impacts of adaptation to heat.

Here, we aim to address these shortcomings. We use the IMAGE 3.4 modelling framework (PBL 2025), an Integrated Assessment Model (IAM) with a detailed energy system model



including a comprehensive representation of the residential sector, to project which populations are vulnerable to heat due to a lack of cooling access throughout the 21st century. We present results disaggregated by world region and income group for both urban and rural population groups, to account for inequalities in cooling access both across and within regions. We also expand our scope beyond AC by including evaporative coolers. We project future cooling energy demand under scenarios with varying climate change mitigation and adaptation efforts. To refine our estimates of potential future energy demand for residential cooling, we account for building insulation characteristics and urban climates.

Methods

Exposure to heat

We first assess current and future exposure to heat, which is assumed in areas exceeding a threshold of yearly Cooling Degree Days (CDD) (Andrijevic et al. 2021). CDDs indicate the number of degrees and days for which outside air temperature is higher than a predetermined set point temperature. CDDs thereby indicate both the extent and intensity of heat throughout a year. We use multi-model ensemble mean gridded CDD data from ISMIP 3b at a 0.5° resolution for multiple global warming levels (1.2, 1.5, 2, 2.5, 3 and 3.5°C compared to a pre-industrial climate) and a set point temperature of 24°C (Werning, Frank, et al. 2024; Werning, Hooke, et al. 2024). Shared Socio-Economic Pathways (SSP) (see section 2.4) population data and projections are obtained at a 0.5° resolution and at five-year timesteps. We calculate the population in areas with over 50, 100, 200, and 400 yearly CDDs and set the population exposed to heat as the median value, following the approach by Andrijevic et al. (2021). Population exposed to heat is calculated at a 0.5° resolution and 5-year timesteps under a scenario of high GHG emissions culminating in 3.4°C of warming by 2100 before being aggregated to the 26 IMAGE regions as regional shares. The share of the regional population exposed to heat per year under each scenario is calculated by scaling with the level of projected global warming in IMAGE.



Vulnerability to heat

Vulnerability to heat is not only determined by exposure to hazards alone, but also to be driven by the ability of social systems to adapt in response to disturbances and hazards (Turner et al. 2003; IPCC 2022). As such, assessing vulnerability to heat requires examining the ability of different populations to cope with heat, defined here as the ability to afford a space cooling appliance – either an AC or an evaporative cooler. We calculate the population vulnerable to heat as the population that is exposed to heat and lacking a cooling appliance, calculated using Equation 1. We focus on whether people are vulnerable to heat, rather than assess the severity of the impacts of heat exposure. This is equivalent to the definition of the cooling gap by Andrijevic et al. (2021); in this paper we exclusively use the term vulnerability to heat.

$$\text{population vulnerable to heat}_{reg,q} = \text{population exposed to heat}_{reg} \times (1 - \text{ability to invest in cooling appliance}_{reg,q,appl}) \quad (1)$$

Where *reg* are the regions, *q* the private consumption quintiles, disaggregated across rural and urban population groups, and *appl* the cooling appliances. As the population exposed to heat is not calculated at the level of private consumption quintiles, we assume that income quintiles are evenly spatially distributed within regions.

Modelling cooling appliance ownership and energy demand in IMAGE 3.4

Cooling appliance ownership and the energy demand required for the provision of cooling as a household energy service are modelled in IMAGE 3.4 (Daioglou et al. 2012; 2022; PBL 2025), for 26 regions (see SI1 for definitions) and five private consumption quintiles for both urban and rural population groups (i.e. a total of 10 quintiles).

Cooling appliance ownership is modelled at the household level as a function of climate and



private consumption (Isaac and Van Vuuren 2009). First, the climate-based demand for ownership is calculated from an exponential function and population-weighted CDDs. This parameter represents observed ownership preferences based on historic data and is not directly related to the heat exposure threshold calculated in section 2.1. Second, we calculate households' ability to invest in cooling appliances assuming a logistic relationship with private consumption projections. Richer households in colder climates have low cooling needs and a high ability to invest in a cooling appliance. Conversely, poorer households in warmer climates have greater cooling needs but lower investing abilities. We model cooling appliance ownership as the product of these two parameters.

Three cooling appliances are modelled: fans, air conditioners, and evaporative coolers. As all three run via electricity, we assume that only electrified households can meet their cooling needs. We use projected electrification shares per region and private consumption quintile (van Ruijven et al. 2012). Access to the different options is based on affordability. Fans are the most affordable cooling appliances; however, they are assumed to only partly fulfil households' cooling requirements, thereby not protecting households from being vulnerable to heat. As households become richer, they can start investing in ACs and evaporative coolers, thereby fulfilling all their cooling needs. The regional distribution between evaporative cooler and AC ownership is based on the share of population living in dry climate zones deemed suitable for evaporative cooler use (Mastrucci et al. 2021).

Energy demand for cooling is driven both by the number of households with cooling appliances and the average energy consumption per appliance. The latter is calculated as a function of CDDs, private consumption and cooling intensity – which is linked to appliance energy-efficiency improvements and building insulation (Daioglou et al. 2022). Energy-efficiency projections for different scenarios are obtained from EIA (2023).

To improve estimates of cooling appliance uptake and associated energy demand, we implement several new developments. First, we represent the Urban Heat Island (UHI) effect, i.e., the phenomenon whereby cities face higher air temperatures than surrounding



non-urban areas, by exposing urban households to different Degree Days than their rural counterparts. With over 55% of the global population currently living in cities, and expected increases projected to reach 60-92% in 2050 across socio-economic futures (Jiang and O'Neill 2017), representing the impact of the UHI effect on cooling energy demand is essential (Santamouris et al. 2015). We set CDDs to be 20% higher (and Heating Degree Days 10% lower) for urban households globally based on findings from Schatz and Kucharik (2016).

Second, we model green roof deployment to explore their potential in reducing cooling energy demand growth. We give households the opportunity to install green roofs in addition to other insulation improvements by building on the residential stock and insulation model of IMAGE (Daiglou et al. 2022). We model green roofs to impact the thermal conductivity (i.e., U-value coefficients, measured in W/m²/K) of roofs, which in turn affects the energy required for cooling and heating. Data is obtained on U-value coefficients from a literature review. We calculate U-value coefficients after green roof installation, assuming a logarithmic relationship with U-value coefficients before installation (see SI). Insulation investment decisions are based on cost characteristics of insulation levels, as well as the possible reduction in fuel costs from lowered heating and cooling demand. Green roof costs obtained from Manso et al. (2021) are annualised assuming an average lifetime of 15 years and added to the costs of the adopted insulation levels (see SI). The market shares of insulation levels are allocated based on relative cost competitiveness, using a multinomial logit function (Daiglou et al. 2022).

Scenarios

The scenarios used in this study follow futures of varying mitigation and adaptation efforts, based on the SSPs (see Table 1 for an overview of scenarios and major assumptions). The SSP scenarios provide exogenous information about key drivers such as population growth, household private consumption expenditure, GINI coefficients and urbanisation rates (Riahi et al. 2017). This paper uses the SSP2 scenario, which represents a continuation of current trends in socioeconomic and technological developments, as our *Baseline* scenario. From this, we derive a scenario looking into a well-below 2°C target (following a path close to the RCP2.6 scenario) using a uniform carbon price which leads to a cost-optimal mitigation



strategy (*Mitigation* scenario). The carbon price incentivises a reduced use of GHG-emitting technologies and activities, as choices in IMAGE are typically based on costs (see PBL 2025).

The *Adaptation* scenario assumes no mitigation efforts (i.e. the *Baseline* scenario), combined with the provision of cooling to all vulnerable households by 2050. We also assume that electrification rates increase by 2050 to ensure near universal access to electricity. The *Adaptation-Mitigation* scenario represents a future with both high adaptation and mitigation efforts.

Finally, the *Integrated Adaptation-Mitigation* scenario explores how a wide and integrated set of measures and strategies could limit increases in cooling energy demand, covering both supply- and demand-side drivers. First, it assumes that cities are designed in such a way that the intensity of the UHI effect is progressively reduced and halved by 2070. Second, green roofs are adopted widely as a passive cooling practice to improve the thermal performance of buildings. Third, simultaneous governmental policies and rapid technological progress enable rapid energy efficiency improvements of the cooling appliance stock. Fourth, behaviour and preference changes lead to increased tolerance of warmer indoor temperatures (driven by e.g. heat acclimatization and environmental consciousness), leading to an increase in CDD set point temperatures (see Table 1), and thus lower overall CDDs. Previous research has demonstrated the moderating potential of adjusting the set point temperature on cooling energy demand growth (Byers et al. 2024). These assumptions in the *Integrated Adaptation-Mitigation* scenario impact neither heat exposure nor cooling access but rather affect the energy demand required for space cooling.



Table 1: Characteristics and assumptions of the scenarios.

Scenario	Climate policy	Heat-vulnerable population	UHI CDD/HDD factor	Energy efficiency	Green roof uptake	CDD set point temperature
Baseline	None, SSP2 baseline	Projected	1.2/0.9	Default	None	23.3°C
Adaption	None, SSP2 baseline	Forced to 0 by 2050	1.2/0.9	Default	None	23.3°C
Mitigation	Endogenous, consistent with RCP 2.6	Projected	1.2/0.9	Default	None	23.3°C
Adaptation-Mitigation	Endogenous, consistent with RCP 2.6	Forced to 0 by 2050	1.2/0.9	Default	None	23.3°C
Integrated Adaptation-Mitigation	Endogenous, consistent with RCP 2.6	Forced to 0 by 2050	1.1/0.95 by 2070	Increased	Minimum market share of 30% by 2050	25°C by 2035

While this model is developed for a global application within IMAGE, we focus on 6 IMAGE regions – Brazil, West Africa, South Africa, India, China, and Russia – due to the relevant dynamics concerning vulnerability to heat in these regions and the wide range of socio-economic and climatic conditions covered.



Results

Baseline

The calculations show that 3.6 billion people worldwide are currently vulnerable to heat i.e. exposed to heat but lacking cooling access. This finding falls in line with Garcia et al. (2022) which estimates 3.7 billion people to be at risk from a lack of cooling access globally, considering other cooling services such as refrigeration. In the *Baseline* scenario, we project an additional 564 million people to become vulnerable by 2050. This is mainly driven by population growth, with the global population share that is vulnerable to heat remaining constant at 43%. Over the second half of the century however, the population share that is vulnerable to heat drops, comprising 3.4 billion people, driven by expected economic growth in South Asia, South America and North Africa and the subsequent adoption of cooling. Given that we represent vulnerability to heat rather than the level of heat-related impacts, the effect of future climate change is minor in regions already experiencing high rates of heat exposure.

We find India to be the region with currently the largest population vulnerable to heat at nearly 1 billion people (931 million). By 2050, 105 million fewer people are projected to be vulnerable due to rising incomes. Between 2050 and 2100, the number of heat-vulnerable people in India is projected to nearly halve due to expected population decline and continued economic growth, dropping to 456 million in 2100. Brazil follows a similar pattern, albeit slightly later in time. Until 2060, over half of Brazil's population is projected to be vulnerable to heat. From 2060 onwards, the projection not only shows an income increase but also a declining population, resulting in a strong decline in the number of heat-vulnerable people (Figure 1).

In contrast, in West Africa the heat-vulnerable population is projected to increase in the future. Nearly 600 million people – i.e., 91% of the region's population – are currently vulnerable. Despite increases in cooling access, it remains limited due to low electrification



rates and incomes. As a result, an additional 400 million people are expected to become vulnerable by 2050, exacerbated by expected rapid growth of the region's population. This corresponds to nearly 1 billion people, surpassing India to become the most vulnerable region in absolute terms (Figure 2). Only from 2090 the vulnerable population is projected to shrink due to slowed population growth as well as accelerating economic growth allowing more households to purchase cooling appliances. Still, well over two thirds of the region's population – 1.3 billion people – are projected to remain vulnerable to heat by 2100.

In South Africa as well, the number of vulnerable people is expected to increase throughout the century, mainly due to rising exposure to heat. By 2050, an additional 6.5 million people are projected to become vulnerable. This trend continues after 2050, despite population decline. Only from 2080 onwards the number of vulnerable people is projected to stop increasing and remain stable at approximately 20 million. Although more marginally, heat-vulnerability is also projected to grow in Russia, despite its considerably cooler climate and declining population. As CDDs increase at a faster rate than private consumption, an additional 2.1 million people become vulnerable to heat between 2026 and 2100 (Figure 1).

In China, on the other hand, the number of heat-vulnerable people is projected to decrease substantially before 2050, due to rapidly rising incomes and steep demographic decline. 121 million people are currently vulnerable to heat with projected decreases to 7.6 million in 2050 and nearly 0 by 2100.



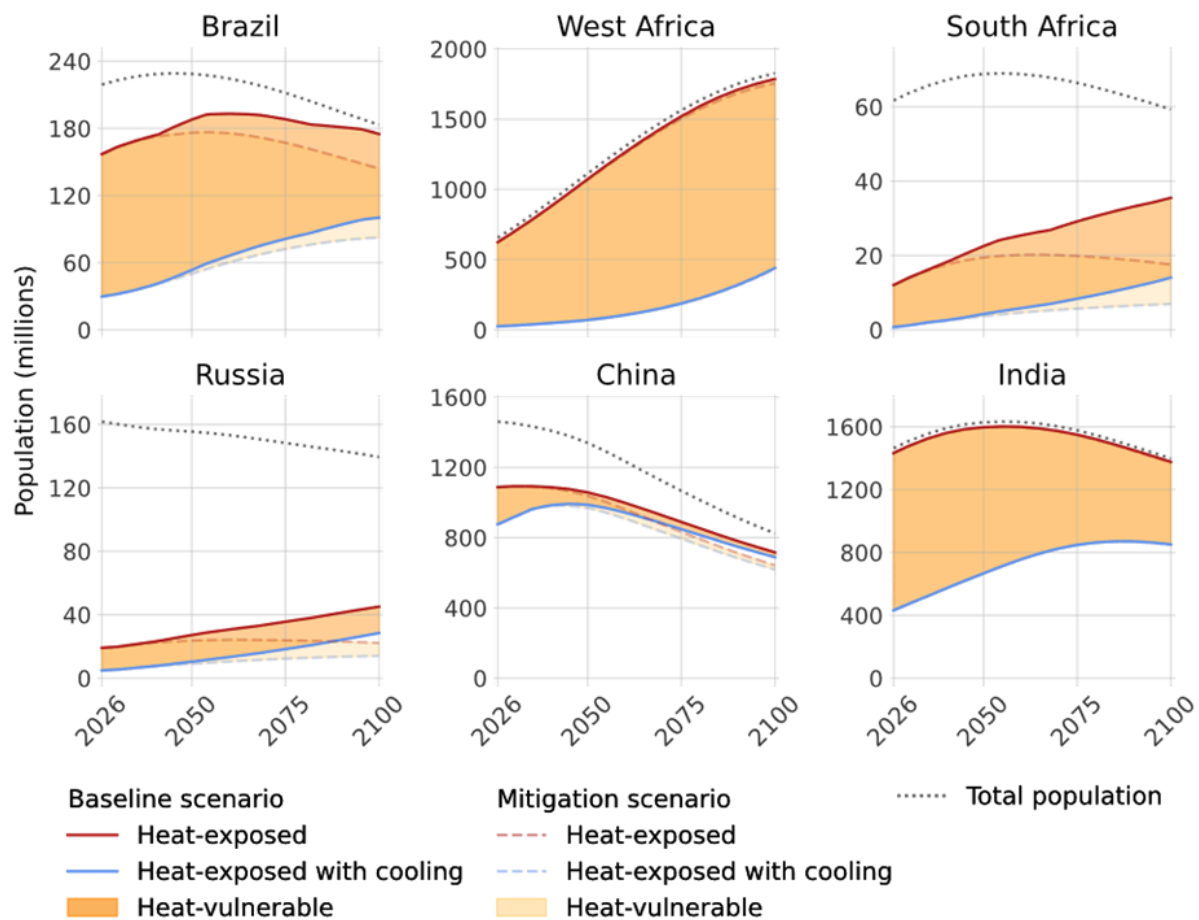


Figure 1: Projected heat exposure and vulnerability to heat under the Baseline and Mitigation scenarios in 6 IMAGE regions.

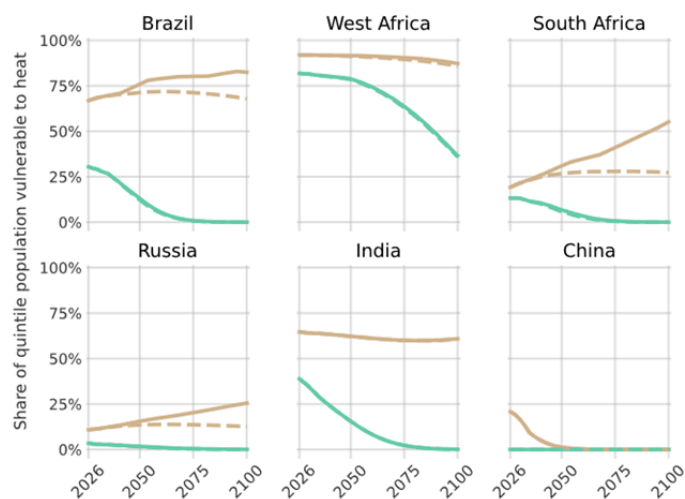
Looking within regions, we find that vulnerability to heat is unequally distributed across population and income groups. Increasing inequalities in vulnerability to heat throughout the century are projected among the private consumption quintiles of most regions under the *Baseline* scenario (Figure 2). This divergence is driven by assumptions on a widening inequality in households' private consumption across quintiles. In low- and middle-income

regions with hot climates, the richest population groups tend to gain cooling access more quickly over time and thereby become less vulnerable to heat, due to private consumption increasing at faster rates than CDDs. At the same time, the poorest population groups remain as – if not more so – vulnerable. In India for example, vulnerability to heat persists within the lowest private consumption quintiles: the share of population within it is projected to decrease by less than 5% in both urban and rural areas by 2100. Indian households in the wealthiest quintiles, on the other hand, are able to fully adapt approximately by 2080. In regions with more limited heat exposure, we project the poorest households to become increasingly vulnerable to heat over time as temperatures increase in the *Baseline* scenario. In Russia and South Africa, the share of the heat-vulnerable population within the lowest private consumption quintiles respectively doubles and triples by 2100. Meanwhile, households in the highest private consumption quintiles become – or remain – protected and unaffected by heat.

China is the sole region which experiences decreasing inequalities in terms of vulnerability to heat throughout the century. While over a third (39%) of households in China's lowest rural private consumption quintile are vulnerable to heat today, by 2070 nearly no households are expected to be vulnerable to heat. Compared to most regions, projected private consumption grows in a more equal manner across quintiles; this enables the poorest households to afford cooling and thereby able to cope with heat.



a)



b)

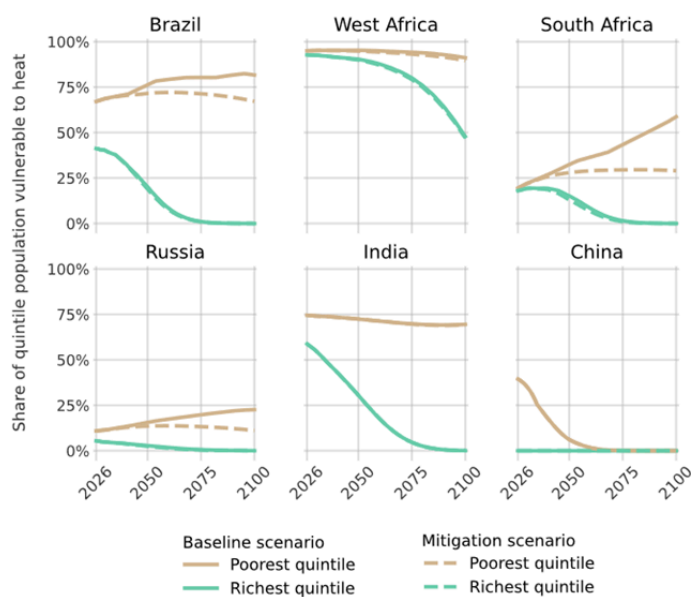


Figure 2: Projections of the population vulnerable to heat in a) urban households and b) rural households for both Baseline (solid line) and Mitigation (dashed line) scenarios, for the highest (green) and lowest (brown) private consumption quintiles of urban and rural population groups.



Mitigation

Climate change mitigation leads, as expected, to lower vulnerability to heat in the future. In the *Mitigation* scenario, 53 million (-1.3%) and 220 (-6.4%) million fewer people than in the *Baseline* scenario are projected to be vulnerable to heat in 2050 and 2100, respectively. The two scenarios clearly diverge after around 2050, as changes in global mean temperatures between the two become more obvious in the latter half of the century (leading to 3°C, and well below 2°C respectively). Regionally, the impact of climate change mitigation on vulnerability varies greatly (Figure 1). Within West Africa, nearly 22 million fewer people are projected to be vulnerable to heat in 2100 in the *Mitigation* scenario, compared to the *Baseline*. Important decreases in the number of vulnerable people are also projected in other regions. In Brazil, nearly 13 million fewer people are projected to be vulnerable under the *Mitigation* scenario than in the *Baseline* in 2100, corresponding to a 18% decrease. South Africa and Russia are projected to experience larger relative benefits, with the number of heat-vulnerable people decreasing by half as a result of mitigation. In these three regions, we find that mitigation actions result in fewer households exposed to high heat and in turn fewer face the risk of becoming vulnerable (Figure 1). Despite these reductions, the number of vulnerable people still grows throughout the century in the *Mitigation* scenario, with over 3 billion people projected to remain vulnerable to heat by 2100. As we focus on vulnerability to heat rather than the severity of the impacts, the effect of climate policy in India, West Africa and China is relatively small as people remain far above the heat exposure threshold and as a result are deemed vulnerable if not equipped with a cooling appliance, despite the lower ambient temperatures compared to the *Baseline* scenario.

Mitigation efforts are found to reduce vulnerability-related inequalities. The poorest households benefit most from the mitigated temperature increases which reduce their vulnerability given their inability to fulfil their cooling needs by adopting cooling appliances. For example, rather than tripling between 2026 and 2100, in the *Mitigation* scenario, the share of heat-vulnerable households in South Africa's poorest quintiles stabilizes at about 28% (Figure 2). While climate change mitigation does not address the underlying inequalities



– diverging households’ private consumption –, it reduces inequalities in terms of heat-vulnerability by improving the conditions of those remaining without cooling.

Adaptation and implications for energy demand and emissions

Under the *Adaptation*, *Adaptation-Mitigation* and *Integrated Adaptation-Mitigation* scenarios, the population vulnerable to heat is set to reach zero by 2050 (Table 2), by ensuring cooling access to all heat-vulnerable populations. This impacts global energy demand for residential space cooling. Under the *Adaptation* scenario (see Table 1) global energy demand for cooling is projected to increase seven-fold by the end of the century, in contrast to the approximately four-fold increase in the *Baseline* scenario (Figure 3). Energy demand under the *Adaptation* scenario is respectively 156% and 76% higher in 2050 and 2100 than under the *Baseline*. In absolute terms, this means it would require an additional 11 EJ in 2050 and 12 EJ in 2100 to ensure cooling access to all, consistent with previous estimates (Byers et al. 2024). Most of this energy demand growth comes from AC use, given that evaporative coolers are more limited in both adoption (due to climate constraints) and are less energy-intensive.

West Africa alone is projected to contribute to just over a third of this global increase in energy demand in 2100, due to its high number of vulnerable people in the *Baseline* who would obtain cooling access in the *Adaptation* scenario, as well as the large amount of CDDs leading to high energy use per appliance. Ensuring cooling access to all heat-vulnerable people is expected to triple the region’s cooling energy demand in 2100, compared to the *Baseline*. South Africa is the second region with the greatest relative energy demand increases at the end of the century under the *Adaptation* scenario, with energy demand projected to be 238% higher than the *Baseline*. These two regions are subject to the greatest relative increases as they both face an increasing number of heat-vulnerable people in the future. In contrast, in China, Brazil and India, cooling demand is expected to grow considerably in the *Baseline* scenario as households are increasingly able to access cooling when needed due to socio-economic development; as such providing cooling for all impacts energy demand growth more marginally.

Climate change mitigation reduces the additional energy required to provide cooling for all. In 2100, the *Adaptation-Mitigation* scenario projects a 58% reduction in global cooling



energy demand of the *Adaptation* scenario; this represents a 226% increase compared to 2026 values (Figure 3). The hampered energy demand growth is driven by lower ambient temperatures – which lead to reduced heat exposure and energy use per appliance – and policies promoting energy efficiency and increased use of technologies emitting fewer GHGs. Similarly to heat exposure and vulnerability projections, energy demand projections of the *Adaptation* and *Adaptation-Mitigation scenarios* only clearly diverge after 2050. While in 2050, energy demand is still higher in the *Adaptation-Mitigation* scenario than in the *Baseline*, by the end of the century the former results in a 26% decrease in global cooling energy demand from the latter, despite all cooling needs being fulfilled. At the regional level, we project energy demand in South Africa and West Africa to still be slightly higher in the *Adaptation-Mitigation* scenario than in the *Baseline* in 2100. Nevertheless, this corresponds to respective decreases of 58% and 59% from the *Adaptation* scenario. While trade-offs can occur between heating and cooling energy demand, the decrease in cooling demand from climate change mitigation is not projected to be counterbalanced by heating demand as the latter also experiences a decrease due to a shift towards less GHG-intensive technologies.

Implementing additional measures (*Integrated Adaptation-Mitigation* scenario) can further reduce cooling energy demand in the medium-term, before the effects of climate change mitigation on cooling energy demand become significant. In 2050, these measures are projected to enable a 27% reduction in global cooling energy demand from the *Adaptation-Mitigation* scenario. By 2100, the difference between the two scenarios is smaller, partially due to the energy efficiency improvements in the *Adaptation-Mitigation* scenario converging with those assumed in the *Integrated* scenario. Still, non-appliance energy-efficiency related measures – i.e., the widespread uptake of green roofs, reduced UHI effect, and behaviour change – are projected to enable an 19% reduction in cooling energy demand from the *Adaptation-Mitigation* scenario in 2100. This corresponds to a 66% and 40% decrease from the *Adaptation* and *Baseline* scenarios, respectively. Looking beyond this global average, the *Adaptation-Mitigation* scenario leads to lower cooling energy demand than in the *Baseline* by 2100 in all six studied regions. Tackling climate mitigation and adaptation to heat simultaneously, with targeted policies to reduce cooling needs and demand, seems to require less cooling energy than acting on neither.



Table 2: Key global results for 2026, 2050, and 2100.

Scenario	Global mean temperature (°C)			Heat-vulnerable population (billion people)			Cooling energy demand (EJ/year)		
	2026	2050	2100	2026	2050	2100	2026	2050	2100
<i>Baseline</i>	1.21	1.78	2.88	3.6	4.1	3.4	3.6	7.3	15.8
<i>Adaptation</i>		1.79	2.91		0	0		18.7	27.9
<i>Mitigation</i>		1.60	1.66		4.1	3.2		6.8	6.7
<i>Adaptation-Mitigation</i>		1.60	1.67		0	0		17.7	11.8
<i>Integrated Adaptation-Mitigation</i>		1.60	1.66		0	0		13.0	9.5



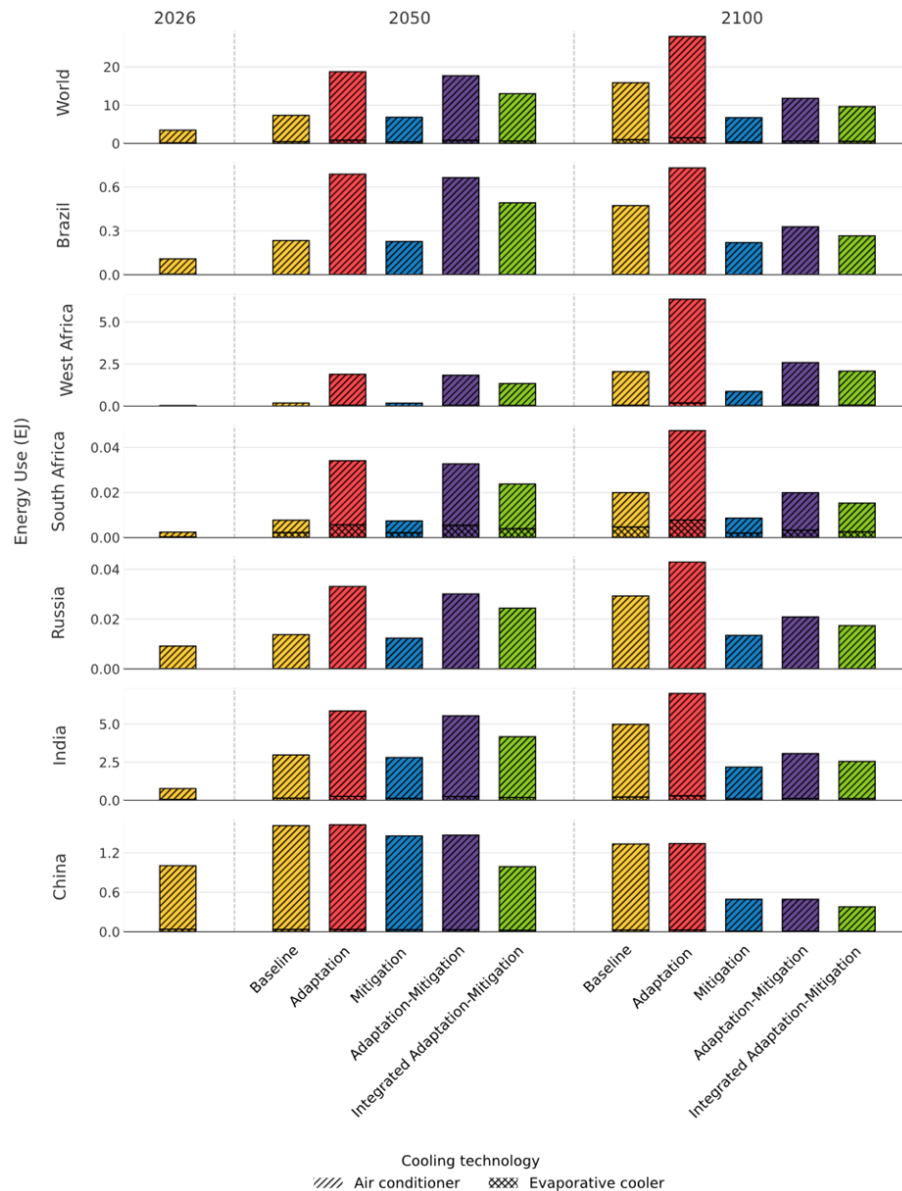


Figure 3: Projections of residential air conditioner and evaporative cooler energy demand for six IMAGE regions and the world total.



In terms of emissions, providing cooling access to all vulnerable households (*Adaptation* scenario) would increase global total energy system CO₂ emissions by over 4% in 2050 compared to the *Baseline*. However, under a scenario of stringent climate change mitigation, energy demand and CO₂ emissions are decoupled due to a decarbonised energy system. Globally, total system emissions increase by a maximum of 2.4% (in 2047) in the *Integrated Adaptation-Mitigation* scenario, compared to the *Mitigation* scenario (Figure 4). In most regions with heat-vulnerable populations, emissions only increase marginally. Total energy system CO₂ emissions increase by 0.4% for Brazil, 262% for West Africa, 1.1% for South Africa, 0.4% for Russia, and 7.3% for India. Although the relative increase is large in West Africa, it only corresponds to 0.05 Gt CO₂/year – approximately 0.5% of global energy related CO₂ emissions in the *Baseline*. These additional emissions are greatest between 2040 and 2050, a decade in which the transition towards providing cooling for all is reaching completion, while mitigation measures are still ramping up.



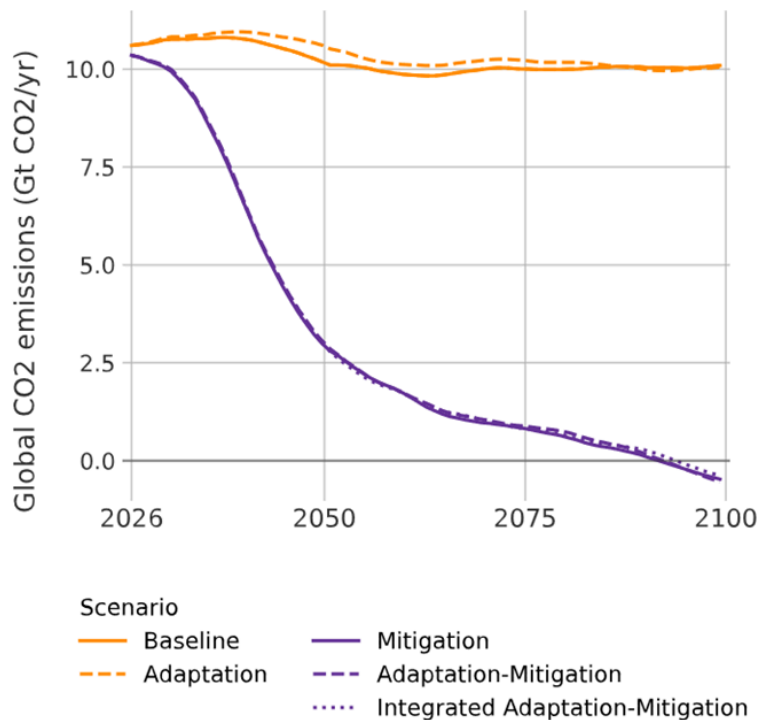


Figure 4: Projections of total energy system CO₂ emissions.

Discussion

This analysis highlights a persistent adaptation gap in the future, concerning households' abilities to cope with heat exposure. Vulnerability to heat is expected to be highly heterogeneous, both across and within regions. While cooling is – or will become – accessible to all in need in high-income regions, billions of low-income households in Brazil, West Africa, South Africa, and India are projected to lack cooling access while also being exposed to heat. In these regions, improvements in cooling access remain heavily concentrated among the wealthiest groups throughout the entire century, and vulnerability to heat persisting within poorer households. This unequal vulnerability to heat within regions



is mainly driven by private consumption of households, modelled based on GINI income inequality coefficients from SSP projections (Rao et al. 2019). The expected widening income inequality prevents the poorest households from being able to afford air conditioners and evaporative coolers to adapt and cope with ever-increasing temperatures.

While we find that climate change mitigation does not have a major effect on vulnerability to heat, its benefits might be underestimated from the yearly CDD threshold used as an indicator of heat exposure. For instance, the effect of climate policy in West Africa and India is relatively small as a large share of the population remains far above the vulnerability threshold; yet the heat they are exposed to – and its associated risks – is greatly reduced in the *Mitigation* scenario. Moreover, temperature extremes exacerbated by climate change and their effects on health are not accounted for, occluding more benefits of climate change mitigation.

The number of heat-vulnerable people depends greatly on socioeconomic conditions. In the futures of SSP1 and SSP5 characterised by rapid income growth, households can purchase cooling appliances more easily as such the number of heat-vulnerable people is projected to decrease considerably, to 3.7 (2) and 2.6 (1.3) billion, by 2050 (2100) respectively. In contrast, in SSP3 the number of vulnerable people increases consistently and reaches 4.6 (6.8) billion in 2050 (2100), due to much slower economic growth as well as high emission levels and severely increasing temperatures. Comparing our projections with other studies shows them to be in line with the estimated 2.4 - 4.1 billion people vulnerable to heat in 2050 by De Cian (2024) and Andrijevic et al - (0.5-7.2 billion in 2100) although with a slightly narrower range of results.

The energy demand required to provide cooling to all vulnerable households also varies considerably among potential socio-economic futures (*Adaptation* scenario). While SSP5 is expected to result in the lowest number of heat-vulnerable people, SSP1 leads to the lowest cooling energy demand with 20EJ/year in 2100, due to its rapid technological progress and mitigated temperature increases. In contrast, SSP5, with its hotter temperatures and slower



technological change, requires more energy – 25EJ/year in 2100 – to fulfil global cooling needs. Under SSP3, energy demand to provide cooling for all is the highest among the SSPs, with 32EJ/year in 2100. Beyond future socio-economic development, the set point temperature assumed to calculate CDDs affects projected cooling energy demand, especially given the lack of consensus on a universally observed adopted global or regional set point temperature.

Regarding policy implications, our results suggest that future expected socio-economic development is largely insufficient to address current vulnerability to heat in many regions. Targeted policies will be needed to achieve the assumptions of universal access to cooling by 2050. At the same time, we show that without stringent climate change mitigation efforts, providing cooling to everyone in need will have a considerable impact on energy demand – and by association, GHG emissions. With both points in mind, the Global Cooling Pledge was launched as a multi-lateral initiative at the COP28 in 2023, aiming to simultaneously expand access to cooling and reduce cooling related emissions over the coming decades. It emphasises the importance of ‘sustainable cooling’ – encompassing, among others, action on energy efficiency and passive cooling strategies – to achieve Paris Agreement climate goals, which this study corroborates. Promoting a wide range of solutions beyond AC to address cooling needs can help mitigate the energy and GHG emissions increases of a growing residential space cooling sector. Efforts to limit warming to well-below 2°C are also expected to lower the impacts of cooling, as deep decarbonisation enables a decoupling of energy demand and emissions. Conversely, limited mitigation action will inevitably increase the need of electricity for cooling, as well as increase the possibility of large portions of the global population being vulnerable to heat, and associated negative health and economic impacts.

Several caveats remain in this paper. First, we use ownership of two cooling appliances – air conditioners and evaporative coolers – as a proxy for cooling access, restricting our assessment of adaptation to the technological realm and ignoring other adaptation strategies with considerable potential to reduce both exposure and vulnerability to heat,



such as urban design, building insulation and passive cooling strategies (Turek-Hankins et al. 2021). While improving the representation of alternative adaptation strategies is crucial to better model vulnerability to heat, this paper incorporates these strategies by focusing on their potential to limit the future energy growth required to adapt to heat.

A second limitation stems from our limited representation of various economic effects and dynamics. We do not consider the phenomenon of energy limiting behaviours reported in low-income and vulnerable households (Huang et al. 2023) as we first assume a binary nature of cooling access, i.e. people either have access to cooling or they do not. In the context of cooling, energy limiting behaviours entail an inability or unwillingness of households to consume – and spend – enough energy to cool their homes to comfortable levels (Huang et al. 2023; Kwon et al. 2023). Low-income households indeed tend to turn on their cooling appliances at higher temperatures than households without significant budget constraints, resulting in a cooling energy equity gap of multiple degrees (Huang et al. 2023; Cong et al. 2022). Nevertheless, this aspect of energy affordability is mainly studied in the context of richer regions; in a global context, access to energy is considered as a major driver of energy poverty (Kwon et al. 2023). Second, we do not account for the potentially regressive nature of climate change mitigation policy and its impacts on the purchasing power of households. Climate policy has been found to exacerbate inequalities when it does not include climate revenue redistribution, i.e. by raising energy costs (Emmerling et al. 2024). It can then hinder poorer households from investing in cooling appliances or efficiency improvements, thereby increasing vulnerability to heat. Accounting for these economic dynamics in the context of vulnerability to heat would improve our understanding of interactions between climate change mitigation and adaptation.

Conclusions

Approximately 3.6 billion people worldwide are currently vulnerable to heat. Despite socio-economic development enabling millions to gain cooling access, more than 4.1 and 3.4 billion people are projected to remain vulnerable to heat by 2050 and 2100, respectively.



West Africa and South Africa experience a growing population vulnerable to heat over most of the century, with rising temperatures and population growth offsetting economic development. We also find increasing intra-regional inequality in vulnerability to heat in all six studied regions apart from China. In nearly all regions, the poorest populations become increasingly vulnerable to heat as they remain unable to afford cooling appliances amidst rising temperatures, while the richest households are protected by space cooling.

Meeting the Paris Agreement would mean 53 million and 220 million fewer people would suffer from severe heat in 2050 and 2100, respectively, due to reduced increases in ambient temperatures. These improvements are projected to mainly be driven by ameliorations in regions in Africa and South America. Mitigation efforts prevent the poorest households within most regions from becoming vulnerable to heat. Mitigated ambient temperature increases improve the conditions of those remaining without cooling due to socio-economic constraints. However, even with stringent climate change mitigation, more than 3 billion people would remain vulnerable to heat in 2100. Ensuring cooling access to all vulnerable households will not be achieved through socio-economic development alone, highlighting the need for stronger targeted adaptation efforts.

Focusing on adaptation action alone, i.e. providing universal access to space cooling, is projected to require a 156% and 76% increase in global energy demand for space cooling in 2050 and 2100, respectively. The impact on energy demand varies considerably across regions; in West Africa a three-fold increase would be required to meet the cooling needs of the 1.3 million heat-vulnerable people in 2100. Globally, focusing on adaptation would result in a 4% increase in total energy system CO₂ emissions, further exacerbating future climate change.

Simultaneous mitigation and adaptation action can meet climate and cooling access goals without significant increases in total energy use and emissions. Cooling energy demand required for adaptation can be more than halved at the end of the century if warming is limited to well-below 2°C. If combined with additional measures such as passive cooling,



sustainable urban planning resulting in cooler cities, fast energy-efficiency improvements of cooling appliances, and behaviour change, cooling energy demand can be cut by two-thirds. With this integrated strategy, we project that providing cooling to all vulnerable populations is possible while keeping increases in global CO₂ emissions at a maximum of 2.6%, compared to a *Mitigation* scenario. Thus, providing cooling to all vulnerable populations through integrated adaptation action can be achieved without interfering with climate change mitigation efforts nor compromising climate goals.

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[1] Global climate models used: GFDL-ESM4, IPSL-CM6A-LR, MPI-ESM1-2-HR, MRI-ESM2-0, UKESM1-0-LL

1.3. Adaptation in the water supply and demand sector, and risks of maladaptation

The increasingly pressing challenge of water scarcity is closely linked with accelerating climate change, demographic shifts and economic development pressures. Human-induced climate change is intensifying droughts and water shortage across many regions, posing significant threats to lives and livelihoods (Gebrechorkos et al., 2025; Li et al., 2024). Still growing populations, expansion of urban areas and economic activities demand ever increasing volumes of water for municipal, industrial and agricultural use. Recent assessments indicate that half of the world's population could face severe climate- and non-climate related water insecurity for at least once per year (Jones et al., 2024; Mekonnen & Hoekstra, 2025), and that the global population exposed to “extreme-to-exceptional” water scarcity could double by 2100, compared to 2000. The difference between limiting the global mean temperature increase to 1.5°C and higher degrees of warming is particularly critical, with higher temperatures amplifying the frequency and severity of hotspots of water stress (Byers et al., 2018). Beyond the direct reduction of water resources, excessive water withdrawal and climate impacts also damage critical infrastructure (Fan et al., 2023) and degrade water quality (Jones et al., 2023), further undermining water security (van Vliet et al., 2021).

Household water requirements are expected to rise with population growth. While about 8% and 26% of the global population do not have access to improved and safely managed drinking water, respectively, climate change might impact the capacity and possibility to



close this gap (“Progress on Household Drinking-Water, Sanitation and Hygiene 2000-2024,” n.d.). The same is true for access to sanitation services, which is tightly linked to hygiene and health conditions, and where the respective access rates are on average 10% lower than those of drinking water. Existing projections of sanitation access focus on some Socioeconomic Pathways but neglect climate variables, and could be expanded in time-horizon, geographical coverage and include drinking water access (van Puijenbroek et al. 2023; Swe et al. 2021).

Possible stressors on the demand side underscore the urgent need for adaptation strategies that address both direct and indirect impacts of water insecurity along the risk chain. Wastewater treatment and recovery (WWT) and desalination technologies offer crucial opportunities to augment freshwater supply, reduce risks of water stress, improve environmental and ecosystem water quality and enhance resilience of affected communities and sectors (Becher et al., 2024; Pistocchi et al., 2020, van Vliet et al., 2021). Both options offer solutions to both short-term issues in water supply and longer-term water security.

WWT is essential for protecting public health, preserving the environment and supporting sustainable development, but it is also an important adaptation option which can enable the reuse of water for irrigation, industry and even potable purposes. Treatment of contaminated water is typically characterized as primary (whereby large debris and solids are removed from water), secondary (which uses biological processes to eliminate organic matter and nutrients) and tertiary treatment (or advanced; whereby remaining contaminants are removed).

Desalination is the process of removing salts and impurities from saline, brackish or contaminated water, thereby creating new water resources for domestic, industrial or agriculture use. This process encompasses a range of technologies which can be broadly categorized as distillation-based (using heat to evaporate water), electrochemical (leveraging electric fields to remove ions) and membrane-based (using membranes to filter salts). Membrane-based technologies are becoming increasingly prevalent globally, owing to their significant improvements in efficiency and affordability (Fig. SI2).

However, scaling up these technologies risks creating new vulnerabilities and exacerbating climate pressures. Technologies that increase water supply tend to be energy intensive



(Magni et al., 2025). One of the most direct results are higher carbon emissions if the technologies are powered by fossil fuels, for which reason desalination and WWT could both be considered maladaptive - leading to (unintended) negative climate consequences and adverse climate-related outcomes (IPCC, 2022). Maladaptation can manifest in various ways, such as by increasing greenhouse gas emissions, increasing or shifting of vulnerability, creating new environmental problems, reducing incentives to adapt otherwise, etc. (Barnett and O'Neill, 2010; Rosa et al., 2026).

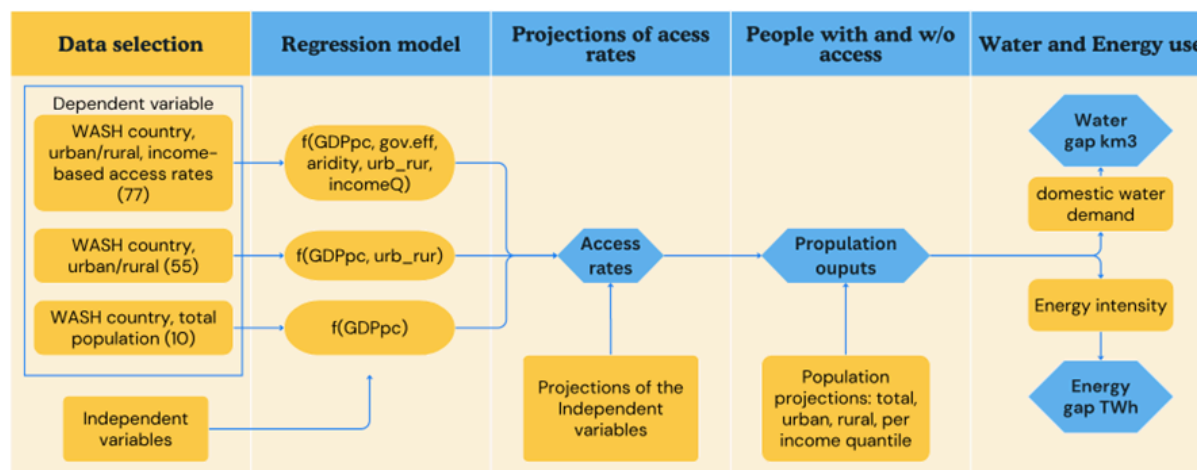
In this study, we offer an insight on the drinking water demand side, exploring projections of access to improved drinking water and sanitation services until 2100 to explore which scenarios might face the highest challenges related to climate change.

On the global-level supply side, we focus on the risks of maladaptation stemming from expanding WWT and desalination capacities across the 21st century. We integrate observational data, machine learning methods and socioeconomic and climate scenarios to project future growth, energy demand and emissions from the two technologies. Our analysis reveals that the type and pace of technological expansion and the underlying energy mix will fundamentally shape the benefits of adaptation and inadvertent negative consequences.



1.3.1. Demand-side projections of improved drinking water and sanitation

Methods



In this study, we develop a logit regression model that explains past increasing trends in improved water and sanitation access.

The Water Supply, Sanitation and Hygiene (WASH) database collects yearly household surveys and summarizes the country access rate for drinking water and sanitation at different quality levels (from surface water, including basic, to safely managed). Data released in 2023 provides the access rates for improved drinking water and sanitation (which includes the basic and limited categories) differentiated for rural and urban areas and income quintiles, for 105 countries with average rates below 99%.

Figure 1 shows the realizations in the data sample, highlighting how both the income quintile and the rural/urban dimension are determinants in defining access rates. The convergence towards access equal to one also shows a visible logistic curve trend, which motivates our model choice.

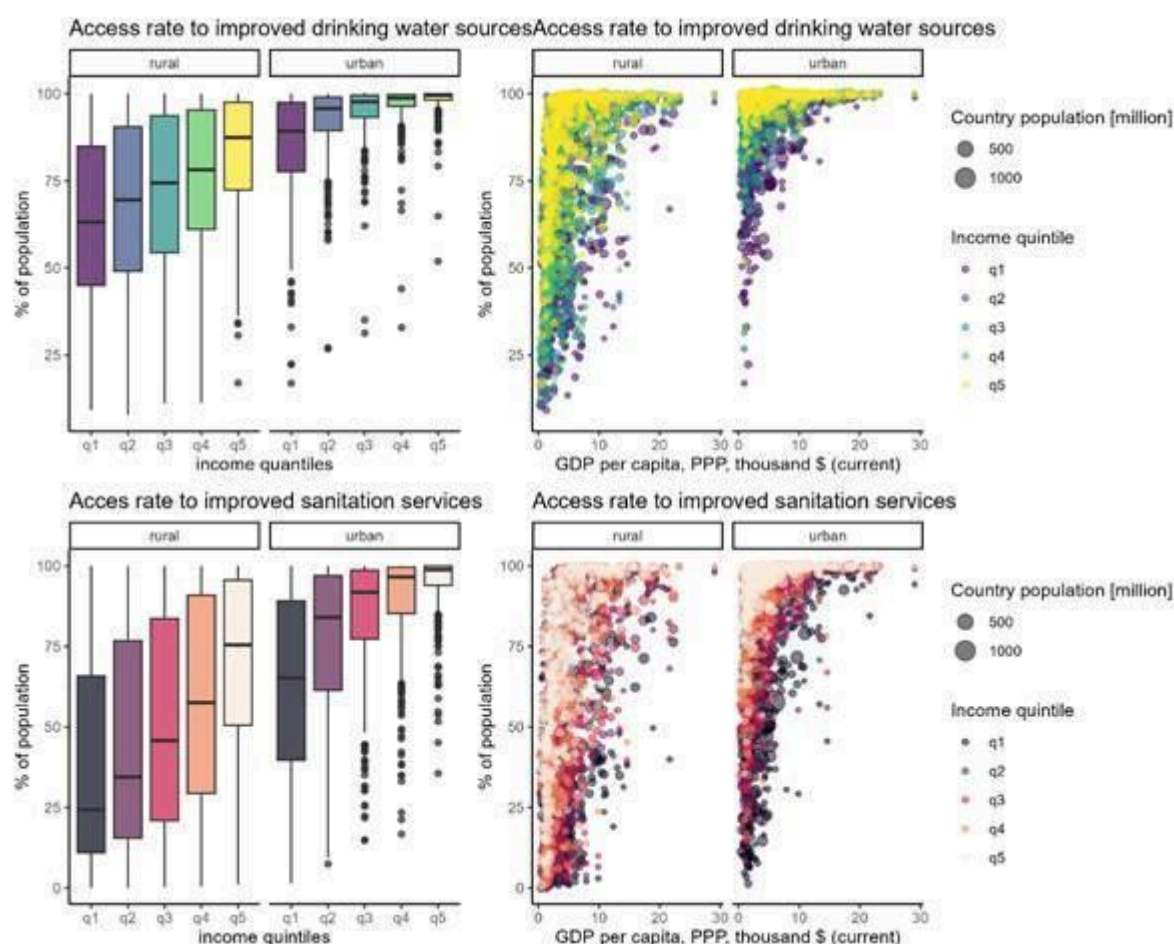


Figure 1: Access rates for improved drinking water and sanitation services for 105 countries in the years 1997 to 2020. Source WASH database 2023.

We use this dataset to build a regression model with different socioeconomic and climate variables (see Table 1.1). However, only 77 of these 105 countries had matching data for both dependent and independent variables in both the regression and projection stages. Therefore, we use simplified model specifications to cover a broader range of countries, combined with the annual version of WASH with simple country access rates, in some case



with urban/rural information (where we adopted model 2), or only total access (for which we used model 3).

The overall set of countries for which dependent and independent variable data sources matched is 142 countries.

We estimated national access to improved drinking water using generalized linear models (GLMs) with a quasibinomial family and a logit link to account for overdispersion in proportion data. For each observation i , let y_i be the share of the population with access and

$$\eta_i = \log\left(\frac{y_i}{1 - y_i}\right)$$

the logit transformation. All models include country fixed effects $\gamma_{c(i)}$ using country identifiers.

Model 3 (Full specification, used for 77 countries with available data)

This model uses all available socioeconomic, governance, climatic, and demographic predictors:

$$\eta_i = \beta_0 + \beta_1 \log(\text{GDPpcPPP}_i) + \beta_2 \text{GovEff}_i + \beta_3 \text{Aridity}_i + \beta_4 \text{IncomeQ}_i + \beta_5 \text{Urban}_i + \gamma_{c(i)}.$$

Model 2 (Reduced specification, 55 countries with available data)

For countries lacking governance and aridity data:

$$\eta_i = \beta_0 + \beta_1 \log(\text{GDPpcPPP}_i) + \beta_2 \text{Urban}_i + \gamma_{c(i)}.$$

Model 1 (Minimal specification, remaining 10 countries with available data)

For countries missing governance, aridity, and rural–urban information:



$$\eta_i = \beta_0 + \beta_1 \log(\text{GDPpcPPP}_i) + \gamma_{c(i)}$$

All models predict the log-odds of access, which are then transformed back to proportions using:

$$\hat{y}_i = \frac{1}{1 + e^{-\eta_i}}$$

This tiered model structure ensures that all countries can be included in the analysis despite differing data availability. For models 2 and 3, we split the basket of countries of those with a rate close to 99% in the historical time period from the others, because of the different explanatory power of the independent variables.

Table 0.1: Data used for regression and projections

Data indicator	Resolution	Source
<i>Historical data for regression</i>		
Drinking water access and sanitation per income decile	105 countries. Years 1997-2020	WASH, WHO 2023
Drinking water access and sanitation per country	All countries, 2000-2022	WASH, WHO 2025
Population	All countries, 2000-2022	WASH



GDP per capita	1960-2022	World Bank
Aridity, Water Stress Index (WSI)	All countries, 1975-2015 + SSP2-26 projection until 2022	ISIMIP3b
Governance indicators	173 countries, 1996-2015 + projection interpolation until 2022	Andrijevic et al., 2020
Water gap	1960-2024	WaterGap map?
<i>Data used for projections</i>		
Aridity	All countries, 2022-2100. RCP2.6 and 6.0, SSP1,2,3	ISIMIP3b
Governance effectiveness	173 countries, 2022-2100, all SSPs	Andrijevic et al., 2020
GDP PPP	177 countries, 2022-2100, all SSPs	OECD ENV-Growth 2023
Population	180 countries, 2022-2100, all SSPs	IIASA-WiC POP 2023



Urbanization, share of urban and rural population	188 countries, 2020-2100, all SSPs	Chen et al., 2022
Income decile, share of population	170 countries, 2020-2100, all SSPs	Narayan et al., 2023
<i>Data used for water and energy allocation</i>		
Municipal water demand	225 countries 2005-2100, SSP1,3,5	Magni et al., 2025
Energy demand and intensity	148 countries 2015, SSP1,3,5	Magni et al., 2025

For projections, we gathered several sources of projections of the independent variables along the SSPs for socio-economic indicators and, orthogonally, the RCP for climate indicators. We then apply the regression models and the fixed effects to deduct future access rates. We obtain projections of access rates for improved drinking water and sanitation services for the five SSP scenarios and RCP 2.6 and 6.0. Combining with corresponding population, urbanization and GINI projections, we can calculate the number of people (or share) per country with or without access to improved services.

Finally, we bring the analysis a step forward, combining the access shares with projections of municipal water demands from the global hydrological model PCR-GLOBWB 2 for SSP1, 3, and 5. From Magni et al., 2025 we also derive the corresponding energy intensity of such demand pathways in 2015 (Sutanudjaja et al. 2018; Magni et al. 2025). Assuming constant energy intensity in the future we can calculate the expected water and energy needs associated with the people without access to drinking water, which we refer to as the



drinking water gap and energy gap.

Results

From experimenting with different socioeconomic and climate variables, the first ones seem to explain changes in access rates, in primis GDP per capita, urban and rural location and income quintiles. The government efficacy indicator is not statistically significant itself (p-value around 0.4), but it statistically improves the model fit according to the Variance Inflation Factor test. Among different climate variables, aridity seems the one that best explains variations in access rates. For sanitation, we have similar results, with the difference that no climate variables seem to be statistically significant, highlighting that adoption of sanitation is mostly driven by economic and societal factors and not strictly linked to water availability or water stress.

The projections of access rates show that the socioeconomic assumptions embedded in the SSPs are determinants of a large spread of possible outcomes in water and sanitation access development, in particular in the lowest income quintiles and in rural areas.



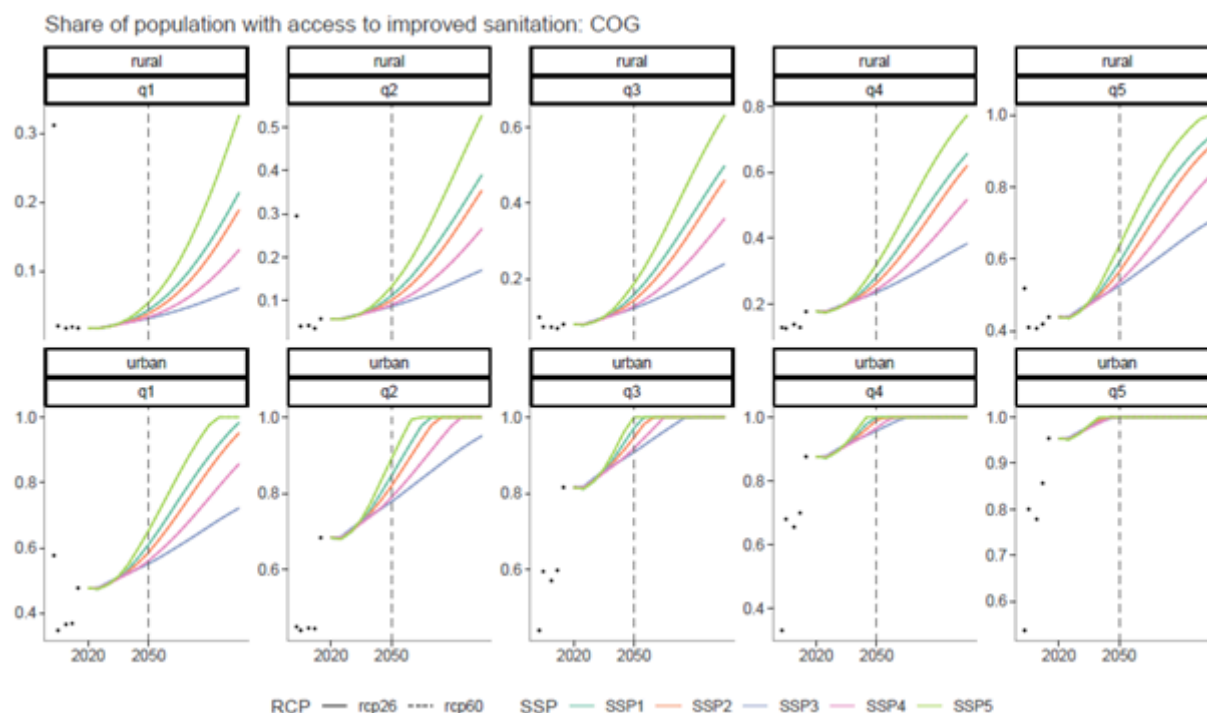


Figure 2: Sanitation access projections per income quintile in Republic of the Congo

Notably, most categories converge towards 100% access in SSP1 and 5, but for SSP 3 and 4 the expected increase in the rest of the 21st century is very limited, even in some urban areas. In urban areas, the upper three quintiles converge to 100% access in the second half of the century, regardless of SSP.

In terms of population, about 880 million people lack access to improved sanitation services in 2025 and 330 million people have no access to improved drinking water resources. Under SSP3, which has a narrative of global rivalry and large inequality, these numbers are likely to remain the same amid global population growth, meaning that the access rates improve, but the number of affected people remains constant. SSP4, with a narrative of widespread international inequality, shows a moderate reduction in the number of people lacking access. SSP2, 1 and 5, show increasingly stronger reduction trends, due to their positive assumptions

on socioeconomic growth. However, under no scenario is there 100% access to improved sanitation, and only SSP5 and 1 lead to more than 99% of the population with access. In this context, achieving the SDG targets of full access to safely managed water in 2030 does not seem realistic, unless strong and effective policies are in place.

Among the 30 countries with the highest number of people without access in 2050, we notice countries with large populations like India and China, that, despite the high access rates, might have a small share of the rural population lacking access, especially to sanitation services.

Ethiopia, the Republic of Congo, Nigeria, Niger, and Sudan, followed by other African countries, are those with still tens of millions of people without access to both improved drinking water and sanitation and relatively low access rates in 2050, with a wide spread given by the SSPs scenarios.



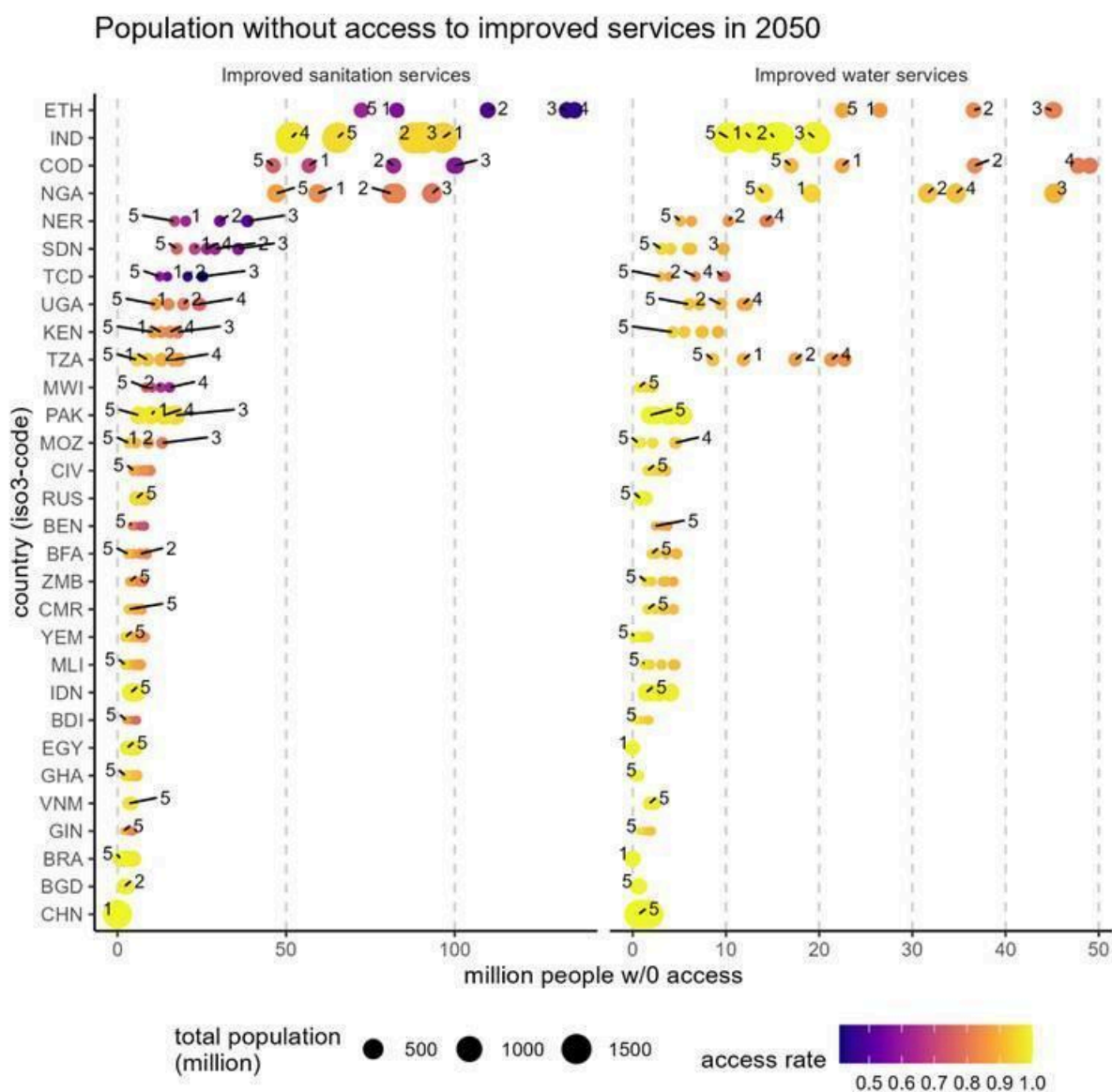


Figure 3: 30 countries with the largest number of people without access to improved water services by 2050. The numbers indicate the SSP scenarios



Looking at the population projection per income quintile, we notice that a large part of the current rural population without access to drinking water falls in the respective mid-high income ranges, with a higher possibility of being connected in the next decades. On the contrary, the number of people without access to drinking water in the lowest-income groups risk, amid general population growth, to remain constant over time (e.g. Figure 3 for Nigeria).

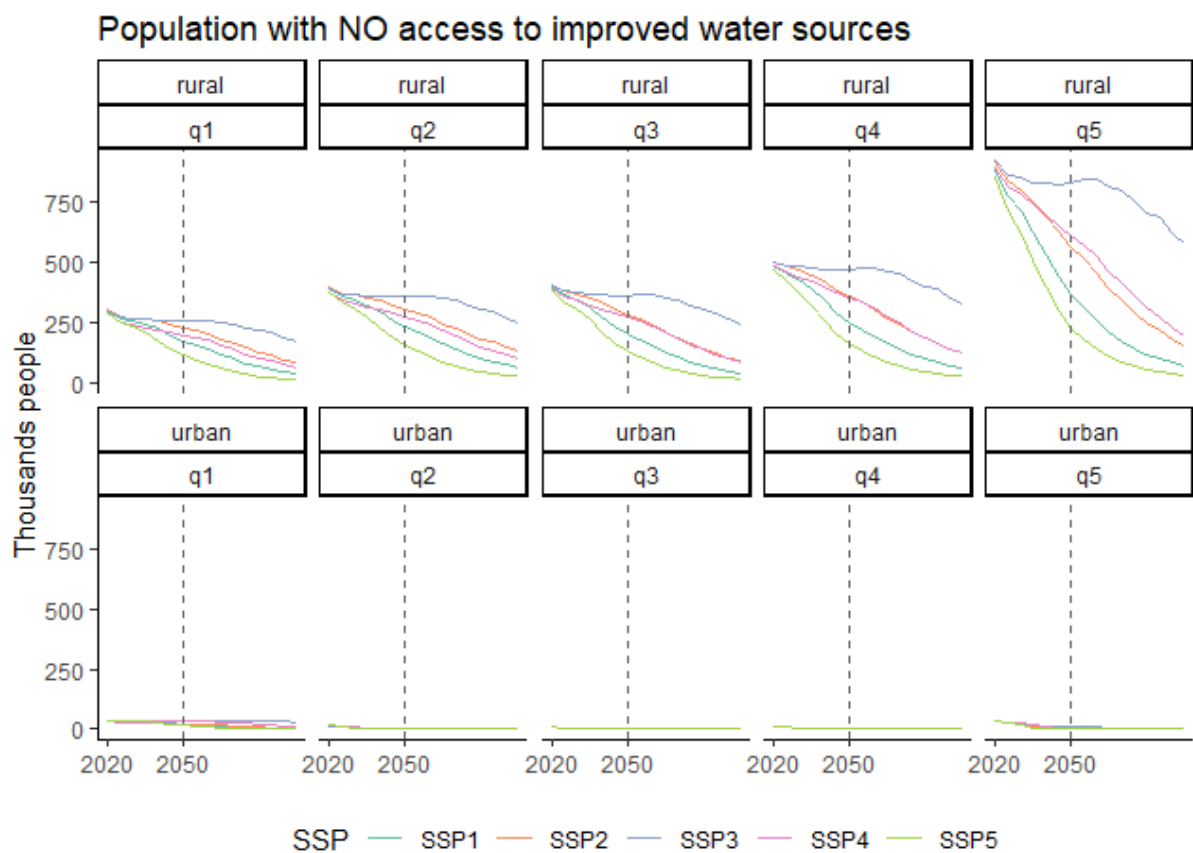


Figure 3: Projection of population with no access to improved drinking water in Nigeria

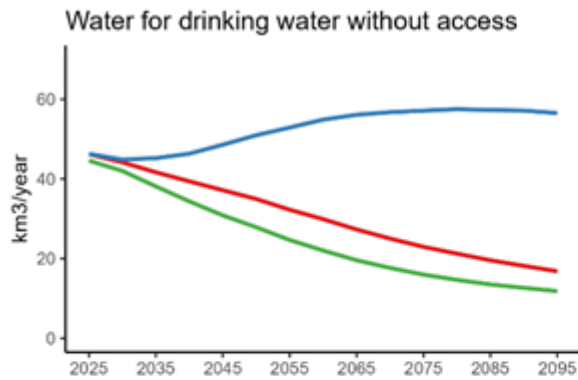
Existing projections of domestic water demands estimate the likely water use for drinking

water proportional to population, taking into account socioeconomics and the country's average water use per capita. Usually, hydrological models that derive water demands assume that the whole population has access to water, or that water quality is not important. They only refer to theoretical water volumes. We apply the improved water access rates obtained by our analysis and obtain the water volumes that are, in fact, accessed at improved standards. Conversely, we can also calculate the water volumes that are currently lacking for the population, either physically or in water quality. We refer to this quantity as the “improved water gap” and it indicates the water volume that should still be improved qualitatively to reach 100% access. It is important to remember that improved water quality is only a preliminary but necessary step to having safely managed water.

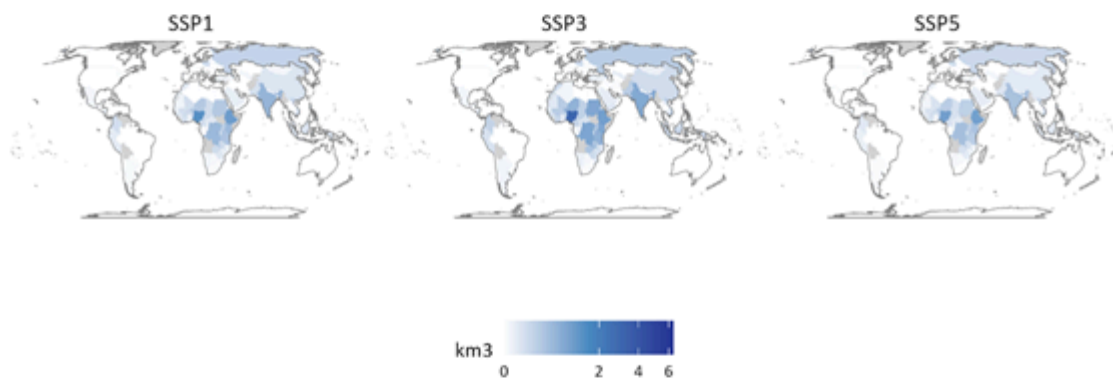
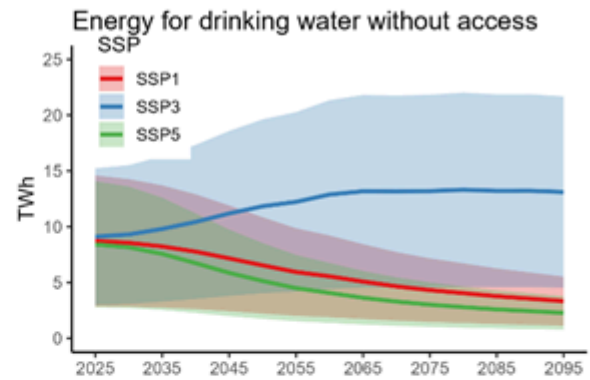
The current gap is 46 km³, only 4% of the overall domestic demand. This is likely to more than halve under SSP 1 and 5 after 2050, while it might remain at similar levels under SSP3. The countries with the highest gap both in 2025 and 2050 are in central Sub-Saharan Africa and India.

We then apply energy intensity values estimated from Magni et al., 2025 and obtain the energy associated with providing the improved water gap. We call this the energy gap. As expected, the regional and time patterns are similar to water demand. The global energy gap related to improved water access in 2025 is about 10 TWh/year, which corresponds to the overall energy consumption of small countries like Uruguay or Estonia.

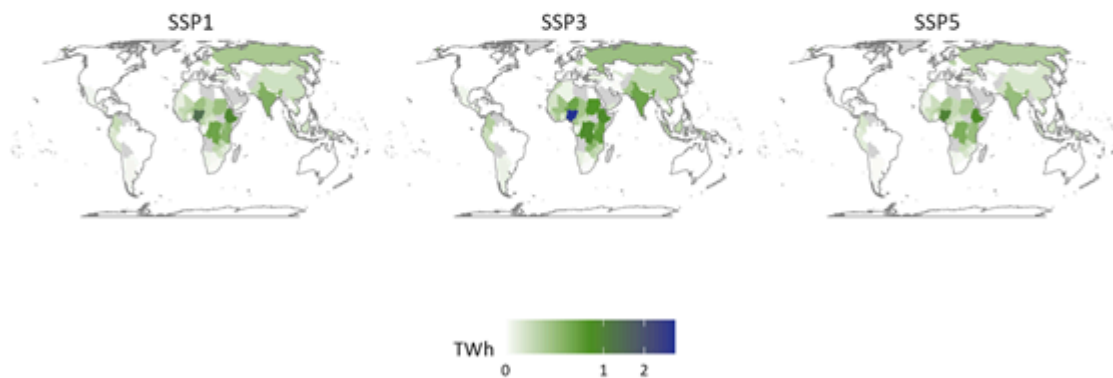




Water gap in 2050, improved drinking water



Energy gap in 2050, improved drinking water



1.3.2. Supply-side adaptation

Data and methods

This part of the analysis extensive global datasets, including historical records of desalination plants and their capacities:

- DesalData from the Global Water Intelligence (data available from 1980 to 2022)
- Wastewater facilities from Aquastat (data available from 1995 to 2022)
- HydroWaste (Ehalt Macedo et al., 2022) (cross section of data from different sources around the year 2020)
- Key socioeconomic variables:
 - GDP per capita (OECD)
 - Urbanization rates (World Urbanization Projections, UN)
 - Population growth (Wittgenstein Centre for Demography and Global Human Capital)
- Climate-related variables:
 - Water gap (Droppers and Wanders, 2023)
 - Aridity (ISIMIP 3b)

We follow the same analytical steps for both technologies, but with several nuances explained below. We first analyze the historical trends of desalination using random forest regression models - an ensemble learning method that constructs multiple decision trees and aggregates their predictions to enhance accuracy and robustness (Boulesteix et al., 2012). The analysis and projections of desalination at the plant-level by Ai et al. (2021) finds machine learning models (and specifically random forest) to perform better than regression models. Here we build on their work, though with data aggregated on the country level and testing for a wider set of predictors spanning socioeconomic and climatic variables. Random forest models can model complex and potentially nonlinear interactions between variables, which other types of regression approaches may miss if the relationships are not specifically parametrized. Additionally, they generally yield higher predictive accuracy compared to more classical regressions (Zhou et al., 2023; Wang et al., 2022).

Calibrated on the estimates of random forest models, internally consistent projections (or



extrapolations) of future trends of WWT and desalination were done using the *predict* function from the R Package *randomForest*. The future values of covariates were collated from different sources: GDP per capita, population and urbanization projections from the latest SSPs update (SSP Scenario Database 3.0). Aridity projections are from the ISIMIP 3b round. Water gap projections are from the National Geographic World Water Map (Droppers and Wanders, 2023).

Additional assumptions for projections of WWT

The WWT quality varies drastically between countries. In Ehalt Macedo et al. (2022), the treatment level is categorized as advanced, secondary and primary. The relationship between volumes, treatment levels and GDP is exponential (see Fig SI1), which is accounted for in the projections where we assume that a country's capacity will be dominated by the level of treatment defined by GDP thresholds, as observed in the present data: primary level is assumed for cases where GDP per capita 3700; secondary level for less than 20000 and advanced for more than 20000 USD.

Additional assumptions for desalination projections

The dominance of technologies in the global mix has been changing over time (see Fig SI2). Currently, technology mixes vary across regions, with the Middle East region hosting more than 30% of the global production while having a unique technology profile, in that more than half of its production is done with distillation-based technologies. For future projections, we define technology development trajectories in line with the SSP narratives, reflecting various degrees of technological progress, transitioning away from fossil fuels and equitable diffusion across regions (see Table 1 in Supplementary Material). SSP1, the scenario of progress towards sustainability and equity, membrane-based technologies, which are the most advanced modern technologies, dominate desalination capacities globally, with distillation-based and electrochemical technologies having a minor share. In SSP2, the scenario of continued current trends, and slow improvements towards equity, the share of membrane-based technologies increase globally but less than in SSP1 and at faster in countries in the Global North than in the Global South. In SSP3, the scenario of regionalization and weak international cooperation, advanced technologies become dominant in Global North countries by mid-century and attain lower levels of Global South.



In SSP4, the scenario of inequality, there's an even starker difference in the presence of most advanced technologies. Finally, in SSP5, where continued use of fossil fuels is envisaged, distillation-based technologies, which are more energy intensive and typically located near thermal fossil fuel plants, still represent around 30% of the capacity globally.

Electrical energy demands were estimated using coefficients of electrical energy calculated per technology from Magni et al. (2024). Energy needed for WWT depends on the volumes and quality of the incoming water (Longo et al., 2016; Niu et al., 2019), and the level of treatment (primary, secondary, advanced). Magni et al. (2024) built a model routing wastewater production to WWT plants using 5 arcmin-treated wastewater volumes (Jones et al., 2021) and population maps.

For desalination, energy consumption is estimated for more than 19,000 plants worldwide that use one of the four main technologies. The energy consumption of membrane technologies depends on the feedwater salinity, while energy consumed for distillation is constant across feedwaters (Lin, 2019; Nassrullah et al., 2020). Specifically for reverse osmosis, energy efficiency is modelled with an exponential decay curve and linearly scaled with salinity.

Finally, electricity supply CO₂ emissions were estimated by multiplying energy demands with emissions intensity coefficients per unit of electricity supply. Regional emissions intensity coefficients were derived from different SSP-based scenarios from the MESSAGE IAM, indicating different speeds of electricity sector transition .

Results

Historical data

Globally, the share of treated wastewater has increased from around 26% in 1995 to 68% in 2022 (Aquastat, 2025). The total volume of treated wastewater has increased 10-fold over this period. However, both the volumes and the pace of change differ widely between regions with Europe, East Asia and North America having currently highest volumes and growth rates, followed by Eurasia and Asia Pacific, Latin America and Middle East. Africa, South-, and South-East Asia currently have the lowest volumes but still with relative



improvements over the observed period (see Fig. 1 on Regional WWT volumes).

The patterns in the historical data were analyzed with a set of socioeconomic covariates (income, governance, demographic shifts), with income, population size and urbanization (share of population in urban areas) emerging as the key predictors. For both WWT and desalination estimates, a factor variable that captures country-specific effects and patterns has also been included. The results of applying the random forest model shown in Table 1. The scores shown reflect the extent to which each variable contributes to the model's predictive accuracy.

Table 1: Random forest estimates for WWT

Variable	%IncMSE ¹	IncNodePurity ²
GDP per capita	61,7	659756,44
Log Population	30,7	175502,66
Urbanization	23,4	267143,23
Country	25,1	142962,43

Desalination volumes have also drastically increased over the observed period: between 1980 and 2022, global capacity has increased by a factor of 500 (Global Water Intelligence,

¹ %IncMSE (% increase in MSE or accuracy) is a measure of permutation importance. It assessed how much model accuracy decreases when the feature's values are randomly shuffled. Higher %IncMSE means the feature is crucial to prediction.

² IncNodePurity quantifies how much a variable reduces node impurity (i.e., variance) across all trees in the forest. Higher scores indicate higher importance.



2022).

Contrary to WWT, which should be an integral component of water management regardless of water scarcity pressures, desalination, in theory, is a response to these pressures that produces alternative water sources. For this reason, we included climatological (aridity) and water stress (water gap) indicators to account for this source of desalination needs, in addition to a suite of socioeconomic indicators, which are consistent with those that explain the WWT trends, although to a different degree of importance. A key variable in the desalination model is the lagged value of the desalination volumes, the inclusion of which substantially strengthened the model performance.

Table 2: Random forest estimates for desalination

Variable	%IncMSE ¹	IncNodePurity ²
Lag desalination per capita	63,8	2048,8
Log GDP per capita	27,9	567,2
Aridity	25,4	529,3
Log Population	22,1	228,9
Urbanization	21,6	400,1
Log Water Gap	21,2	135,3
Country	19,3	108,2



Calibrated on the estimates of random forest models, internally-consistent projections (or extrapolations) of future trends of WWT and desalination were done using the *predict* function from the R Package *randomForest*. The future values of covariates were collated from different sources: GDP per capita, population and urbanization projections from the latest SSPs update (SSP Scenario Database 3.0). Aridity projections are from the ISIMIP3b round. Water gap projections were modelled with the PCR-GLOB model.

The remainder of the results section shows projections of volumes, energy demand and emissions for each technology. Projections results are shown either aggregated into 10 macro regions as defined by integrated assessment models (IAMs) in the 6th Assessment Report of the IPCC (the list of countries within each region can be seen in the SI Table x) or as global aggregates. We present results for SSP1, SSP3 and SSP5. The set of scenarios is limited by the availability of projections from the ISIMIP 3b protocol which are needed for aridity and water gaps: SSP1-RCP2.6, SSP3-RCP7.0 and SSP5-RCP8.5.

Projections of volumes



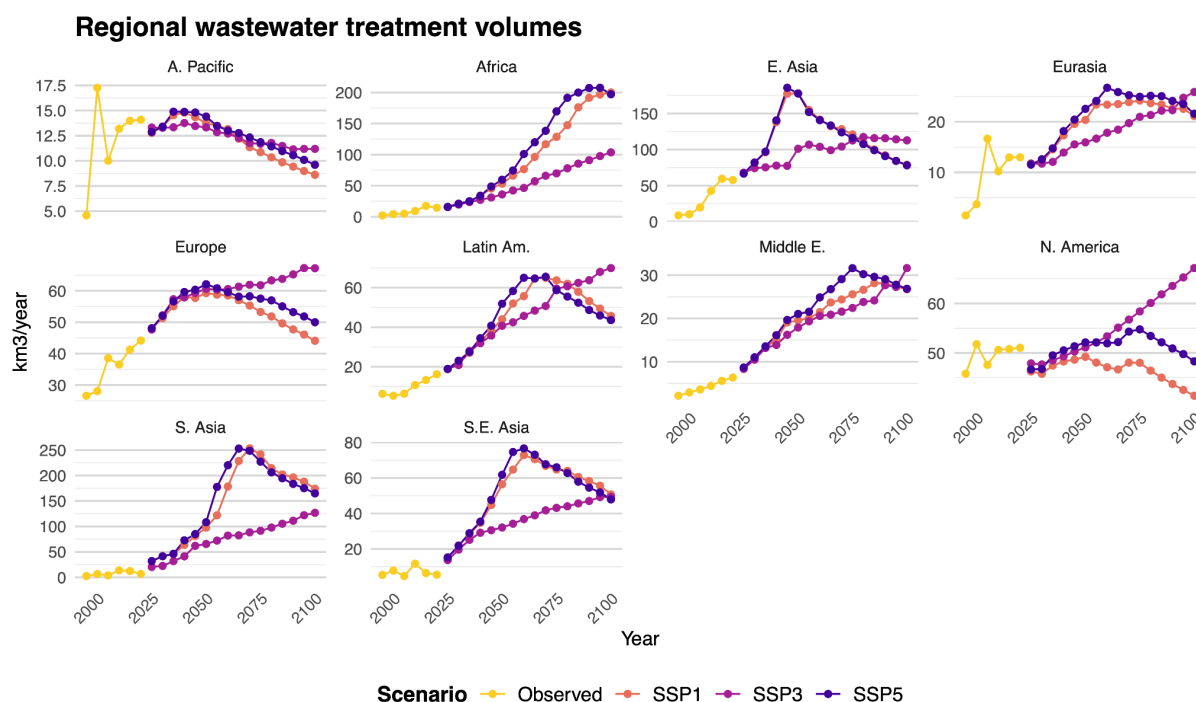


Figure 1: Regional WWT volumes and projections

Figure 2 shows the current regional distribution of the WWT capacity and projections for future capacity expansion. Regions such as Europe, East Asia, the Middle East and North America have the highest existing WWT capacities as well as robust projected growth, reflecting their already advanced treatment infrastructure and higher GDP levels. North America shows a distinct scenario-driven pattern in that, in the second half of the century, their capacities are highest in the SSP3 scenario, due to continued population growth in these regions and relatively high income. In scenarios SSP1 and SSP5, driven by shrinking populations, volumes of treated wastewater substantially decrease after mid-century for almost all regions, and for Europe and North America, they return to close to today's levels. Current capacities are lowest in Africa, South and South-East Asia, but are projected to climb and become globally highest in the second half of the century, owing to continued population growth, accompanied by economic development and urbanization.

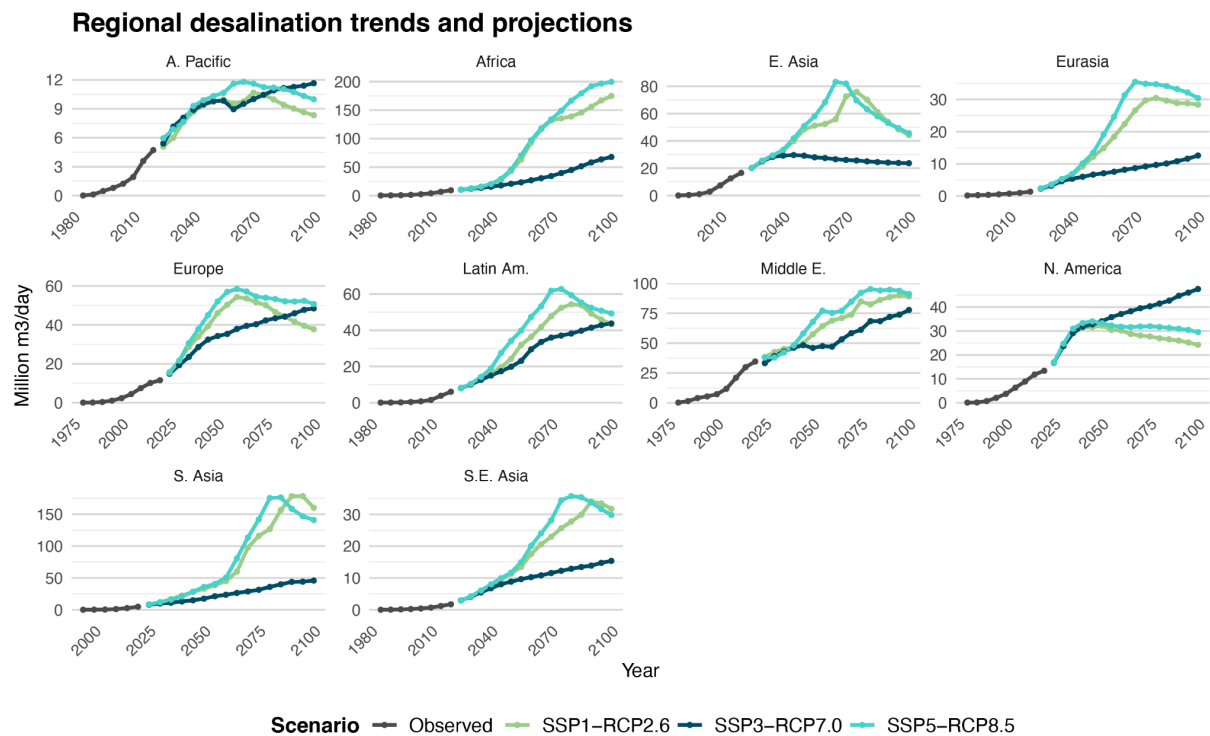


Figure 1: Regional desalination volumes and projections

Desalination capacity, on the other hand, is globally highest in the Middle East, followed by East Asia and North America. All other regions have smaller current volumes but for most cases rapid projected growth, driven by a combination of climate-related and socioeconomic pressures. As is the case with volumes of WWT, Africa and South Asia are projected to develop globally highest desalination capacities, also because of growing demand from growing population, urbanization and increased economic activity. The climate fingerprint in terms of water scarcity, which would demand higher desalination capacities is not obvious – the difference between scenarios SSP1-2.6 (which, in simplest terms is high development – lower emissions) and SSP5-RCP8.5 (high development – extreme emissions) is relatively small and does show substantial sensitivity to the climate conditions. In other words, increase in projected desalination capacity is attributable largely to changing socioeconomic conditions.

Projections of energy demand

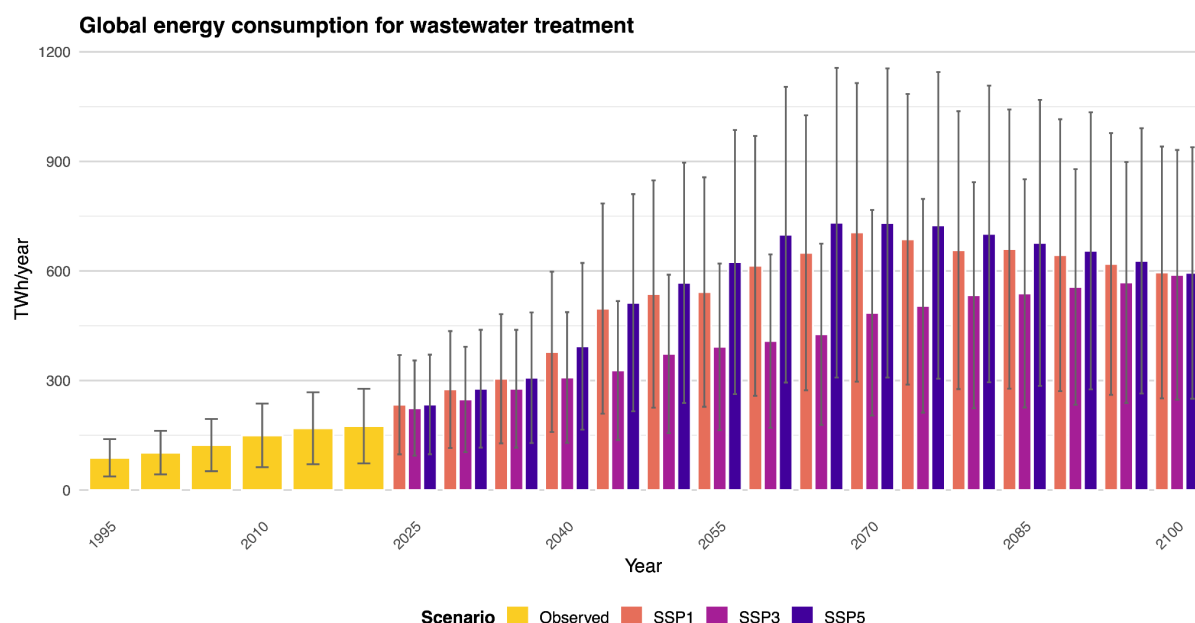


Figure 4: Global energy demand for WWT. The whiskers show the high-low range proposed by Magni et al. (2024).

Projected volumes were multiplied by energy use coefficients estimated in Magni et al. (2024) to derive energy demand projections. Current energy demand for WWT is about 170 (70-270) TWh/year. In scenarios SSP1 and 5, energy demand roughly triples to 540 (230-850) and 575 (240-910) TWh/year respectively and then decreases to about 600 TWh/year by 2100. In SSP3, it about doubles to 360 (150-560) TWh/year and reaches also about 600 TWh/year at the end of the century.



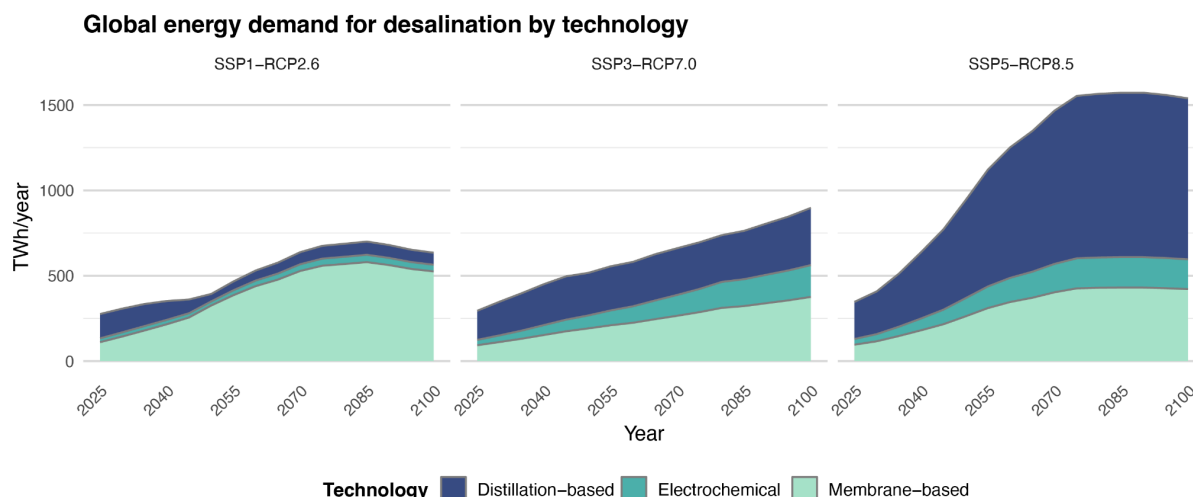


Figure 5: Global energy demand for desalination

For desalination, because of large differences in energy use between distillation-based, electrochemical and membrane-based technologies, energy demand profiles are more nuanced between scenarios. In SSP1, due to membrane-based technologies becoming the dominant desalination technology, energy demand peaks around 2085 when the current energy demand is tripled. For SSP3, which globally has roughly equal proportions of membrane-based and distillation-based technologies, as well as continued presence of electrochemical technologies, demand for energy surpasses that of SSP1 around 2070 and continues to grow to around 800 TWh/year. In SSP5, which is a scenario of continued fossil fuel use, energy demand grows rapidly and increases more than 5 times from the current estimate of just over 250 TWh/year.

Estimates for mean energy intensity are shown in Fig. 4, and in Fig. SI4, the uncertainties related to energy demand are shown for each technology separately.



Projections of emissions

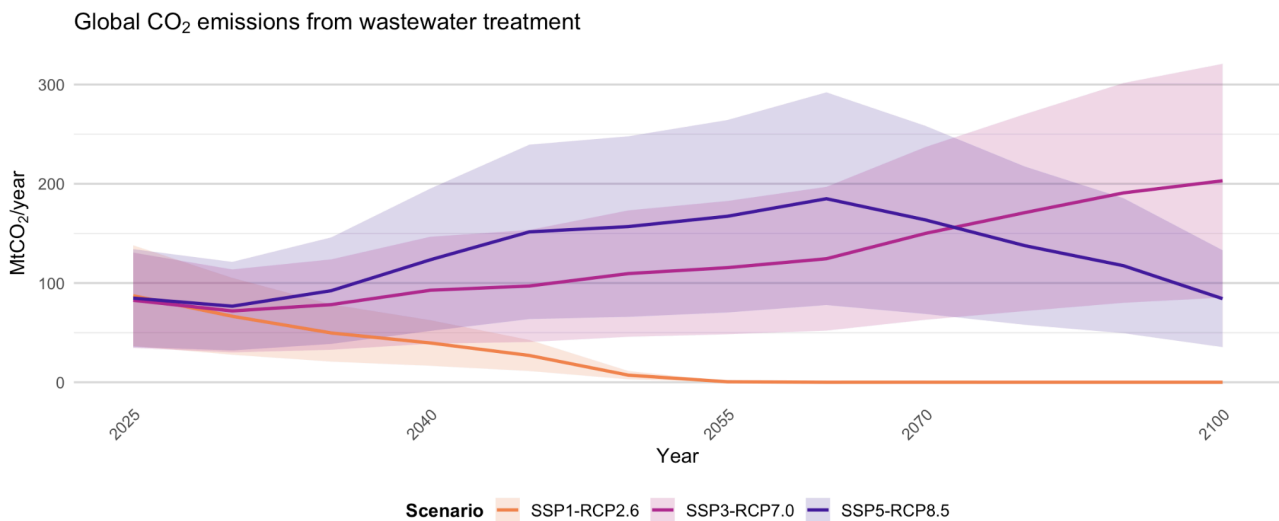


Figure 6: Global CO₂ emissions from WWT. The uncertainty range of emissions trajectories here stems from the uncertainty of the energy consumption.

Global emissions trajectories of wasteWWT are shown on Figure 6. Scenarios start to diverge after 2030, though trajectories under SSP3-RCP6.0 and SSP5-RCP8.5 largely overlap throughout the century, though with different trends. In SSP5-RCP8.5, emissions from WWT peak around 2060 and decline to around 150 MtCO₂/year at the end of the century (compared to 100 MtCO₂/year currently). For SSP3-RCP6.0, emissions are steadily rising and stabilizing around the end of the century. This is due to a steady increase in the volumes of treated wastewater which are in turn driven by growing global population and their water consumption.



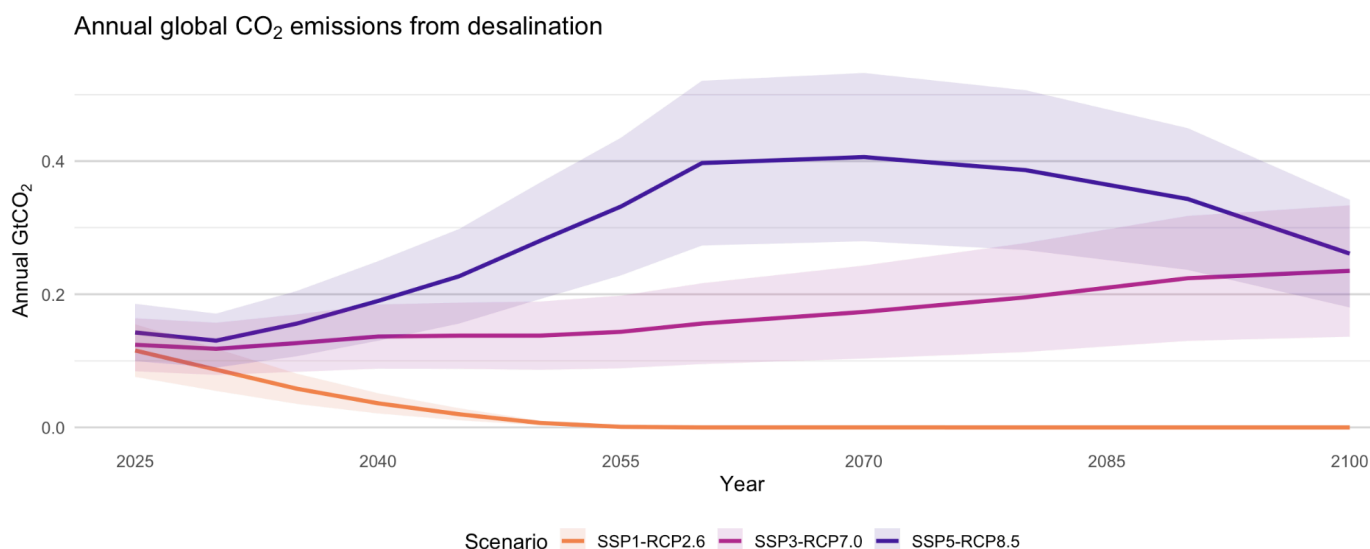


Figure 7: Global CO₂ emissions from desalination. The uncertainty range of emissions trajectories here stems from the uncertainty of the energy consumption.

For desalination, the emissions trajectories shown in Figure 7 show a somewhat different picture, especially with respect to the difference between SSP3-RCP6.0 and SSP5-RCP8.5 pathways, which diverge to a larger extent than is the case for WWT. However, due to similar dynamics as for WWT, related to population- and economic activity-driven demand for desalinated water, in SSP5-RCP8.5 emissions peak around the year 2070 at around 550 MtCO₂/year, but they decrease only to around 400 MtCO₂/year later in the century, which is still twice the current levels. In SSP3-RCP6.0, emissions steadily rise to around 300 MtCO₂/year in 2100. For SSP1-RCP2.6, similar to the pattern for WWT, emissions become neutral past 2055.

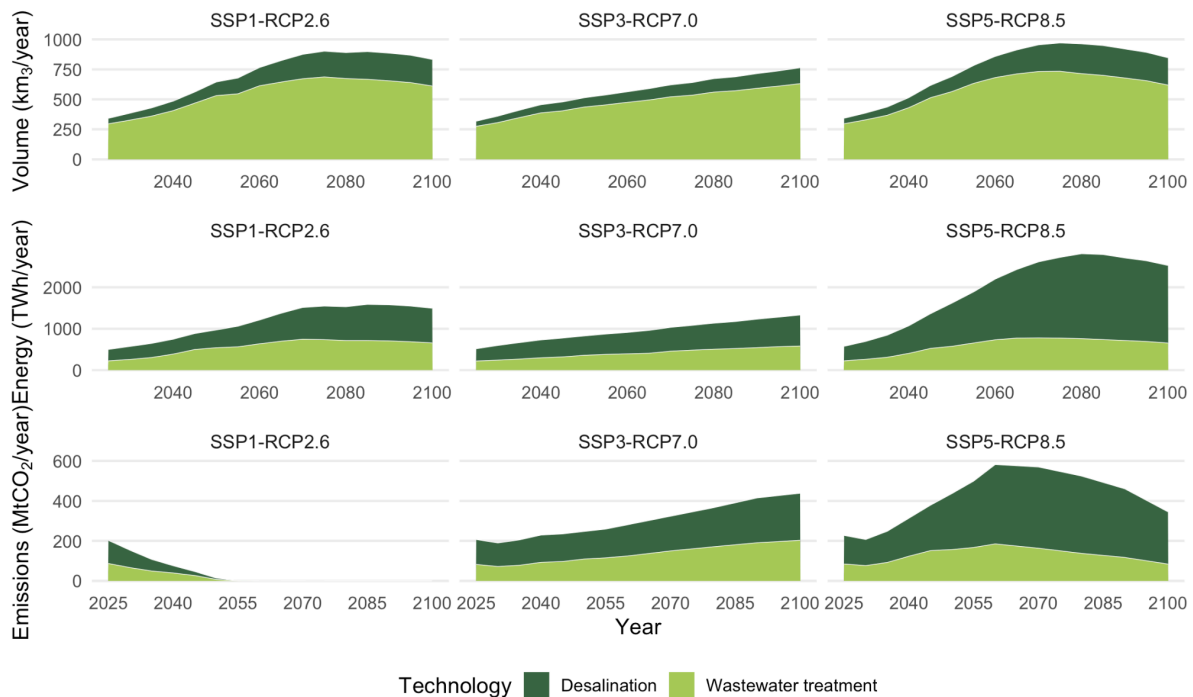


Figure 8: Combined desalination and WWT estimates.

Figure 8 displays a direct comparison of the key estimates for WWT and desalination, highlighting the difference in energy intensity between the two technologies, whereby WWT produces almost 7 times as much water for the same amount of energy (and emissions). This, however, is to be interpreted with caution as the quality and usability of water might not be entirely substitutable between the two technologies. However, in terms of the assessment of maladaptation, this indicates that desalination is substantially more at risk of being maladaptive.

Discussion and conclusion

WWT and desalination could be critical solutions to address water scarcity in a changing climate. Here we shed light on plausible future trajectories of expansion in all world regions

and for three scenarios. Crucially, we assess the energy and emissions ramifications from the inevitable expansion of the two technologies, to better understand the risks of emissions-related maladaptation. Their energy demand will become increasingly significant as capacities scale up. However, compared to another technology that is rapidly expanding under climate change – cooling with air conditioning and other technologies – whose energy demand is projected to reach between 1100-1600 TWh/year (4-6 EJ/year), these two key water technologies are projected to demand only about half of that. WWT is projected to demand 350-500 TWh (1.25-2 EJ/year) and desalination 280-700 TWh/year (1-2.5 EJ/year). However, in both cases, the analysis in this study underscores the importance of decarbonizing energy inputs to maximize climate adaptation value of these technologies.

It is important to highlight that the issue of maladaptation extends beyond emissions alone. WWT entails additional risks, primarily when treatment processes are insufficient, resulting in water that still carries pathogens of contaminants, thereby posing health hazards and environmental threats if reused or discharged. Desalination, particularly seawater plants, result in brine production that can adversely affect marine ecosystems if not managed properly (Belatoui et al., 2017; Gacia et al., 2007; Jones et al., 2019). Similarly, inland plants pose risks to terrestrial environments. However, here lies also an opportunity for circular economy approaches that could create value streams from byproducts such as brine.

Alongside environmental concerns, justice-oriented questions relating to the ownership and commodification of water resources warrants attention. For desalination, expanding capacities without adequate governance frameworks that ensure equitable access to water may exacerbate existing inequalities or introduce new ones. Introduction of new or shifting of existing vulnerabilities is also a key feature of maladaptation (Schipper, 2020).

One key limitation of current assessments including ours is the lack of consideration for how climate hazards and impacts, such as sea level rise, rising temperatures and salinity shifts, may affect operational capacities and efficiency of plants over time. Infrastructure for both WWT and desalination may prove vulnerable to such changes, potentially undermining the effectiveness as long-term adaptation strategies. This is especially pertinent for a scenario combination like SSP5-RCP8.5, which assumes unprecedented levels of socioeconomic development in an unprecedented climate. This highlights both the need for methodological advances in integrating impacts directly in models such as integrated assessment models and



in practical planning for resilient infrastructure. In a similar vein, our analysis does not account for potential reduction in effectiveness of water-related adaptation at higher levels of global warming (Lissner et al., 2024). However, we also do not account for potential efficiency improvements that may come through innovation that might occur only in the future.

Another consideration and an avenue for future work is that the scenario set that we used in the analysis does not encompass overshoot scenarios to capture the situation in which emissions may temporarily exceed the limits set by the Paris Agreement but return to them in the long run. Overshoot scenarios entail large-scale carbon dioxide removal which is expected to have substantial effects on water demand (Rosa, 2021), all the while the effects of temperature overshoot on hydrology and water resources more generally are only starting to be understood (Marshall, Grubert and Warix, 2025).

WWT and desalination emerge from this analysis as indispensable yet imperfect adaptation options, whose future contributions will crucially depend on how their expansion is powered and embedded in broader water and energy systems. While their projected energy use remains lower than that of rapidly growing cooling demand, reliance on carbon-intensive power poses substantial maladaptation risks. Beyond the scope of this analysis are other sources of maladaptation such as insufficient treatment and brine management, and inequitable access, ecosystem damage and new social vulnerabilities. At the same time, integrated analyses with climate impact drivers and impacts such as sea-level rise, warming, and salinity shifts can reveal when and where these technologies may lose effectiveness or require scaling up, particularly under high-warming or overshoot pathways where hydrological change is increasingly non-linear. Advancing low-carbon supply, circular-economy uses of by-products, robust governance that safeguards justice and affordability, and impact-aware modelling of water and carbon-removal futures will determine whether WWT and desalination ultimately deliver durable, climate-resilient water security rather than short-lived fixes that exacerbate the very risks they seek to address.



Supplementary information

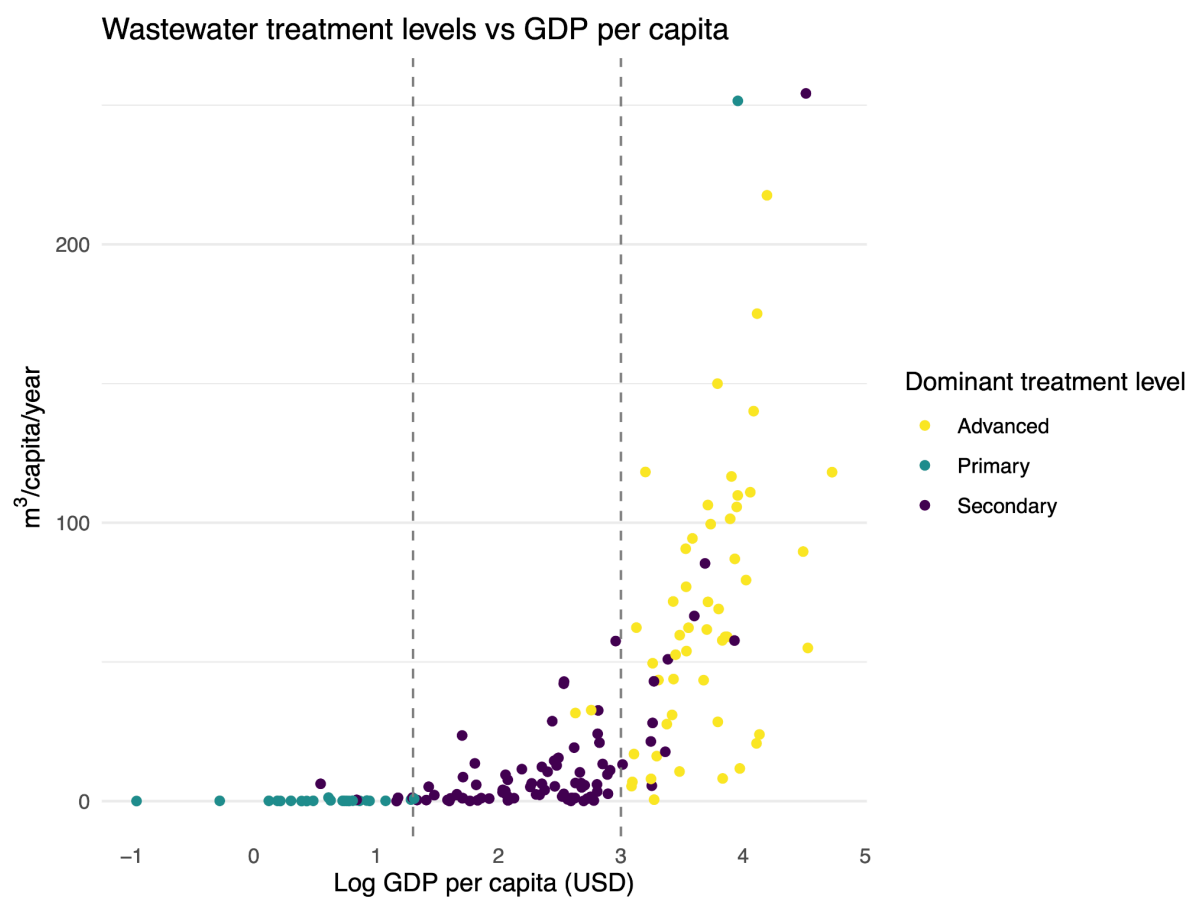


Figure S11: Relationship between wastewater treatment levels and GDP per capita. The dashed lines show cut-offs used to define the treatment level dependent on GDP in projections.



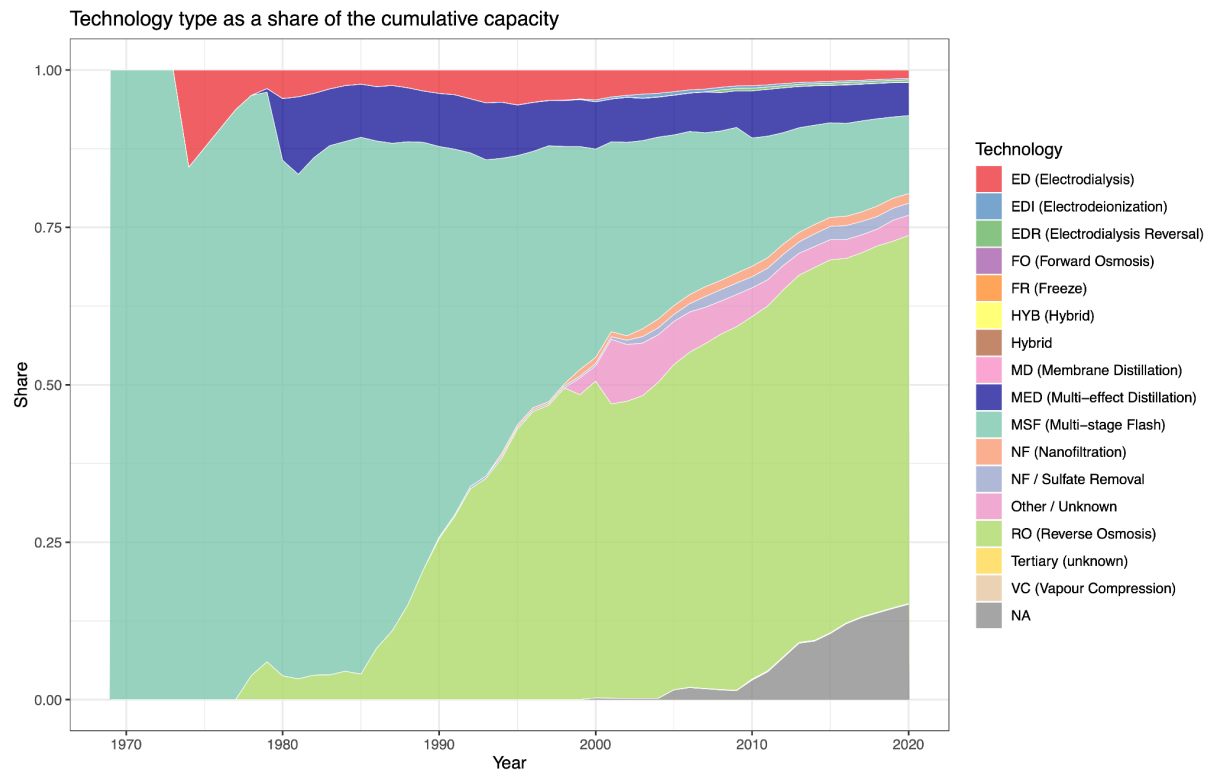


Figure SI2: Observed historical changes in proportions of desalination technologies.



Regional desalination capacities and shares of technology (2020)

Total global capacity: 130 million m³/day

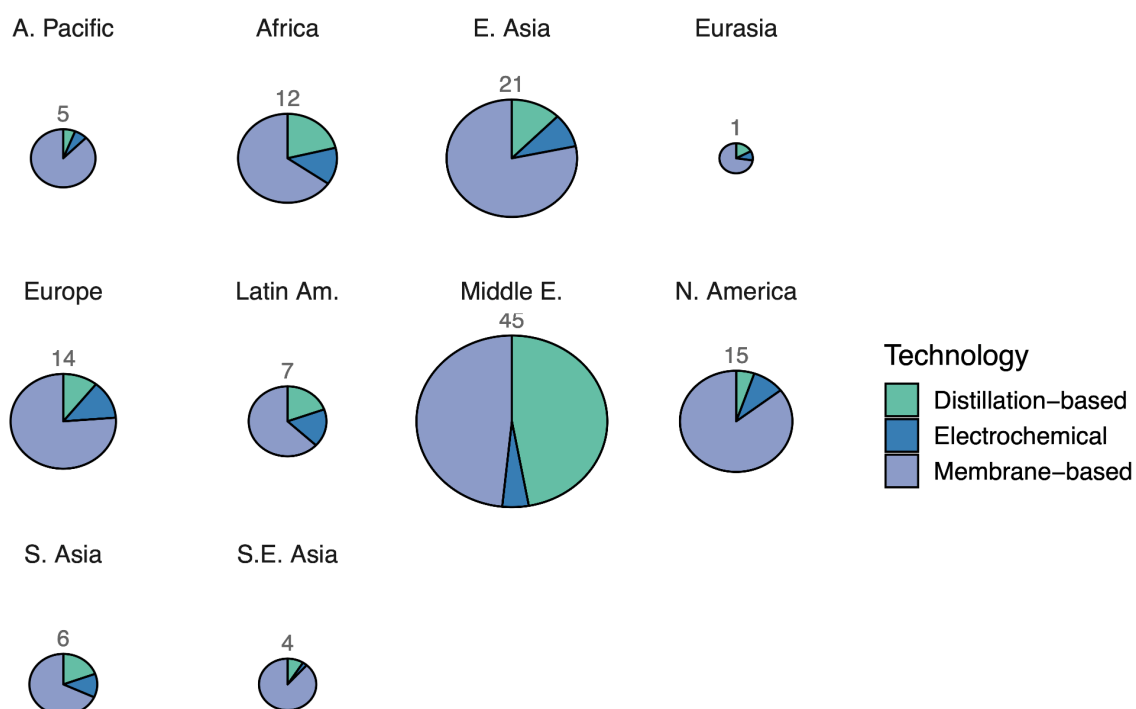


Figure S13: Desalination capacities scaled by their relative size and with proportions of three main groups of technologies.

Table 1: Desalination Technology Shares under SSP Scenarios

Scenario	Membrane-based (%)	Electrochemical (%)	Distillation-based (%)
SSP1	95% (Global) by 2050	2.5%	2.5%
SSP2	90% GN by 2050 90% GS by 2080	5% (GN and GS)	5% (GN and GS)
SSP3	90% (GN) by 2050 70% (GS) by 2050	5% (GN) 15% (GS)	5% (GN) 15% (GS)
SSP4	80% (GN) by 2050 50% (GS) by 2050	10% (GN) 25% (GS)	10% (GN) 25% (GS)
SSP5	60% (Global) by 2050	10% (Global)	30% (Global)

Notes: GN = Global North (includes Europe, North America, Eurasia, and Asia Pacific); GS = Global South (Africa, Latin America, East Asia, Middle East, South Asia and South-East Asia)

Table 2. Energy intensity (kWh/m³) by desalination technology and feedwater type from Magni et al. (2024)



Technology	Feedwater	Low	Mean	High
Membrane-based	Pure	0.6	1.31	2.02
	River	0.63	1.38	2.11
	Wastewater	0.71	1.59	2.41
	Brackish	0.8	1.8	2.71
	Seawater	2.59	5.53	8.48
	Brine	4.53	10.9	16.0
Electrochemical	Pure	0.55	0.79	1.03
	River	1.03	2.23	3.43
	Wastewater	2.23	6.91	11.6
	Brackish	3.43	11.6	19.8
	Seawater	19.8	34.2	48.9



	Brine	48.9	150.0	252.0
Distillation-based	Pure	14.3	16.8	19.3
	River	14.3	16.8	19.3
	Wastewater	14.3	16.8	19.3
	Brackish	14.3	16.8	19.3
	Seawater	14.3	16.8	19.3
	Brine	14.3	16.8	19.3

Values are expressed in kWh per cubic meter of desalinated water. “Low,” “Mean,” and “High” represent estimated ranges from the literature. Distillation-based values are averages computed from multiple technologies (MSF, MED, MVC, etc.).



Table 3. Energy intensity (kWh/m³) by WWT level from Magni et al. (2024)

Treatment level	Unit	Low	Mean	High
Primary	kWh/m ³	7.2e-05	0.00654	0.013
Secondary	kWh/m ³	0.2	0.49	0.78
Advanced	kWh/m ³	0.4	0.95	1.5

Values are expressed in kWh per cubic meter of treated wastewater.



Global desalination energy demand by technology and scenario

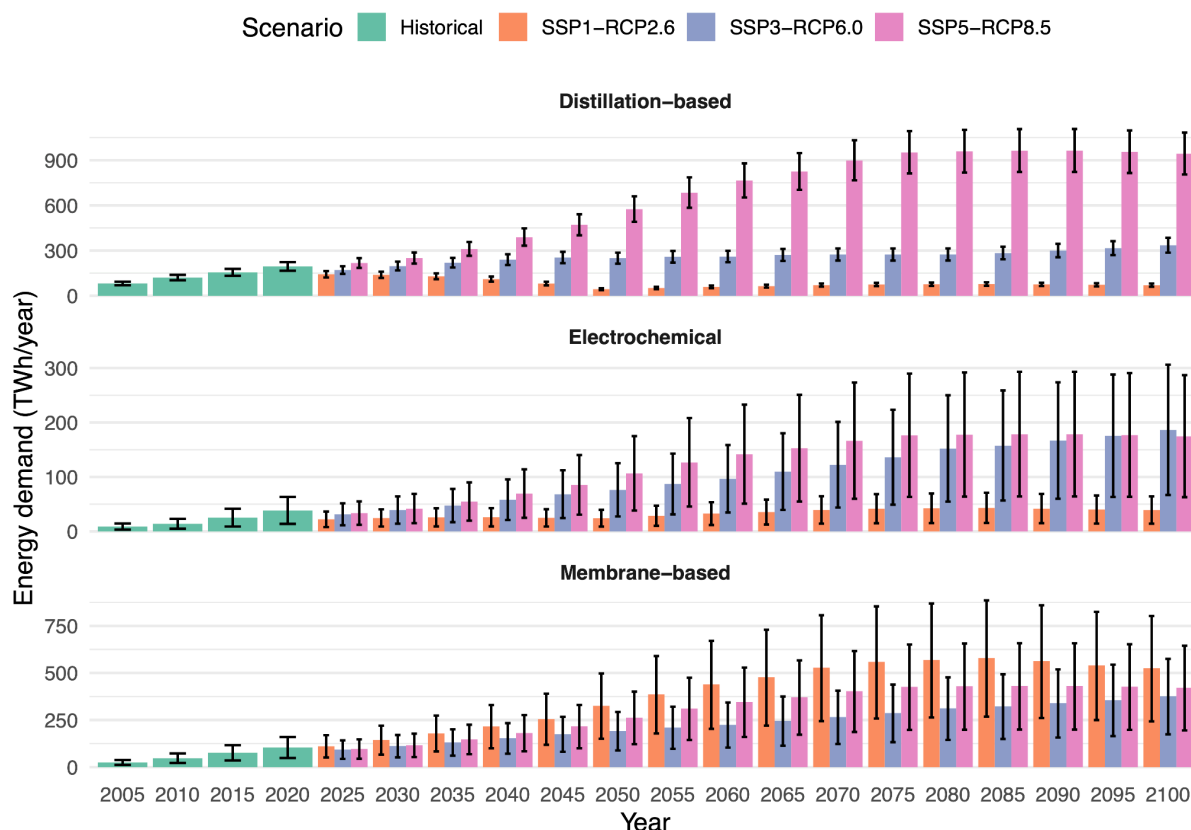


Figure SI4: Energy demand by technology and scenario.

Shared Socioeconomic Pathways (SSPs)

Shared Socioeconomic Pathways provide a scenario space to explore the range of plausible changes in socioeconomic conditions over the next century. SSPs quantify five different narratives of socioeconomic futures, including dimensions such as population and demographic characteristics, income, urbanization (O'Neill et al. 2017). The five scenarios span different combinations of low to high challenges to adaptation and mitigation, based on the socioeconomic parameters. They are a widely used tool in the climate research

community, indispensable for integrated assessments of the dynamics between socioeconomic and climate change variables and are also the scenario framework used in the Sixth Assessment report of the Intergovernmental Panel on Climate Change (IPCC).

SSP1, the ‘sustainability’ scenario, is characterized by low challenges to mitigation and adaptation, a result of increased investments in education, health, renewable energy sources and declining inequalities between and within countries, thus limiting impacts and increasing adaptive capacity. SSP2, the ‘middle of the road’ scenario, maintains premeditated challenges to adaptation and mitigation, and is a pathway of uneven and slower socioeconomic progress, compatible with the continuation of historical trends. SSP3 is characterized by high challenges to both mitigation and adaptation, which are a product of a growing divergence between economies, weak international cooperation and increase in internal and international conflicts. SSP4, the scenario of ‘inequality’, leads to low challenges for mitigation, due to technological advancements in high income countries, but high challenges for adaptation, because of an unequal distribution of advancements and resources across countries. Finally, SSP5 is similar to SSP1 in the fast socioeconomic progress on all fronts, but with the major difference of the progress being powered by fossil fuels, which produces substantially higher emissions and resulting climate impacts but assumes low adaptation challenges because of high socioeconomic development.

Climate forcing data

This analysis uses an indicator of aridity from the ISIMIP 3b model database ensemble of GCM/GHMs from CMIP6 (H08, MIROC-INTEG-LAND, WaterGAP2-2e). The data was downscaled to the grid-scale level and then aggregated to country level with population-weighting for each year. A 5-year rolling window is applied to smooth out variation between individual years and the resulting value is assigned to the middle year.

GCM model runs are forced by the greenhouse gas and radiative forcing trajectories from Representative Concentration Pathways (RCPs). RCPs are scenarios of future greenhouse gas emissions and air pollutants – and therefore of future warming – which are used as inputs to climate models and for assessment of future climate impacts. They are used in conjunction with the SSP scenarios which show the socioeconomic component of the future pathways. In this analysis we used RCP2.6, RCP7.0 and RCP8.5 with respective global mean temperatures



1.7°C (1.6°C); 1.9°C (2.9°C) in 2050 (2100) and 2.1°C (4.4°C) in 2050 (2100) (Schleussner and Mengel, Warming Attribution Calculator, n.d.) higher compared to the pre-industrial level.

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3. Economic impacts

3.1. Evaluation of climate change impacts on factor productivity (labor, capital, technological change)

3.1.1 Update of the representation of climate impacts in the IMACLIM-R World model

The representation of climate change impacts in IMACLIM, a general equilibrium model to study the interactions between energy systems and the economy, has been updated for the PRISMA project. In the previous version, impacts were based on epidemiological studies (Roson and Sartori, 2016) and were implemented as a decline in labour productivity resulting from regional temperature increases, differentiated by sector. The average annual temperature in each of the 12 regions was calculated using a transient climate response to cumulative carbon emissions (TCRE) equation (Leduc et al, 2016). As the TCRE fails to properly capture climate dynamics and carbon cycle feedbacks, which can lead to incorrect estimation of the magnitude and pace of required emission reductions, and thus of mitigation costs (Dietz et al, 2021), we have improved the model by developing a climate module based on the FAiR V.1.6.3 model, closely linked to the IMACLIM model, which updates global and regional average annual temperatures at each time step based on emissions from previous years.

Additionally, we have developed a climate impacts module that represents the impacts of climate change not only on labour productivity, but also on the productivity of all production factors. This update improved the versatility of the IMACLIM model as it allows for the direct integration of most damage functions representing aggregate damages on factor productivity or gross domestic product.

Total factor productivity does not exist *stricto sensu* in IMACLIM. To obtain an effect analogous to that of a decline in TFP in a neoclassical model, we reduce the labor productivity (measured as units of output per working hour), production capacity, and the efficiency of input conversion into output. If we use an economy-wide aggregated damage function, we assume that the productivity loss is identical across all non-energy sectors and affects all production factors equally. With the novel development for the PRISMA project, the climate impacts are integrated in the Imacsim-R model in a fully endogenous manner :



the general equilibrium calculated at each time step accounts for the decline in productivity, which leads to higher costs and lower demand, and leads to reduced economic activity and greenhouse gas emissions. The size of the productivity drop is chosen to match the subsequent GDP drop with the targeted GDP reduction obtained from the damage function. This is done with a recalibration of the productivity drop at each timestep.

This new development of the Imacsim-R model will allow us to build scenarios that account for the macroeconomic damages of climate change and represent their endogenous feedback on pathways modelled: on economic growth and its structure and distribution between regions, on investments, on production and consumption, and on emissions. The versatility of the implementation allows it to test a wide diversity of macroeconomic damage functions. An implementation and analysis is presented in section 3.2.1 of this report.

3.1.2 Climate change impacts on economic inequality

Beyond macroeconomic impacts aggregated at the country or regional level, the distribution of impacts and their effects on economic inequality is a critical next step to introduce in IAMs, to be able to assess the equity and justice implications of emission and mitigation pathways. To prepare this next step, and gather robust evidence to build the representation of the distribution of impacts within models' regions, we conducted a systematic review of the evidence on climate change impacts on economic inequality. This work resulted in a publication, appended to this report in Annex I: Méjean, Aurélie, Peron Collins-Sowah, Céline Guivarch, Franziska Piontek, Bjoern Soergel, et Nicolas Taconet. 2024. « Climate change impacts increase economic inequality: evidence from a systematic literature review ». *Environmental Research Letters* 19 (4): 043003.

We reproduce below the abstract of the corresponding article, which summarizes the main findings:

While it is widely assumed that poor countries will suffer more from climate change, and that climate change will exacerbate inequalities within countries, systematic and large-scale evidence on this issue has been limited. In this systematic literature review, we examine and synthesize the evidence from the literature. Drawing from 127 individual papers, we find robust evidence that climate change impacts indeed increase economic inequality and



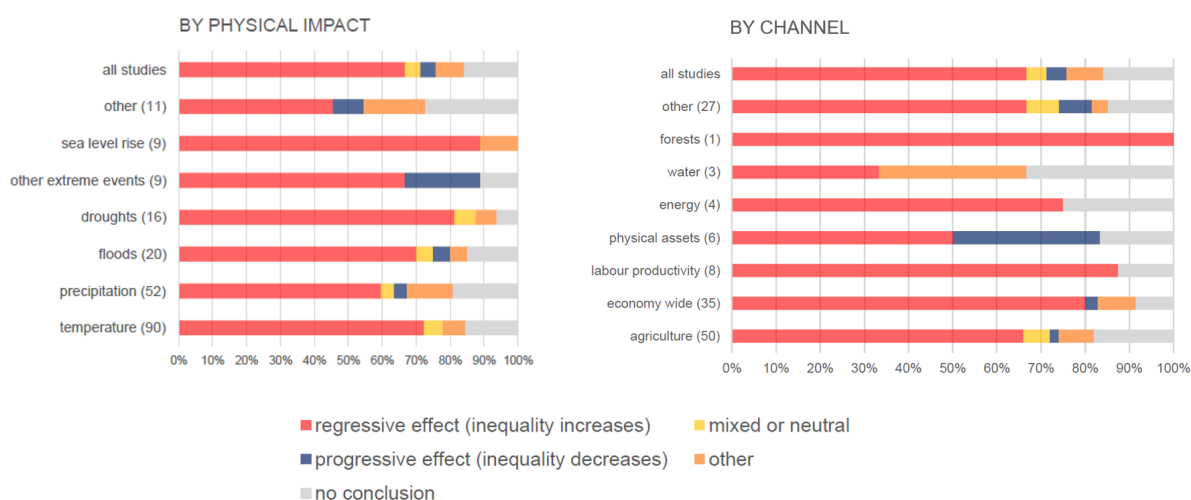
disproportionately affect the poor, both globally and within countries on all continents. This result is valid across a wide range of physical impacts, types of economic inequality, economic sectors, and assessment methods. Furthermore, we highlight the channels through which climate change increases economic inequality. While the diversity of different approaches and metrics in the existing literature base precludes extracting a universal quantitative relation between climate change and economic inequality for use in future modelling, our systematic analysis provides an important stepping stone in that direction.

The proportion of papers finding that a particular physical impact increases inequality or has a greater impact on the poor (on the left here) ranges from 60% (precipitation) to 89% (sea-level rise), depending on the type of physical impact (Figure below). Most of the papers (90) focus on the impact of temperature. In these cases, 72% of the papers conclude that temperature changes increase inequality or affect the poor the most. It is in the case of extreme events that most studies find a reduction in inequality. This is often due to the fact that these studies measure the impact on physical assets, which are mostly owned by the richest.

Several channels translate climate change impacts into effects on economic inequality. These channels include economy-wide effects affecting all sectors, agricultural revenues (through declining crop yields, livestock revenues, or agricultural total factor productivity), declining labour productivity, impacts on infrastructure and physical assets, energy demand, water availability, and forests. We find that papers that identify labour productivity (8 papers) as the main channels through which climate change affects economic inequalities overwhelmingly conclude that inequalities increase or that the poor are more impacted. A decline in labour productivity may indeed increase inequality if it reduces the income of low-skilled workers more than that of high-skilled workers. In particular, outdoor workers and indoor workers in workplaces without air conditioning may be more affected.

We note that a large proportion of the papers where physical assets are identified as the main channel show that inequalities decrease due to climate change or that the rich are more affected. These correspond to the papers in which rich agents suffer greater losses due to the higher value of their property.





Impact of climate change on economic inequality by physical impact (left panel) and by sector (right panel). The numbers between brackets indicate the total number of occurrences for a given category. The sum of those numbers may differ from the total number of papers (127), as some papers may fall into several categories, for instance in the case where several types of physical impacts are discussed in a single paper. Extracted from Méjean et al. (2024)

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3.2. Implementation of damage functions into IAMs

3.2.1 Comparing the direct impacts and the total impacts from climate change in IMACLIM

The model development presented in section 3.1.1. was used to implement a macroeconomic damage function into the model, and design study to compare direct and total impacts from climate change and highlight the role of capital accumulation in the amplification of damage. Annex II presents the working paper version of this study. Below, we summarize the main points.

The effects of the drop in productivity due to climate change are felt in IMACLIM-R both in real time, when the static equilibrium is calculated, and over time, as the lower productivity of past years translates into less income, less savings and therefore an investment deficit that increases over time and puts a strain on the economy's growth. We use the IMACLIM model to analyze the difference between the direct impacts of climate change, i.e. the drop in GDP attributable to lower productivity in the current year, and the total impacts, which include the cumulative effects of the lack of investment.

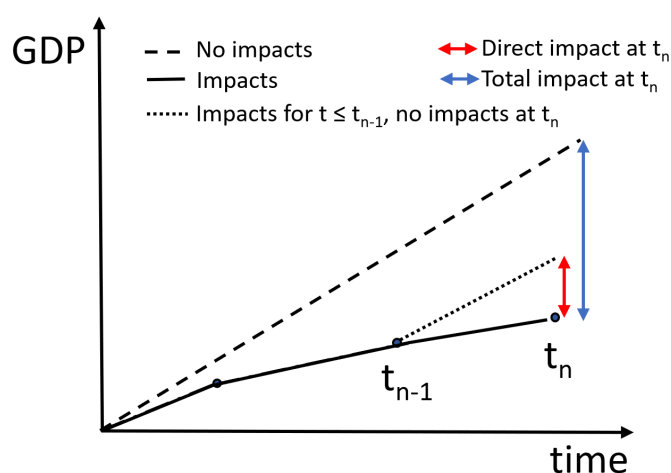


Figure 1: Schematic illustration of total and direct impacts of climate change.

Total impacts are larger than direct impacts mainly because of the loss of production capacity caused by reduced investment. However, IMACLIM-R models second-best development scenarios in which production capacity may be underutilized. In such cases, lower investment does not necessarily translate into a lower GDP in the following year, but simply into a higher utilization rate of production capacities. The economic vulnerability to reduced investments thus depends on the balance between labor supply, which is determined by population and labour productivity, and available production capacities, i.e. capital supply. The balance between labour and capital in IMACLIM-R depends on assumptions about a set of macroeconomic drivers, including trends in labor productivity, demographic dynamics, saving rates, the international capital flows, technological assumptions such as energy efficiency, and the availability of fossil fuels. These assumptions vary from one socio-economic scenario to another. We therefore assess how these macroeconomic drivers can influence the gap between the direct and total impacts of climate change, by contrasting these drivers across three shared socio-economic pathways (SSP1, 2 & 3).

Two main results emerge from our scenarios. Firstly, total impacts may be much larger than direct impacts, but the ratio between total impacts and direct impacts strongly depends on the SSP scenario: it is much lower in SSP1, as we assumed that international financial flows are channelled towards the most capital-scarce areas, and because the lower population growth mitigates the need for production capacities. Secondly, the amplification of direct impacts into total impacts is very contrasted across regions, as total impacts is up to five times larger than direct impacts in regions where capital is the scarcest. To summarize, the macroeconomic mechanisms that we highlight with IMACLIM-R have the potential to exacerbate future damages due to climate change, surpassing current projections and extending the already considerable uncertainty surrounding the magnitude of these damages.

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3.2.2. Incorporating Ocean-Based Climate Damages into the Social Cost of Carbon

Summary

Oceans provide essential benefits to people and the economy, underpinned by the extent and condition of marine ecosystems and infrastructure or “blue” capital. However, the impacts of climate change on blue capital have been largely overlooked in influential indicators such as the social cost of carbon (SCC). In this chapter we present research that integrates the latest ocean science and economics into a climate-economy model, capturing climate change impacts on corals, mangroves, seaports, fisheries, and mariculture to estimate their welfare repercussions at a global scale. Conceptually, this ocean-based SCC (blue SCC) represents a component of the total SCC currently omitted in standard estimates. We estimate the blue SCC to be \$48/tCO₂ [38-70, 25th-75th percentile] with baseline discounting, and more than three times as high for an annual rate of 2%. This represents an almost doubling of the SCC estimate from the same model and the existing literature without considering ocean-related impacts.

Introduction

Despite the ocean’s critical role in supporting global economies and human well-being, the economic damages to marine ecosystems and ocean-dependent activities have been notably absent from social cost of carbon (SCC) calculations. This chapter builds on Bastien-Olvera et al. (2025) to present the first comprehensive estimate of an ocean-based SCC (blue SCC), addressing a significant gap in climate-economy modeling that has been repeatedly highlighted by systematic reviews and regulatory assessments.

The blue SCC represents the economic impact on humanity from climate-induced damages to ocean-based natural and human-made capital. We integrate the latest ocean science and economics into a climate-economy integrated assessment model, capturing climate change impacts on corals, mangroves, seaports, and fisheries and mariculture to estimate their welfare repercussions at a global scale. Our approach explicitly distinguishes between market



values, non-market use values, and non-use values of ocean-based assets, acknowledging that these different types of welfare benefits are imperfect substitutes.

We estimate the blue SCC to be \$48 [38-70, 25th-75th percentile] per ton of CO₂ in 2020, representing a substantial addition to current SCC estimates. The figure more than triples with an annual rate discount rate of 2%. This represents an almost doubling of the SCC estimate from the same model and the existing literature without considering ocean-related impacts. This finding has important implications for climate policy design, suggesting that existing SCC estimates may significantly undervalue the true social cost of carbon emissions by omitting ocean-related damages entirely.

Analytical Framework and Methodology

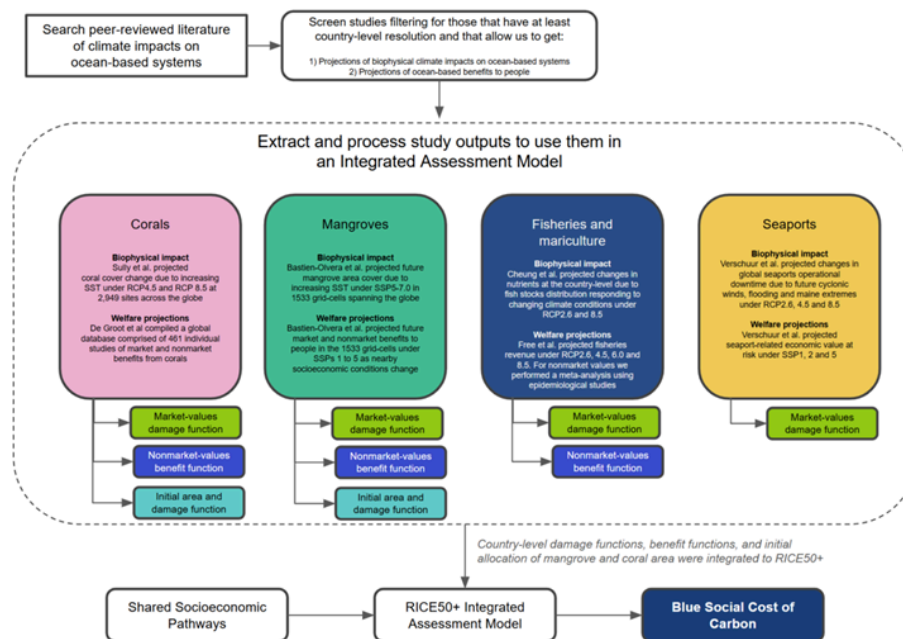


Figure 1: Analytical framework of the ocean-based social cost of carbon.

Our analytical framework systematically integrates projections from biophysical and

economic valuation studies available in the peer-reviewed literature. We conducted a structured literature search focused on studies quantifying climate-induced impacts on ocean-based assets or marine ecosystems, with explicit consideration for those providing corresponding economic welfare valuations.

The search resulted in four sufficiently developed sectors that fulfilled two key criteria: (1) availability of geographically explicit biophysical projections at the national or subnational scale, and (2) associated economic valuations enabling welfare impact estimation at comparable spatial resolutions. These sectors comprise corals, mangroves, fisheries and mariculture, and seaports.

Our approach required matching two distinct methodological components. The biophysical component captures climate-driven changes in asset availability (e.g., mangrove coverage, coral reef health, fisheries productivity, port functionality), derived from peer-reviewed climate impact modeling studies. The economic component translates these biophysical changes into welfare impacts using valuation methods appropriate for different categories of value: market use, non-market use, and non-use.

Valuation Categories and Implementation

We distinguish among three value types that are fundamental to understanding the full welfare implications of ocean-based climate damages:

Market values represent welfare impacts corresponding directly to observable market prices, such as fishery revenues and maritime trade through ports. These values are relatively straightforward to quantify and are already partially reflected in GDP calculations.

Non-market use values represent benefits from direct ecosystem service use without explicit market pricing, such as nutritional health derived from fisheries or coastal protection from mangroves. These services provide tangible benefits to people but are not traded in markets, making their valuation more complex but no less important for welfare calculations.

Non-use values reflect welfare impacts stemming from the intrinsic existence of ecosystems independent of direct human use, such as biodiversity preservation in coral reefs. These



values capture the broader societal willingness to pay for ecosystem preservation, even among populations that may never directly interact with these systems.

Not all ocean-based assets exhibit all value categories due to either theoretical constraints or data limitations. For instance, non-use values are conceptually irrelevant for seaports, while non-use values for fisheries, although theoretically plausible, lack sufficient empirical quantification at the required spatial resolution.

Modified RICE50+ Model Structure

To calculate the social cost of carbon for ocean-based welfare, we enhanced the RICE50+ integrated assessment model to include the latest ecological and economic findings on climate change impacts on blue capital. The RICE50+ model (Gazzotti et al. 2021) represents a dynamic framework dividing the world into 155 regions, allowing for region-specific assessments of the costs and benefits of carbon emissions.

We modified the utility function to account for use and non-use values of the four different ocean-based systems. The modified utility function takes the form:

$$Utility_{c,t} = \frac{1}{1-\eta} [(1-s_{2,1}) \cdot Use_{c,t}^{\theta_2} + s_{2,2} \cdot Nonuse_{c,t}^{\theta_2}]^{\frac{1-\eta}{\theta_2}}$$

$$Nonuse_{c,t} = \sum_{b=mangorives,coral} V_{c,t}^{b,nonuse}$$

$$Use_{c,t} = \left[(1-s_{1,1}) \cdot C_{c,t}^{\theta_1} + s_{1,2} \cdot \left(\sum_{b=mangorives,coral,fisheries} V_{c,t}^{b,nonmarket use} \right)^{\theta_1} \right]^{1/\theta_1}$$

This formulation explicitly recognizes that market and non-market values are imperfect substitutes, captured by the elasticity of substitution $\theta_1, \theta_2 = 0.21$ based on recent literature.



Sector-Specific Damage Functions

For each of the four blue capital categories, we developed sector-specific damage functions linking global mean surface temperature changes to country-level economic welfare impacts:

Coral Reefs: We integrated site-level relationships between sea surface temperature and coral cover from a comprehensive analysis of over 7,000 surveys conducted from 1997 to 2018. The site-level impacts were scaled to global mean surface temperature and aggregated spatially to the country level. Economic valuation drew from the Ecosystem Services Valuation Database, categorizing coral values into market use, non-market use, and non-use types.

Mangroves: Our approach uses high-resolution grid-cell level estimates of mangrove climate responses and economic values. Climate impacts on mangrove area were derived using local sea surface temperature of the hottest month and then aggregated to the country level, with damage functions normalized to global mean surface temperature. Local value estimates were based on meta-regression informed by income elasticity findings.

Fisheries and Mariculture: Market values were assessed through changes in fisheries profits under climate scenarios, using country-level projections that assume optimal management to isolate climate effects. Non-market use values focused on the nutritional role of seafood, quantifying how warming reduces availability of key nutrients (calcium, omega-3, protein, and iron) and linking these declines to increased disease risk based on epidemiological meta-analyses.

Seaports: We integrated site-level estimates covering approximately 1,300 ports worldwide, combining projections of future climate hazards with expected economic growth under multiple scenarios. The analysis captures direct physical damage to port infrastructure, operational downtime, and impacts on maritime trade activities.

Results and Key Findings

The annual country-level damage trajectories from 2020 to 2100 vary significantly across market use, non-market use, and non-use values. Under a middle-of-the-road socioeconomic

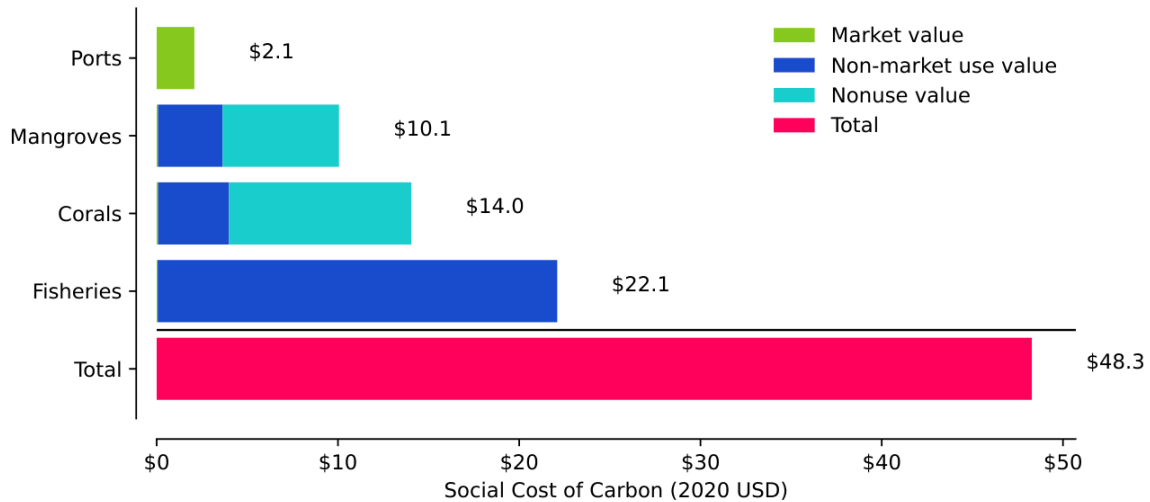


development scenario (SSP2) leading to approximately 3.6°C warming by century's end, damages increase substantially over time as economies grow.

We estimate the blue SCC starts at \$48 per ton of CO₂ in 2020. Slightly less than half of the blue SCC can be attributed to non-market-related losses from fisheries and mariculture, with the other half stemming mostly from corals and mangroves (Figure 2A). The welfare impacts from changes to market use values of ports are relatively small despite their large absolute damages. This reflects the essential welfare role of oceans' non-market use and non-use services after accounting for limited substitutability, as well as their geographical distribution and the higher marginal utility in lower-income countries where these impacts are concentrated.



A. Blue social cost of carbon in 2020



B. Uncertainty in the Blue social cost of carbon in 2020

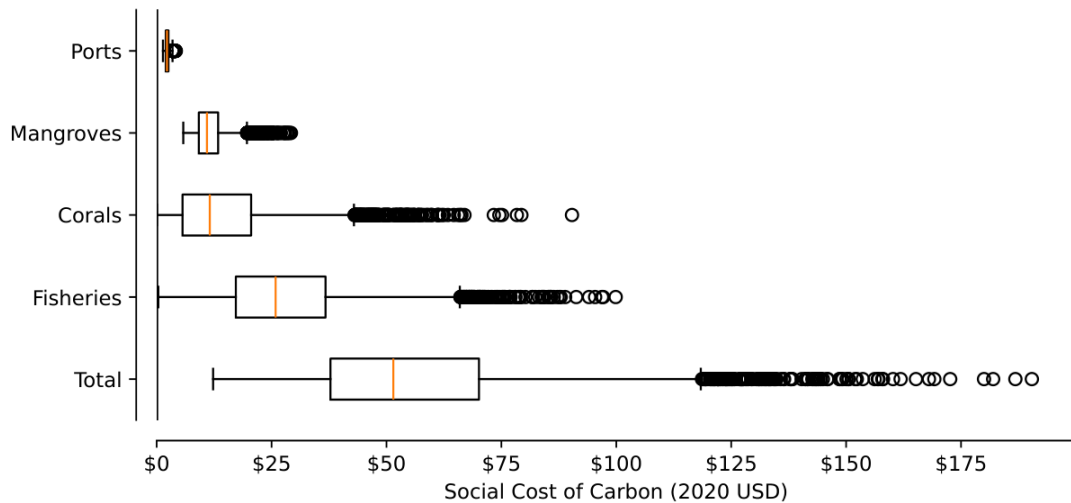


Figure 2: Decomposition of the ocean-based social cost of carbon.

The blue SCC implies a substantial increase relative to the SCC obtained when running the

standard RICE50+ model without ocean-based damages. Specifically, our results indicate that including ocean-based welfare would almost double the standard SCC derived from the same integrated assessment model. When we calibrate our model to the near-term 2% discount rate used in recent SCC estimates from the US Environmental Protection Agency (EPA) (applied in U.S. policy as of 2024), our result (\$168) represents an 88% increase in the EPA's SCC.

We quantify uncertainty using a Monte Carlo approach with 10,000 combinations of parameter values, allowing us to partition uncertainty associated with damage functions, ecosystem services value functions, and the degree of substitutability between different value types. The interquartile range (25th to 75th percentile) of the blue SCC is estimated between \$38 and \$70 per ton of CO₂ (Figure 2B). The most important driver of uncertainty in the blue SCC is the elasticity of substitution between market and non-market values in the utility function. The non-normative input parameters that yield the largest influence on the SCC are those regulating the value of the largest components, namely those stemming from the non-market use values of fisheries and the non-use value of corals.

Conclusions

This study presents the first comprehensive estimate of the social cost of carbon for ocean-based welfare, addressing a significant gap in climate-economy modeling that has persisted despite repeated calls for integration from scientific and policy communities. The blue SCC of \$48 per ton of CO₂ in 2020 represents a substantial addition to current estimates and highlights the importance of systematically accounting for ocean-based damages in climate policy assessment.

Our approach demonstrates the feasibility of integrating diverse ocean science findings into a coherent economic framework for policy analysis. The explicit treatment of market, non-market use, and non-use values provides a more comprehensive assessment of climate damages than approaches focusing solely on market impacts.

The distribution of ocean-based welfare impacts is highly unequal across the world, with islands and small economies being disproportionately affected. This pattern underscores the importance of considering equity and distributional impacts in climate policy design,



particularly given that many of the most affected regions, including India and Indonesia, have contributed least to historical greenhouse gas emissions.

As the ocean takes a central role in climate policy, from carbon sequestration to broader interventions, it becomes crucial to address both the impacts of policy actions and the direct effects of climate change on ocean ecosystems. Only by integrating these perspectives can we fully understand the challenges and opportunities of preserving and restoring blue capital.

The blue SCC provides one tool for synthesizing the global consequences detailed in the extensive literature on climate change impacts on the ocean. It should be noted that, in the present form, it does not encompass the value of many, if not most, of the ecosystems services provided by the oceans, such as climate regulation, the supporting sea-based food systems, and many forms of amenity values. However, this research provides a framework that can be easily extended to additional forms of ocean-based capital and more accurately reflect the economic value of marine ecosystems and the true costs of greenhouse gas emissions.

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3.2.3 Climate-Debt Dynamics: Integrating Climate Impacts and Adaptation into Sovereign Debt Sustainability Analysis

Introduction

This chapter is based on Calcaterra et al. (2025) and presents a methodology that couples stochastic debt sustainability analysis (SDSA) with integrated assessment models to evaluate climate risks to sovereign debt and assess the effectiveness of adaptation investments and fiscal policies in reducing these risks. As climate impacts intensify, understanding these fiscal dimensions becomes necessary for designing climate strategies that maintain economic



stability while pursuing decarbonization and adaptation goals.

Methodological Innovation and Enhanced IAM Capabilities

The methodology integrates the RICE50+ integrated assessment model (Gazzotti et al., 2021) with a stochastic debt sustainability model (Zenios et al. 2021). This coupling enables evaluation of multiple risk dimensions. Physical climate risks to economic growth interact with adaptation investments and debt sustainability concerns, generating stochastic debt projections. Since the purpose of the paper is to evaluate climate risks to sovereign debt, the paper assumes for transparency that climate change is not mitigated and, therefore, that climate trajectories follow those of the marker RCPs (Representative Concentration Pathways).

The framework employs aleatory scenario trees to capture uncertainty in economic, fiscal, and financial variables, generating forward-looking debt projections under different combinations of Shared Socioeconomic Pathways (SSPs) and RCPs. The stochastic optimization approach estimates state variables and conditional probabilities to match mean values, standard deviations, and correlations with empirical data (Consiglio et al., 2016). The analysis uses the 75th percentile of debt distributions, to assess tail risks relevant for fiscal planning. Indeed, the trajectory of the tail is a powerful indicator to assess debt un-sustainability since, if increasing, it denotes a vicious cycle of exploding sovereign debt in the 25 percent most adverse states of the world. The debt projection is therefore deemed sustainable only if the 75th percentile is not increasing in the long term.

Traditional IAMs optimize climate outcomes subject to economic efficiency criteria but abstract from institutional and fiscal realities. The SDSA-IAM coupling contributes to this gap by modeling how climate damages affect fiscal sustainability.

The integration operates through three channels. First, chronic GDP losses from temperature increases affect debt-to-GDP ratios through reduced economic output. Second, adaptation investments are modeled with cost-benefit calibration, where investments reduce residual damages while potentially requiring fiscal resources. Third, scenarios on primary balance adjustments capture the fiscal policy responses needed to maintain debt sustainability under climate stress, accounting for both revenue losses and expenditure pressures.



The coupled model employs two climate impact functions to capture uncertainty in damage estimates. The “low” impact function follows Kalkuhl and Wenz (2020), characterized by moderate damages, while the “high” impact function follows Burke et al. (2015).

Adaptation is modeled following the seminal work of Agrawala et al. (2010), that determines residual damages as a percentage of no-adaptation impacts and distinguishes between adaptation investments with contemporaneous benefits (*reactive*) and those with delayed benefits (*proactive*, building adaptation capital), while also considering *adaptive capacity*, linked to the level of economic development and investments in R&D. The original calibration was based on more benign damage functions, so we recalibrated its out-of-sample behavior through a formulation , with calibration ensuring that under high climate damages residual damages converge to approximately 75% of initial impacts. Results align with current estimates of the adaptation benefit-cost ratio of between 2:1 and 10:1 (Global Commission on Adaptation, 2019), with ratios of around 4:1 and as high as 8:1 at the end of the century, and present values from 2:1 to 3:1 .

Application Results: Climate-Debt Dynamics

The stress testing of representative countries demonstrates the framework’s ability to quantify climate-induced debt risks based on geographic vulnerability, initial debt positions, and socioeconomic development pathways. Under moderate scenarios (SSP2-RCP4.5), low-impact assumptions generate manageable debt increases with expected cost of debt financing rising by approximately 0.25% of GDP on average over the century. High-impact functions show larger effects, with costs increasing up to 3% of GDP for vulnerable countries.

The combination of regional rivalries with high emissions (SSP3-RCP7.0) produces more severe outcomes. Under high-impact functions, multiple countries exhibit explosive debt trajectories, with the 75th percentile of debt distributions showing continuously upward trends that fail standard sustainability criteria. These impacts accelerate significantly after mid-century, indicating the importance of early action and the long-term nature of climate fiscal risks.



Adaptation Effectiveness and Fiscal Trade-offs

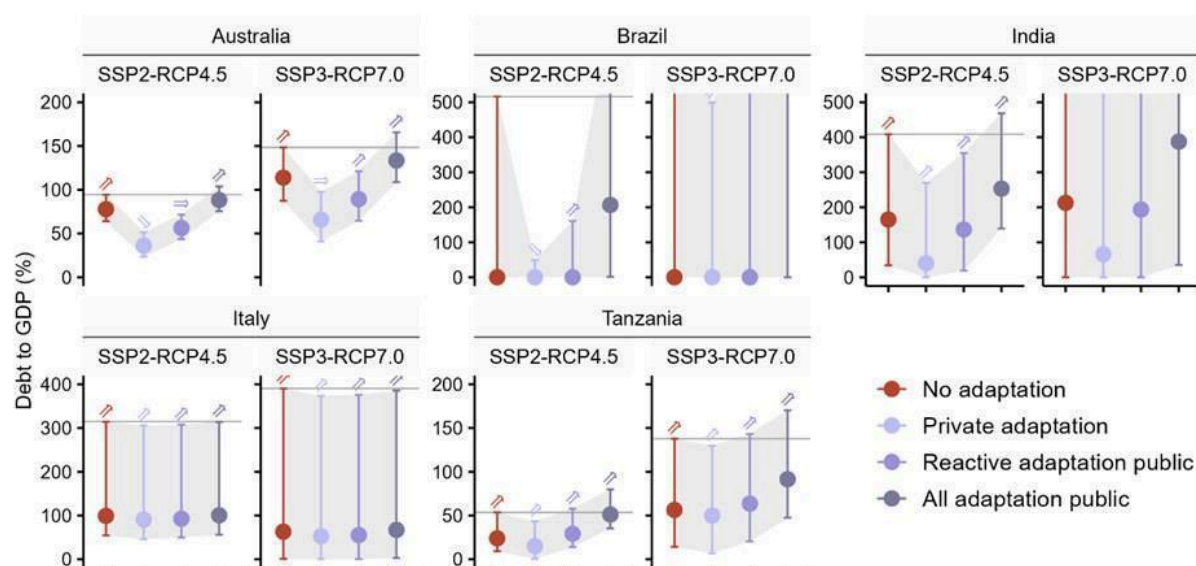


Figure 2: Adaptation effect on debt ratios. This figure displays the end-of-century debt ratios with climate change adaptation under high climate damages. It shows the inter-quartile range of debt for different adaptation policies, with the horizontal line denoting the 75th percentile without adaptation. The double arrow at the top of each interquartile range indicates the direction of the debt ratio; horizontal or downward-pointing signifies stable or declining debts, and upward-pointing signifies unsustainable debt trajectories. The large span of debt-to-GDP in the scenario SSP3-RCP7.0 is given by the high sensitivity of the public debt of warm developing countries to adverse states of the world in a scenario with relatively low growth and higher warming.

The analysis reveals that adaptation's role in managing climate-induced debt stress depends critically on financing arrangements. When adaptation is fully privately financed, governments achieve the most favorable fiscal outcome: they collect additional tax revenues from GDP gains generated by reduced climate damages without bearing investment costs. Full public financing of adaptation represents the least favorable case for sovereign debt, as governments bear all investment costs while capturing only a fraction of economic benefits through tax revenues. Public financing limited to reactive adaptation, lies in the middle, with fiscal benefits from reduced damages approximately offsetting public investment costs.

Quantification of fiscal consolidation requirements shows the challenge climate change poses to fiscal management. Under high climate impacts in SSP3-RCP7.0, required primary balances to stabilize debt exceed historical feasibility thresholds for multiple countries. Brazil would need to maintain primary surpluses of 4.0% of GDP, India requires 3.8%, and Italy needs 3.4%, representing increases of 1.6 to 3.6 percentage points above zero-damage baselines.

When governments maintain constant tax rates, climate damages reduce nominal revenues proportionally to GDP losses, forcing reductions in real public spending even when debt is successfully stabilized. Under low-impact scenarios, average spending reductions reach 7.5% over the century, while high-impact scenarios generate cuts reaching 50% for highly vulnerable countries. This creates tension between maintaining debt sustainability and providing public services at a time when climate adaptation and social protection needs are increasing.

Conclusions

Integration of climate impacts and adaptation into debt sustainability analysis reveals challenges that span climate, development, and fiscal policy domains. The methodology advances IAM frameworks by incorporating fiscal dynamics that traditional models overlook, demonstrating that climate change poses significant risks to sovereign debt sustainability through mechanisms that interact with and constrain optimal climate policies.

These results indicate the importance of incorporating fiscal sustainability constraints in climate-economy models. Models that optimize climate outcomes without accounting for fiscal limits may recommend strategies that are theoretically optimal but practically infeasible. The enhanced representation of climate-debt dynamics provides insights for more comprehensive assessments of viable climate pathways, contributing to improved understanding of the institutional and fiscal boundaries within which climate policy must operate.

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3.2.4 Decomposing costs and benefits of climate change in integrated scenarios

We present work for which a paper draft was close to completion when the damage function used in the analysis (Kotz et al. 2024) came under scrutiny with the publication of two Matters Arising (Schötz 2025, Bearpark et al. 2025). This led to a retraction of the original paper and an ongoing revision process by Kotz and co-authors (see an updated version of the paper at <https://zenodo.org/records/16758580>) which has not been completed with a new peer review. Therefore, at this point we are not able to get results based on this damage function, but focus here only on the methodological and implementation work undertaken as part of PRISMA, and show some results with a different damage function.

Introduction

The literature explicitly quantifying the benefits of mitigation together with the costs along transformation scenarios is scarce. A few studies use post-processing approaches for such analyses (e.g. Drouet et al. 2022). This allows for a comprehensive treatment of uncertainties but misses feedback effects both on the impacts themselves through macroeconomic dynamics (Fankhauser & Tol 2005, Piontek et al. 2021) and on the mitigation (Schultes et al. 2021). They find a high likelihood of net benefits of climate policy. Brown & Saunders (2020) use a modified version of the DICE model to assess the costs and benefits of high-end damage estimates (Burke et al. 2015) along different mitigation trajectories without full endogenization of both. They find net gains of mitigation but only relatively late in the century. van der Wijst et al. (2023) conduct cost-benefit analyses with three different IAMs, using a damage function derived with bottom-up methods, and quantify benefit-cost ratios for different preference parameters. In such fully integrated analyses it proves challenging to disentangle the costs and benefits properly.

Here, we propose a framework to decompose costs and benefits and apply it with the process-based integrated assessment modeling framework REMIND-MAGPIE to study the effect of fully integrating economic damages into climate policy scenarios. We show illustrative results comparing a baseline scenario with currently implemented climate policies, but no additional efforts (current policy scenario), and a climate policy scenario compatible with the Paris Agreement of below 2° warming. Warming in the current policy scenario in 2100 is 2.8°.



Damage functions

The persistence of macroeconomic damages is one of the key open questions as it has a strong influence on the magnitude of the damages and the social cost of carbon (Schultes et al. 2021, Piontek et al. 2021). Typical econometric damage estimates either assume level (Kalkuhl & Wenz 2020) or growth damages (Burke et al. 2015), relatively little work has been done to actually assess the persistence. In the study by Kotz et al. (2024) this was the key focus. Building on damage estimates related to a range of climate drivers (mean temperature - Kalkuhl & Wenz 2020, temperature variability - Kotz et al. 2021, precipitation – Kotz et al. 2022) persistence was estimated through a lagged approach and found to be between 4 and 10 years. Considering this a key advancement we chose to implement this damage function in the REMIND-MAGPIE model. Other key reasons were the possibility to assess the full uncertainty range of the damage estimate (resulting from climate and econometric model uncertainty) and the availability of country-level damage estimates, allowing for a more granular assessment of differentiated damages. As pointed out above we describe here the implementation only but refrain from showing results given the retraction and ongoing revision of the paper.

In the REMIND-MAGPIE framework the small-scale climate model MAGICC is used to translate emission pathways into climate and in particular temperature outcomes. Unfortunately, no other climate drivers are available beyond global mean temperature. Therefore, we developed an emulator for the damage function using a global warming level approach. Kotz et al. (2024) provide a large ensemble of projections for different global climate models (GCMs) along different emission (RCPs) and socioeconomic (SSPs) pathways. For each projection the country-level GDP loss in a given year was linked to the RCP-GCM-specific global mean temperature of that year. Through a regression a new aggregate damage function of the standard form was estimated, where T is the global mean temperature in year t , and α and β are country-specific parameters and D is the GDP loss in %. This also translates the growth effect into a level damage function which captures the persistence. The uncertainty is captured through a set of 1000 realizations for the parameter sets. For the application in the model we take the median as well as the 5th and 95th percentile. We calculate damages on the country level and then aggregate to the REMIND regional level using GDP weighting.



We now proceed to show results using the predecessor of Kotz et al. (2024), the damage function by Kalkuhl & Wenz (2020). We use their preferred specification which only depends on year-to-year variation of annual mean temperature and interaction terms, but not on temperature levels directly. An emulator is not needed (only a downscaling of global mean temperature to regional level temperature) and it is directly implemented as a growth damage function, affecting the growth rate through $y_{r,t}^c = y_{r,t-1}^c (1 + g_{r,t} + \delta_{r,t})$. $g_{r,t}$ is the growth rate of per capita GDP without climate, $\delta_{r,t}$ is the climate effect given by $\delta_{r,t} = \alpha_1 \Delta T_{r,t} + \alpha_2 \Delta T_{r,t-1} + \beta_1 T_{r,t-1} \Delta T_{r,t} + \beta_2 T_{r,t-1} \Delta T_{r,t-1}$. Here we do not have a full uncertainty range directly through the parameters. To reflect the inherent uncertainty, we use the 95th percentile of the confidence interval based on the standard error (SE) for $\delta_{r,t}$ which we calculate from the variance and co-variance parameters of the coefficients α and β . The “high” damage estimate is given by $\delta_{r,t}^{high} = \delta_{r,t} - 1.96 SE_{r,t}$. To really sample the high end of damages we combine these high damage estimates with a high climate sensitivity. Damages are calculated for additional warming beyond 2020 levels, assuming present day GDP already includes climate impacts.

Decomposition and modeling framework

In REMIND-MAGPIE we integrate climate damages as GDP reductions. The direct damage effect accumulates through investment and savings dynamics, leading to a larger long-term loss than projected by a damage function applied purely in post-processing (Figures 1 and 2). Note that this also means that consumption losses are larger than the GDP loss itself, as relatively more focus is still on capital investment.



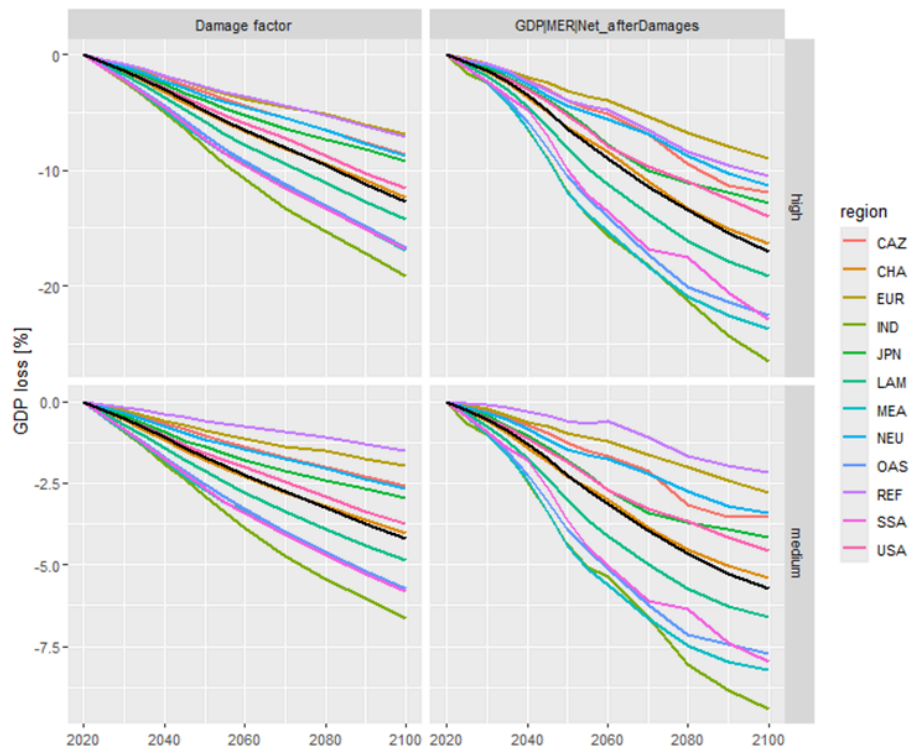


Figure 1: The direct and indirect effects of climate damages in a current policy scenario for high (top row) and medium (bottom row) damages. The left column shows the direct damages as given by the damage function. The right column shows the net GDP loss, including dynamic responses through savings effects. Colors indicate results for different regions, the black line is the global GDP loss.

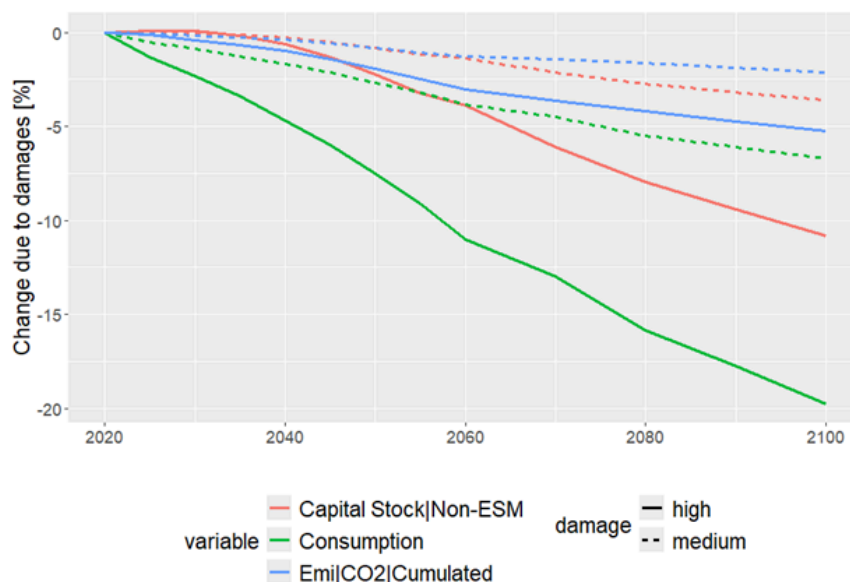


Figure 2: Global changes in capital stock (red line), consumption (green line) and cumulated CO₂ emissions (blue line) due to the incorporation of medium (dashed line) or high (solid line) damages in a current policy scenario.

In addition, there are feedback effects on the energy system, largely driven by reduced energy demand due to lower GDP. This leads to slightly lower emissions in the baseline (Figure 2). For the damage function by Kalkuhl & Wenz (2020) global cumulative CO₂ emissions in 2100 are lowered by 2-5%.

In climate policy scenarios we endogenize damages fully into the optimization by including a policy signal through the social cost of carbon associated with the given damage function (Schultes et al. 2021). This is combined with a policy target which is specified with a guardrail carbon price which is adjusted up and down based on the magnitude of the social cost of carbon. If the damage is high enough to fulfill the policy target, the social cost of carbon dominates and essentially a cost-benefit analysis is run. Otherwise, the final carbon tax is a combination of both components, essentially hedging against the fact that a given damage function does not account for all relevant damages, in particular extremes and non-market effects. For the Kalkuhl & Wenz (2020) damage function applied in a policy scenario with a “Below 2°” target this is shown in Figure 3. This illustrates well the feedback effect of the

damage function on the optimal mitigation pathway: more ambitious early climate action, allowing for lower carbon prices later on.

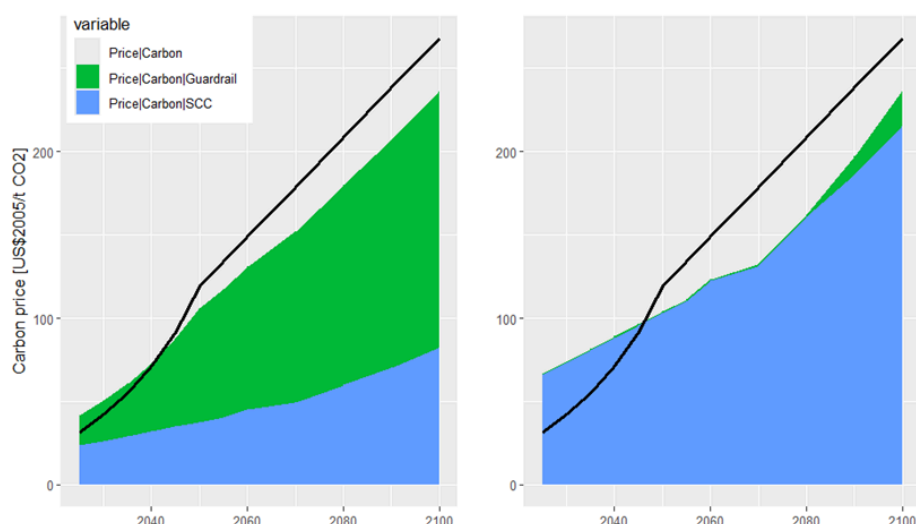


Figure 3: Carbon price in climate policy runs integrating climate damages compared to pure cost-effectiveness runs without damages (black line). In the former, the total carbon tax consists of the damage-related social cost of carbon (SCC) and the guardrail tax driven by the policy target. The left panel shows results for medium damages, the right panel for high damages.

The final GDP change in such a scenario compared to a baseline is driven by the combined effect of the costs of climate policy and the residual climate damages. Due to the economic dynamic effects discussed above it is not straightforward to disentangle the two. Furthermore, separating costs and benefits requires comparisons to different baselines, as the standard baseline captures neither climate policy nor climate impacts. We therefore develop a decomposition framework illustrating the need for additional model runs to calculate the separate effects (Figure 4). Such a setup allows the comparable assessment of mitigation costs, residual damages, avoided damages, net benefits and total losses for a given integrated scenario across different models. A key component is the definition of mitigation costs as the total GDP (or consumption) changes between a baseline with current policies implemented and a scenario without climate damages but a mitigation effort comparable to a fully integrated run. In the case of REMIND this means a similar carbon price



trajectory. While the gross benefit is simply the avoided damages, the net benefit is the avoided damages plus the costs from mitigation, while total loss sums the costs from mitigation and the costs of residual damages.

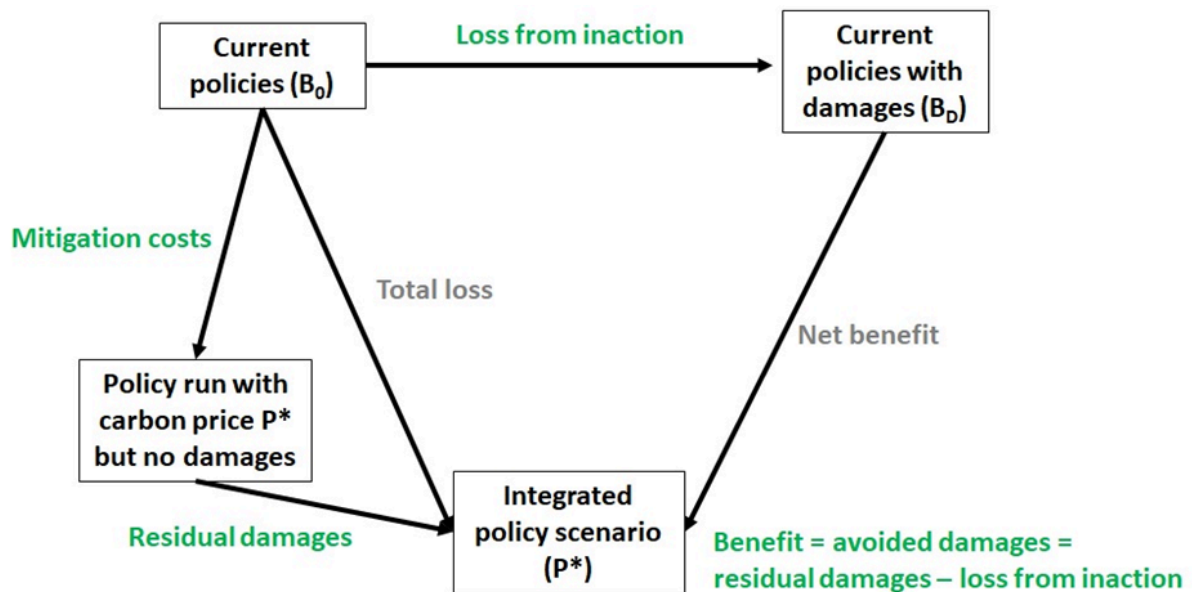


Figure 4: Decomposition of different cost and benefit components in an integrated assessment framework for climate policy scenarios.

Figures 5 and 6 illustrate applications of this decomposition on a global and regional level. In the near term the mitigation costs dominate and combine with residual damages to an increased burden. This can be alleviated through adaptation (which would, however, incur additional costs) and redistribution of carbon tax revenues (not modeled here, see e.g. Soergel et al. 2021, Emmerling et al. 2024). In the long-term, benefits of reduced climate damages dominate strongly, although residual damages remain.

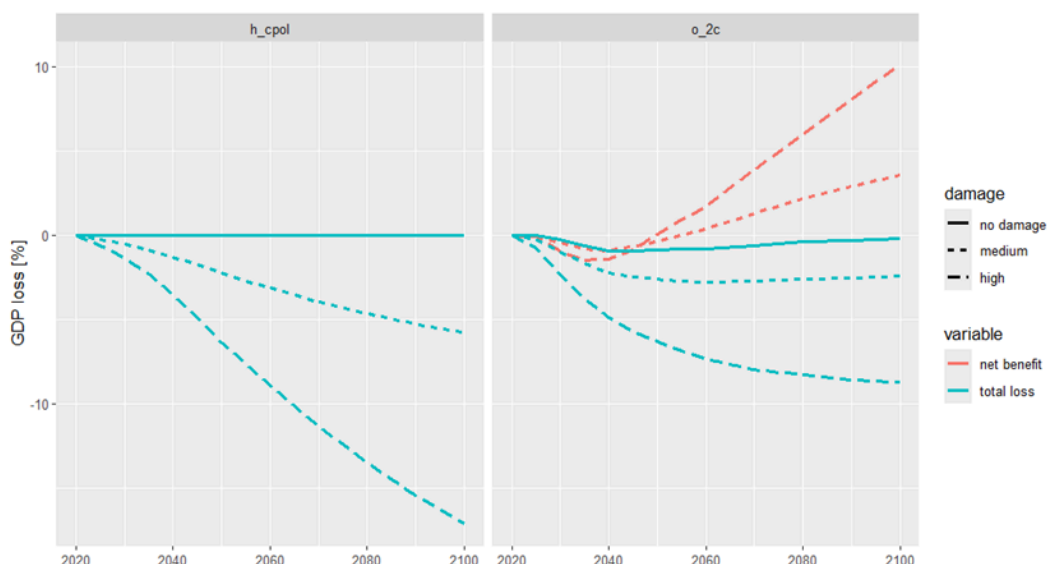


Figure 5: Global GDP change from mitigation only (solid line), medium or high (dashed lines) damages, in a current policy (left panel) and a “Below 2°” policy scenario (right panel). The red lines indicate net benefits, i.e. taking into account avoided damages, while the blue lines only show total effects from mitigation costs and residual damages.

While these dynamics are similar across regions they vary in magnitude (Figure 6). Largest long-term benefits are found in developing regions (e.g. India, Sub-Saharan Africa). However, these regions also face large losses from mitigation and residual damages. For many regions these losses remain relatively constant over time, with only small medium-term peak losses if any. More pronounced peaks are seen in regions with large emissions and mitigation efforts, e.g. Japan, the Reforming Economies, Latin America, Middle East and North Africa and the CAZ region (Canada, Australia, New Zealand). Largest burdens are found in the fossil-dominated regions REF and MEA. REF, the region with the smallest damages but largest mitigation burdens. The transition point from losses to benefits also differs between regions.



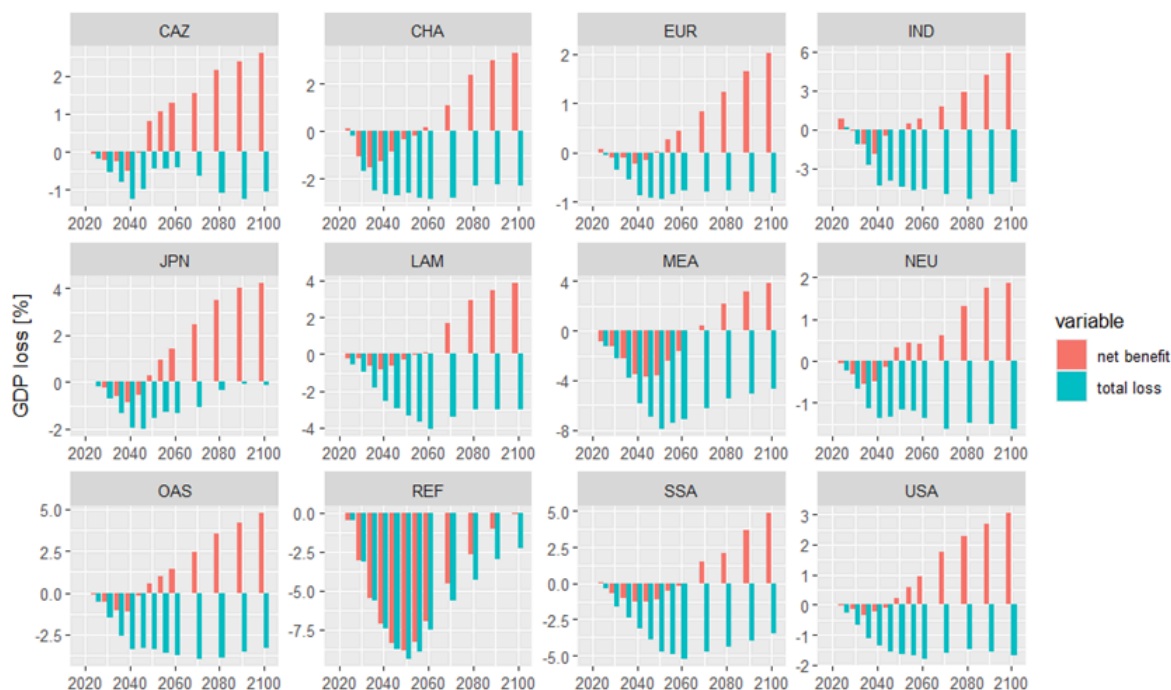


Figure 6: Same as Figure 5, but only for the “Below 2°” policy scenario with medium damages, showing results for different regions.

Conclusions

The magnitude of economic impacts of climate change remains a key uncertainty in the integrated assessment of climate policy and damages. The large ranges create a significant challenge for policy advice. A full integration of climate damages is key to quantify total losses but also benefits consistently. This requires a well-defined decomposition, necessitating additional model runs beyond the scenarios of interest. Nevertheless, this should be a standard component of scenario assessment.

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3.2.5 Comparing Economic Impacts of Net-Zero Transition with Climate Damage Uncertainties

This study has been published in the peer-reviewed scientific journal *Environmental Research: Energy*: “Aron Denes Hartvig, Marton Simo, Dora Fazekas, Panagiotis Fragkos, Kostas Fragkiadakis, Dimitris Fragkiadakis and Zoi Vrontisi, Comparing economic impacts of net-zero transition with climate damage uncertainties using a dual-model approach, *Environmental Research: Energy*, Volume 2, Number 3, DOI 10.1088/2753-3751/ade5e” (see Annex III).

Abstract

This study conducts a scenario analysis of global net-zero emissions by 2050 using two macroeconomic models with distinct theoretical foundations: E3ME (non-equilibrium) and GEM-E3 (equilibrium). The analysis quantifies the economic impacts of increasing climate policy ambition to meet the global 1.5°C warming target and highlights key differences between the models in projecting GDP, employment, and sectoral transitions. The findings indicate that while economic outcomes of decarbonization may vary depending on the model paradigm used, the uncertainties in climate damage projections far exceed those of mitigation costs. The study finds that the costs of mitigation are lower and more predictable than the potential climate damage costs. Limiting warming to 1.5°C yields net economic gains in almost all countries examined, while a 3°C trajectory could trigger widespread losses. The study reinforces the need for immediate global mitigation efforts.

Introduction

To mitigate the risk of potentially severe economic and environmental losses associated with climate change, it is imperative for the global community to reduce greenhouse gas (GHG) emissions and transition toward a net-zero emissions trajectory. Net-zero pathway analysis supports ambitious emissions reduction targets by identifying specific actions, strategies, and



interventions across various sectors (Dafnomilis et al., 2023; DeAngelo et al., 2021). However, climate damages are rarely included in these analyses and therefore it is difficult to assess the trade-offs between transition risks and climate damages. Transition risks arise from the regulatory and structural changes in moving our economic and energy systems towards net-zero emissions; however, if global warming keeps increasing to more than 3°C, it is likely that the world will face severe economic losses from the physical risks of climate change.

The paper contributes to existing literature in two ways. Firstly, by defining an innovative net-zero scenario where global emissions reach net-zero by 2050 and identifying the range of expected economic outcomes for policymaking using the dual-model approach. The second objective is to compare the expected costs and impacts of decarbonisation with the economic benefits of avoiding potential climate damages that would result from inaction. We estimate the range of economic impacts from achieving net-zero emissions using global macroeconomic models based on different theoretical foundations. These results are then compared with estimates of climate damage costs drawn from the literature and calculated using a variety of methodological approaches. This unique comparison helps assess the uncertainties inherent in both sets of estimates and supports drawing conclusions based on multiple analysis approaches. The study shows that economic losses are considerably lower compared to scenarios with higher temperature increases.

Climate damages

In recent years, climate research has concentrated on studying average temperature rises of 1.5-2°C which are viewed as an optimistic or even best-case scenario (Sharpe, 2023).. Currently, temperature rises of 2.5-3°C are considered the most likely scenarios if current policies and trends continue by 2050 (IEA WEO, 2024). Nevertheless, even less probable situations, such as temperature increases exceeding 4°C in the longer term, should not be ruled out.

Burke et al. (2015) establishes a key feature of damage functions that represent the feedback loops between emissions and economic development. The authors show that damage functions follow a highly non-linear pattern to temperature changes, which would result in 23% GDP losses in a high-emissions scenario relative to a scenario without climate change by 2100. Furthermore, even these estimates might underestimate the impacts if extreme



outcomes, like significant sea level rise, occur at 2°C or higher but not at 1.5°C. Kotz et al. (2024) find that the world economy will have to face a 11-29% reduction in incomes even in a 2°C warming scenario by 2100 relative to a baseline without climate impacts. Similarly, Bilal & Känzig (2024) estimate that the global macroeconomic damages resulting from rising temperatures would reduce global GDP by 12%. Burke et al. (2018) suggest that limiting warming to 1.5°C instead of 2°C by the century's end not only reduces climate damages but also decreases global inequality, with poorer countries benefiting the most.

Keen (2020) has criticized economists' forecasts of climate change damages for being overly optimistic. Economists often underestimate damages due to assumptions that GDP remains unaffected, using current temperature-GDP relationships for future impacts, and diluting scientific warnings with optimistic expectations. Pindyck (2013) states that integrated assessment models have flaws, including arbitrary input assumptions on discount rates and a lack of a consistent theory for capturing climate damages. Instead, they address the issue in an ad hoc manner. Correcting these errors suggests climate damages could be much worse. Lately, the 2023 temperature anomaly emerged unexpectedly, revealing a knowledge gap not seen since satellite data began offering real-time insights into Earth's climate system 40 years ago (Schmidt, 2024). If the anomaly persists, it suggests global warming is altering the climate system sooner than expected, casting doubt on past predictions for droughts and rainfall patterns.

Methodology

The E3ME and GEM-E3 models are widely used to assess the economic impacts of various policies, as well as their potential effects on the environment and society (Fragkos et al., 2023; Lynch et al. 2024). Both models have a particular emphasis on robust economic representation and are founded on Input-Output (IO) tables derived from the national accounts system. Building on the initial information captured in the IO-tables, main macroeconomic indicators are derived, such as GDP, consumption, capital formation, employment, trade, etc. Both models capture the complex interlinkages between economy, energy system and environment, which are connected through bottom-up representation of energy system dynamics (focusing on electricity supply, industries, transport and buildings) and emission calculations, the accumulation of which results in global warming. While both models share similar principles, they differ significantly in how specific elements are



designed, leading to distinct modelling outcomes. A key distinction is that GEM-E3 is an equilibrium model, assuming that the economy remains in an optimal equilibrium in each scenario, whereas E3ME is a non-equilibrium model, acknowledging that the economy is not always in equilibrium (Mercure et al., 2019). Equilibrium models ensure a closed system approach that allows a consistent comparison across scenarios of different policy options and an explicit comprehension of system dynamics and long-term structural changes. While a new generation of hybrid equilibrium models, like GEM-E3, incorporate empirically estimated behaviours of markets, for example by featuring endogenous unemployment, decisions still comply with optimization rules.

Table 1: Overview of the key macroeconomic model similarities and differences, source: Mercure et al. (2019)

	E3ME-FTT	GEM-E3
Model type	Macroeconometric (E3ME), hybrid with bottom-up evolutionary modules (FTT)	CGE model, hybrid with bottom-up modules
Macroeconomic theory branch	Non-equilibrium (Demand driven)	Equilibrium (Supply driven)
Technological change	Endogenous (power, road transport, domestic heat, and steel sectors)	Endogenous (power, road transport, heating)
Labour market representation	Imperfect and flexible labour markets	Imperfect and flexible labour markets, 5 skill levels are represented
Investment & Finance	No crowding out, no fixed limit on finance	Crowding-out and alternative financing options are available. Finance is constrained at the global level.
Sector coverage	43 (70 in the EU)	65
Regional coverage	71 countries and regions	46 countries and regions



Scenario Design

We assess two alternative scenarios. The "Current Policies" scenario simulates the continuation of historical trends and existing national climate policies, excluding unlegislated pledges like net-zero commitments. The scenario assumes that current climate policies will extend beyond their expiration around 2030, with carbon pricing extrapolated using the GDP growth rates from 2030 to 2050, maintaining 2030 levels of climate ambition in each country. The global average temperature rise in the Current Policies scenario by 2100 is around 3°C. In the "Net-zero" scenario, a global carbon price is introduced after 2025 progressively increasing to 2050, affecting all sectors aiming to ensure a cost-efficient global transition towards net-zero emissions by 2050. The scenario includes additional ambitious policies including energy taxes, biofuel mandates, investments in clean technologies, and CO₂ standards and regulations on vehicles and boilers. Further policy measures include caps on new fossil fuel capacities, biofuel blending, a phase-out of unabated coal power by 2050, and afforestation investments. Substantial subsidies are used to support decarbonizing industrial processes through electricity, hydrogen, and CCS technologies. These coordinated efforts aim to significantly reduce emissions and achieve the average temperature rise of 1.5°C, while transitioning to a sustainable, low-carbon future.

Results

In the Current Policies scenario, global emissions remain high, especially in developing economies like India, driven by economic growth and rising living standards. However, in case of committing to the global net-zero scenario, these high emitting countries also achieve significant emission reductions to reach global net-zero targets. The net-zero scenario achieves global net-zero CO₂ emissions by 2050, with large emissions reductions achieved already by 2035 to meet the Paris Agreement's 1.5°C goal. Mitigation efforts can vary by region, with some regions achieving net-negative emissions by 2050 to offset residual emissions elsewhere. Brazil, for example, achieves negative emissions through afforestation and bioenergy with carbon capture and storage (BECCS), while India continues to use fossil fuels to meet its increasing energy needs (UNFCCC, 2015).

The short- and long-term socioeconomic impacts depend on how climate policies are integrated into economic systems. GEM-E3 projects an initial economic slowdown due to



higher clean energy costs compared to the Current Policies scenario, followed by reduced economic activity by 2050, largely driven by the crowding-out effects of decarbonisation investment, reducing the productive investment in other activities. In contrast, E3ME anticipates short-term growth driven by investment stimulus given its money creation assumption, followed by a period of slowdown during debt repayment, before stabilizing in the long run.

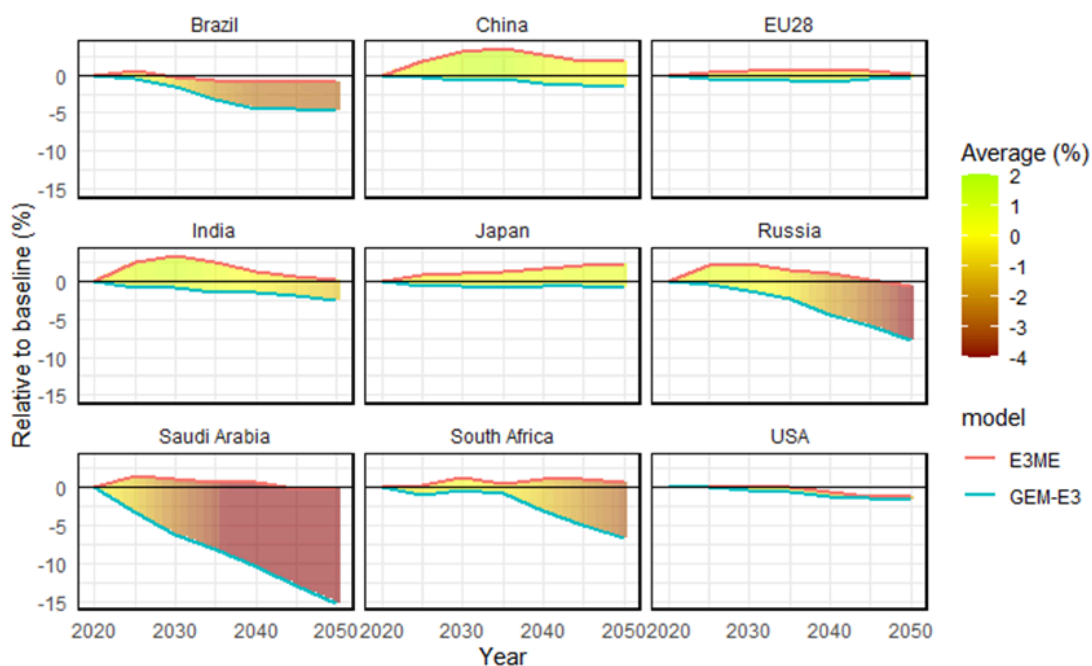


Figure 1: GDP impact of the Net-Zero scenario compared to Current Policies. The green-yellow-red shaded area of the figure shows the average difference from baseline (in %) across the two model results. The red (E3ME) and blue (GEM-E3) lines show the two models' estimates.

GDP impacts vary across countries, with some benefiting from the net-zero transition while others face severe economic challenges. These impacts depend on factors such as their energy costs, policy frameworks, and economic integration, while the regional economic impacts are massively influenced by the country's role in fossil fuel trade (importer/exporter)

and by its carbon intensity, as shown in (Lynch et al. 2024).

Developed economies such as the EU, the USA, and Japan, which already have established climate policies and lower carbon intensity, generally experience moderate economic impacts. In contrast, fossil fuel-exporting countries face greater uncertainty, with projections indicating lower GDP in the net-zero scenario by 2050, particularly for Brazil, Russia, and Saudi Arabia. China, India and Japan exhibit the most favourable economic effects of the net-zero scenario, either showing the highest positive GDP impacts (E3ME) or the least negative effects (GEM-E3). China's proactive investment in reducing coal dependency and expanding renewable energy infrastructure plays a key role in this trend. E3ME projects a 3% GDP increase by 2035, stabilizing at 1.7% in 2050, while GEM-E3 anticipates a slight decline of economic activity, offset by higher exports of clean energy technologies such as solar PV, batteries, and electric vehicles.

Unlike the EU, the USA faces small relative GDP losses according to both models due to its extensive shale oil industry that is hit by ambitious climate regulations. E3ME and GEM-E3 indicate a limited reduction in country's GDP as strict assumptions on oil phase-out affect the USA's oil export reliance. Europe, leading in climate action with the European Green Deal, shows initial GDP growth as a result of reduced fossil fuel imports (E3ME) and small long-term GDP impacts in both models.

In summary, the model-based analysis indicates that certain countries benefit more than others from the energy transition assumed in the net-zero scenario. China, India, and Japan emerge as winners, showcasing favourable economic trajectories due to investments in renewable energy. In contrast, the USA faces relative GDP losses attributed to its shale oil industry, though existing climate policies mitigate the impact. According to both models, Europe experiences a marginal GDP impact. Oil-exporting countries, especially Saudi Arabia, face significant GDP risks, with substantial losses predicted from reduced fossil fuel export revenues.

Comparison of economic impacts and climate damages

The estimated economic impacts presented in the previous chapter are based on a net-zero scenario, which keeps global average temperature increase at 1.5°C compared to



pre-industrial levels. In contrast, the Current Policies scenario would result in an approximate 3°C average temperature increase by 2100. The macroeconomic impacts of the net-zero scenario represent the mitigation costs associated with implementing ambitious climate action measures. In this chapter, we compare these costs and benefits of mitigation with the cost of climate inaction, based on a comprehensive review of climate cost estimates.

Figure 3 presents a regional breakdown of the estimated economic impacts of climate change in 2050. Relative GDP change in percentage terms is shown on the x-axis for each region/country included in the analysis. The blue range shows the potential range of GDP impacts of mitigation that stem from the model-based results of a global net-zero scenario. This uncertainty range of economic analysis is derived from the maximum and minimum GDP impacts of the dual-modal analysis for 2050. A review of the climate damage literature reveals consistent evidence that the costs of climate damages are expected to increase over time, largely irrespective of the level of climate action. This finding is further supported by recent NGFS short-term scenarios (NGFS, 2025), which indicate substantial climate-related damages even in the near term. These short-term impacts stem from extreme regional weather events, such as droughts, floods, and storms, that lead to significant GDP losses and financial stress, with global repercussions through trade and financial linkages. Over the longer-term, climate damages are expected to intensify considerably.

Furthermore, the figure shows point estimates of damage costs in the same year. The grey ranges, representing point estimates of climate damage costs under a 3°C global warming scenario compared to a 1.5°C global warming scenario, illustrate the potential variability in climate-related costs resulting from inaction. These costs reflect the estimated impacts of rising temperatures on regional GDP, based on the empirical methods employed in the referenced studies. The ranges presented illustrate comprehensive, scientifically robust, peer-reviewed and recent estimates of damages to reflect the potential costs of climate inaction. The costs associated with lower climate ambition, as estimated using different climate damage functions, cover a much larger range than the mitigation costs derived from the dual-model analysis of the net-zero scenario in all regions. This indicates the much higher uncertainty of the potential economic damages from climate change compared to the potential economic impacts of a transition towards global net-zero. However, the greater variability in damage cost estimates may, in part, be attributable to the broader and methodologically more diverse estimates on damage costs, in contrast to the mitigation cost



estimates considered in this paper, which are derived from only two models.

A comparison with existing literature can provide context for the relative magnitudes of mitigation costs and climate damage costs. Van de Ven et al. (2025) report in the IPCC AR6 scenarios that mitigation costs are projected to be between 2-4% of total GDP by 2050. Our results fall at the lower end of the IPCC range, due to key mechanisms in our models differing from those in existing literature. Van de Ven et al. (2025) mainly use CGE models, which tend to predict more negative economic impacts than macroeconometric models like E3ME. Within CGE models, GEM-E3 (used here) incorporates endogenous technology learning, lowering clean technology and thus mitigation costs compared to other CGE models.

Besides the larger uncertainty in estimating climate damage costs, the current analysis indicates a higher average economic cost of climate damages compared to the estimated mitigation costs of the net-zero pathway in all countries except for Russia.

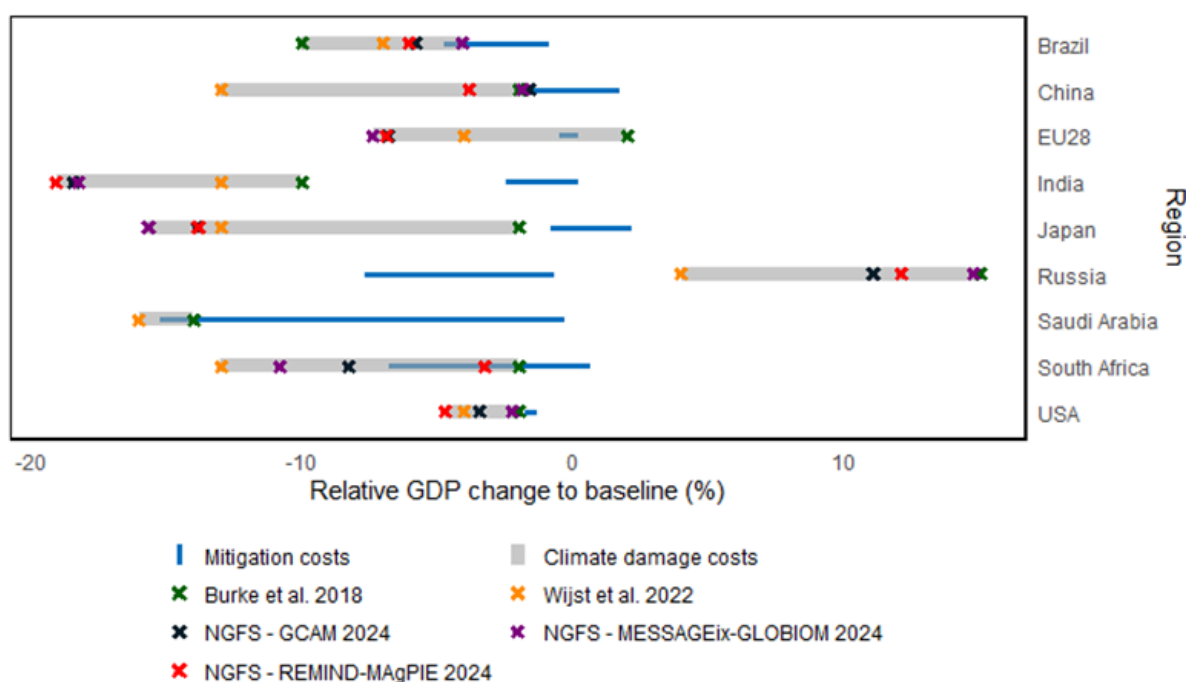


Figure 3: Range of GDP outcomes based on economic and climate modelling. The climate damage costs shown in the figure represent the additional climate damages in a single year, 2050, compared to a 1.5°C scenario. This specification ensures comparability with the mitigation costs derived from our dual-model analysis. The blue range illustrates the mitigation costs and benefits associated with emissions reductions in the net-zero scenario, while the grey range represents the additional climate damages under the Current Policies scenario (3°C).

Wijst et al. (2022) present relatively high GDP impact estimates from climate damages in multiple regions, such as China and South Africa compared to other studies. However, the MESSAGEix-GLOBIOM estimates indicate more severe economic losses for the EU and Japan, demonstrating that climate damages can be significant even in highly developed economies. The most negative outcome is projected for India, where its GDP could decline by nearly 20% by 2050 under a high-emissions scenario compared to estimates excluding climate change impacts. Similarly, Japan and Saudi Arabia are expected to experience GDP losses of 15-16%.

On the other hand, some regions may see economic benefits from rising global temperatures. According to Burke et al. (2018) and the NGFS scenarios (2024), Russia is projected to achieve a GDP increase of more than 10%, primarily due to the potential expansion of arable land in previously frozen regions. Canada may also experience similar effects. However, other studies on climate inaction costs estimate more moderate economic outcomes, reflecting differences in methodological and modelling approaches.

Figure 4 demonstrates the combined effects of mitigation costs and avoided climate damages in the Net-Zero scenario in comparison to the Current Policies scenario. When considering the avoided climate damages, most regions exhibit a positive impact across almost all estimated damages and mitigation costs. Specifically, some regions such as India and Japan may achieve close to 20% higher GDP, while the majority of regions experience GDP impact between 0-15% compared to the baseline. Russia is an exception, as climatic changes are estimated to have a positive GDP impact, suggesting that higher average temperatures boost economic output. As a result, Russia appears on the negative side of the plot when avoided climate damages are considered.



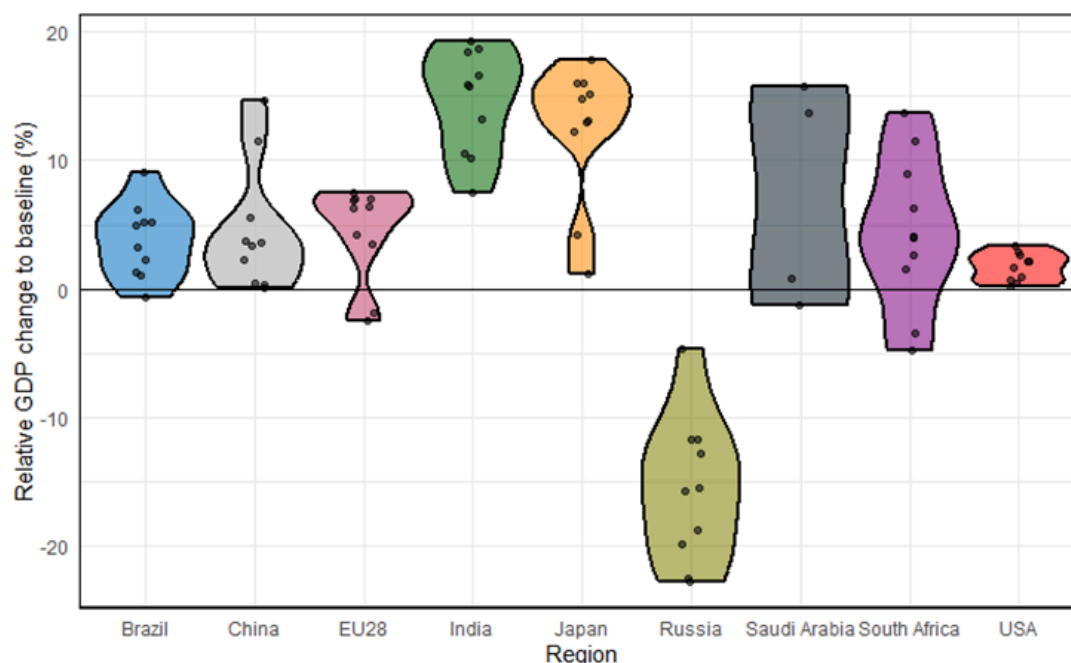


Figure 4: Combined impacts of mitigation and climate damage costs by region in 2050. The combined impacts for each region in 2050 are calculated by subtracting the climate damage costs under the Current Policies scenario from the mitigation costs associated with the net-zero pathway. These estimates are based on both the E3ME and GEM-E3 models, as well as the climate damage cost estimates from the studies referenced. This results in 10 values per region (2 mitigation cost estimates $\times$ 5 climate damage cost estimates). A violin plot is then used to visualize the distribution of these combined total economic impacts of the net-zero pathway.

These results highlight two key findings of the research. First, the range of uncertainty for the cost of avoided climate damages is significantly larger than that of the potential mitigation costs associated with an orderly and early net-zero transition. Second, a comprehensive assessment of the net-zero transition must consider both mitigation costs and avoided climate damages. When accounting for the climate damages that would have occurred under a baseline scenario, the net-zero transition is expected to have a positive impact on GDP across most countries.

Conclusions

This study underscores the intricate relationship between economic growth, climate change, and policy responses. It highlights that immediate and ambitious climate action has a lower -and much less uncertain - cost compared to the pathway resulting from the current policies for all major economies analysed (except for Russia). The economic impacts of climate damages across regions and models show significant discrepancies in the literature. For example, Saudi Arabia and India could face very high GDP losses of up to 50% and 37%, respectively, while Russia and Canada might see economic benefits under certain warming scenarios. Critiques highlight the optimism in economic forecasts of climate impacts, often neglecting future risks and the non-linear nature of climate damages. The accelerated pace of climate change further complicates predictability.

Comparing the economic impact of climate damages with the mitigation costs of committing to ambitious climate action indicates an economic advantage for the net-zero pathway. In contrast, failure to mitigate climate change results in significant negative socioeconomic and environmental consequences. Limiting global warming to 1.5°C could result in net global economic benefits, whereas a 3°C increase – if current trends and policies do not intensify – could massively reduce GDP in most countries globally. Global cooperation for climate action combined with tailored and ambitious policies in specific countries are essential for supporting the transition to net-zero emissions, especially for vulnerable economies. Immediate climate action, guided by comprehensive research and scenario analyses, is necessary to mitigate the very high climate damage risks and future economic losses and ensure sustainable development and a just transition.



3.2.6. Integrating GDP- and Labour productivity impacts in IMAGE

As a process-based simulation model, the strength of IMAGE lies in its detailed representation of sectors, processes and their interactions. However, it has a limited representation of the macro-economy, with changes in GDP and sectoral value added normally being treated as exogenous inputs, rather than endogenously calculated outputs. Consequently, economic damages due to global warming also have to be accounted for at this input level, making it difficult to relate the damages to the warming level in a certain scenario. In an earlier assessment (in the NAVIGATE H2020 project, Van Vuuren et al, under review at ERL), economic damages were included in the scenario design, but not incorporated in the model. In this PRISMA exercise, PBL has implemented labour productivity (LP) and other GDP impacts in IMAGE as an optional scenario setting (see Figure 3.2.6a for a schematic overview of the new routine). The LP data is based on a recent update of an empirical study by Dasgupta et al. (2021). In the new update, the temperature response functions have been tailored to the 26 IMAGE world regions, whereas, in the original 2021 study (and in NAVIGATE), response functions were only determined on a global macro region level. The data represents effective labour impacts (i.e. impacts on both working hours and productivity) in the full economy at different temperature increases compared to pre-industrial levels (at a later stage, the LP impacts can be specified by sector and linked to sectoral processes in IMAGE). Historical adaptation is represented in the empirical data, but not disentangled from impacts.

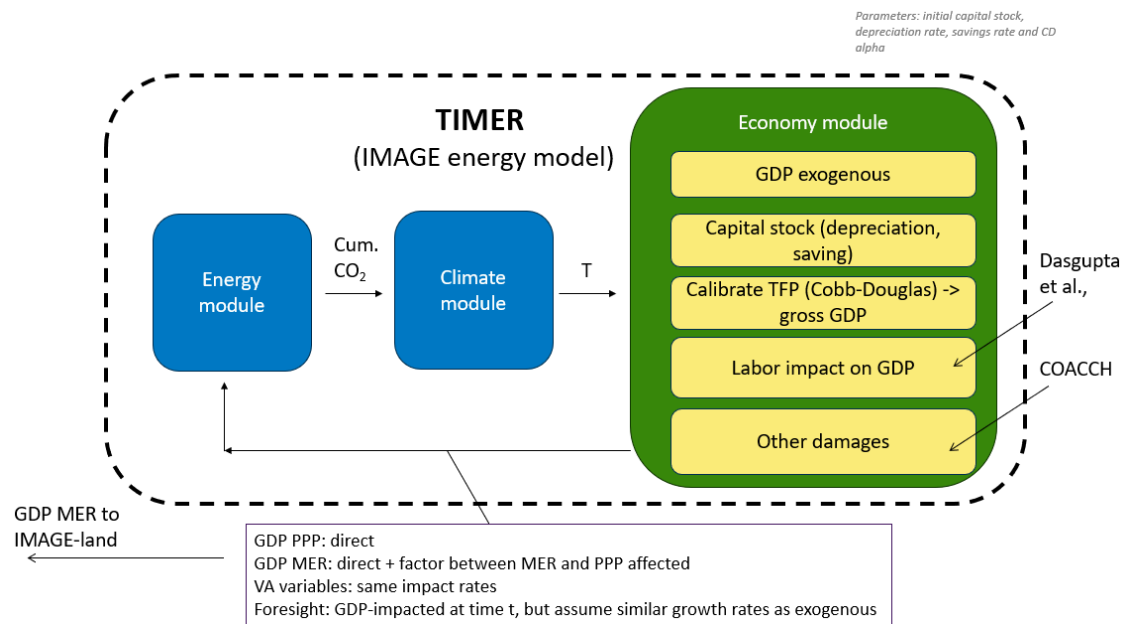
Other GDP impacts are based on the COACCH damage curves (Van der Wijst et al., 2023)(see Figure 3.2.6a (bottom panel)). These have been developed using projections of physical impact models and include the following impacts: Crop yields, wood production, fish catches, sea-level rise and riverine floods (land loss, asset loss, flooded people, protection cost), road transportation, energy supply (wind and hydro), Energy demand (households, industry, agriculture, services). The curves are so-called level damage functions: they directly impact economic output instead of economic growth. For this assessment, we also include indirect damages, derived from the COACCH function. This is a lagging damage effect resulting from reduced investments, which lead to higher impacts in later years. The median value of the curves is very close to that of Howard & Sterner (2017), whose estimates were based on large meta-analyses of global climate damages. The net global GDP decline is estimated at about 7.5% at 2dC.



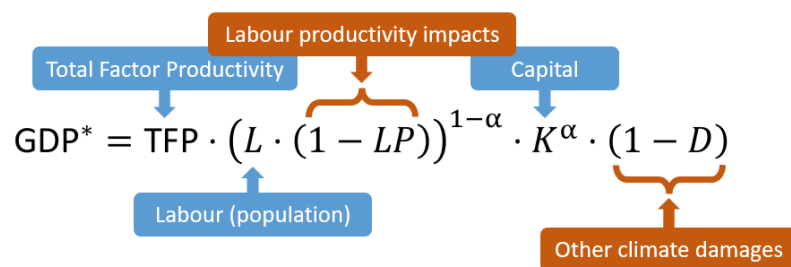
The labour force impacts in COACCH have been substituted by the LP data from Dasgupta et al., using the climate related GDP impact (Cobb-Douglas) function from the MIMOSA model (<https://www.copernicus-model-atlas.uu.nl/model/MIMOSA>), a Ramsey-type growth model, which has also been used for the construction of the COACCH damage curves. Figure 3.2.6a shows the function and its components. It represents the assumed relation between GDP, labour (people) and capital stock (financial and physical assets). In the formula, L is the labour force (usually taken to be equal to population), K is the capital stock and TFP the Total Factor Productivity, which represents technological improvements. Climate impacts are indicated by LP, i.e., the labour productivity impacts, and D, the other climate damages. In the projections of economic damages, it also takes into account accumulated historical GDP damages. The function has been calibrated to the GDP projections used in IMAGE (i.e. OECD Env-Growth growth rates (release 3.2) (OECD, 2025), using IMAGE-regional estimates of the share of effective labour losses in total GDP losses. Scenario-dependent temperature changes are estimated in TIMER (IMAGE's energy model), based on cumulative CO₂ emissions, and used as input for the LP and GDP impact calculation.



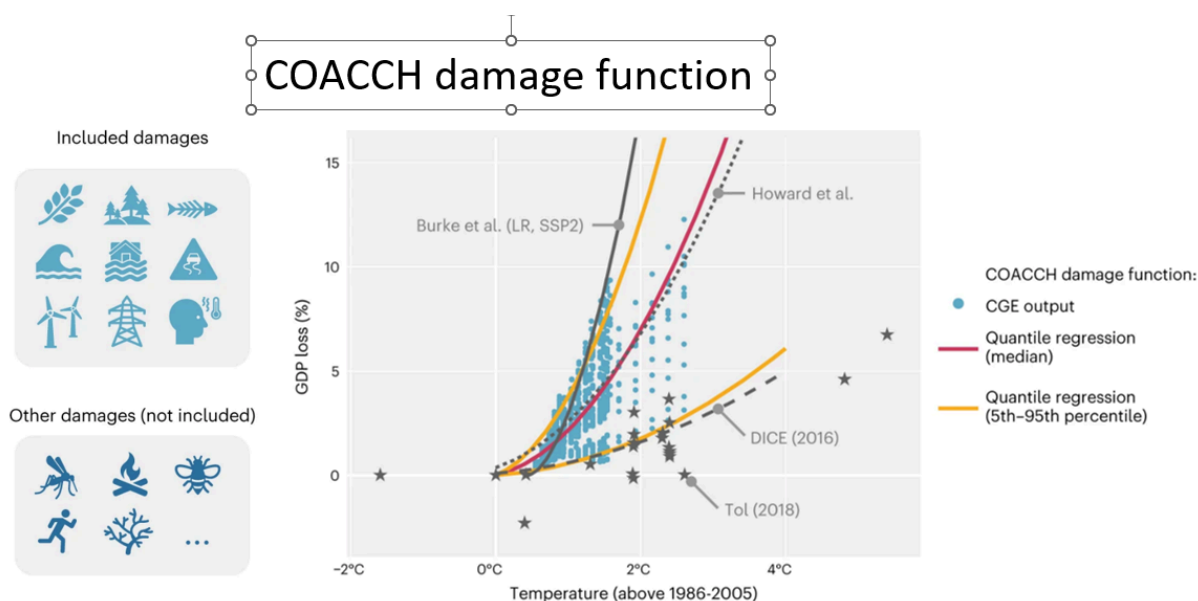
a. Implementation in IMAGE/TIMER



b. GDP impact calculation



c. COACCH damage function



Preliminary results

The following figures show preliminary results of a scenario exercise based on the new updates. Results are shown for key IMAGE regions, for the reference (CP = Current Policy) and mitigation (VLLO = very low emissions, roughly 50% of staying below 1.5dC) scenarios, with and without impacts. Figure 3.2.6b shows how GDP is projected to increase in all regions compared to today, with and without climate impacts, although some regions in the CP scenarios are projected to peak and decline before the end of the century. The total GDP decline reaches up to 31% in tropical regions such as India (Figure 3.2.6c), due to higher temperatures (and the non-linear impacts) and the higher prevalence of unsheltered (outdoor) labour (e.g., agriculture and construction). Other impacts are more balanced across regions. As expected, the climate impacts are much smaller in the mitigation scenario. With the current setup, labour productivity is found to make up half of the total damages (3.2.6d and e). As final energy use is largely driven by economic growth, reductions in final energy follow reductions in GDP (Figure 3.2.6f).



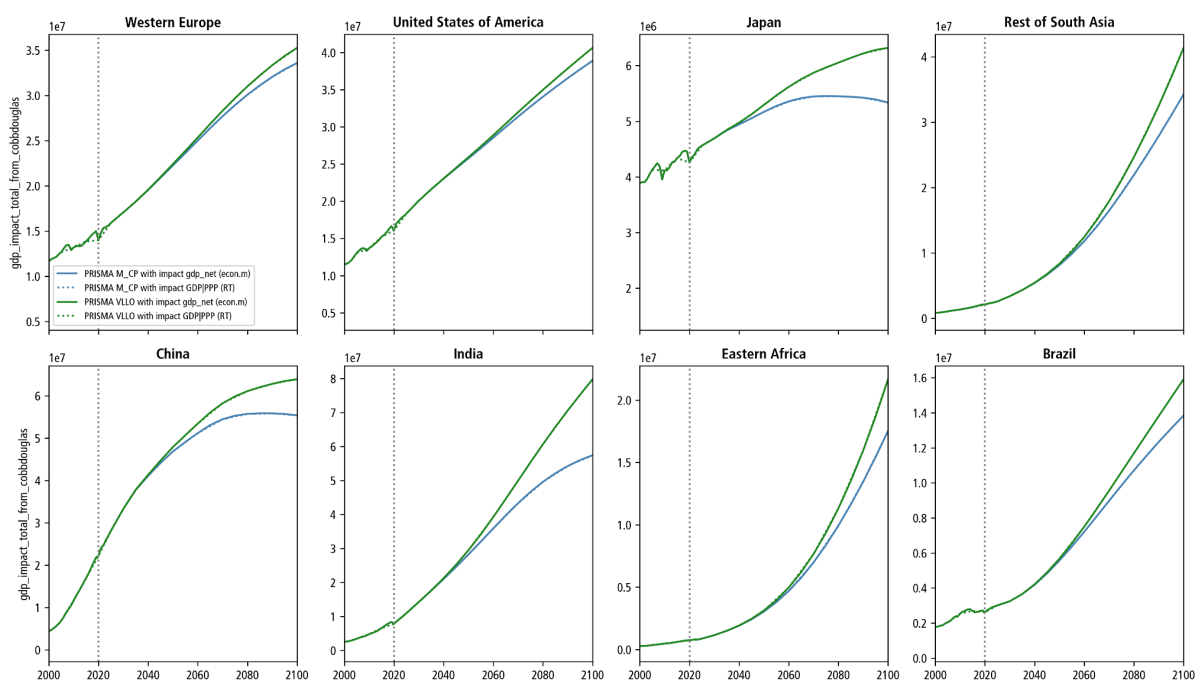


Figure 3.2.6b: Projected GDP (ppp) development in key IMAGE regions, for the reference (CP = Current Policy) and mitigation (VLLO = very low emissions, roughly 50% of staying below 1.5dC) scenarios, with and without impacts. Projected GDP (ppp) development in key IMAGE regions, for the reference (CP = Current Policy) and mitigation (VLLO = very low emissions, roughly 50% of staying below 1.5dC) scenarios, with and without impacts (note: the GDP_{net} scenarios are only used to check for model-internal consistency).

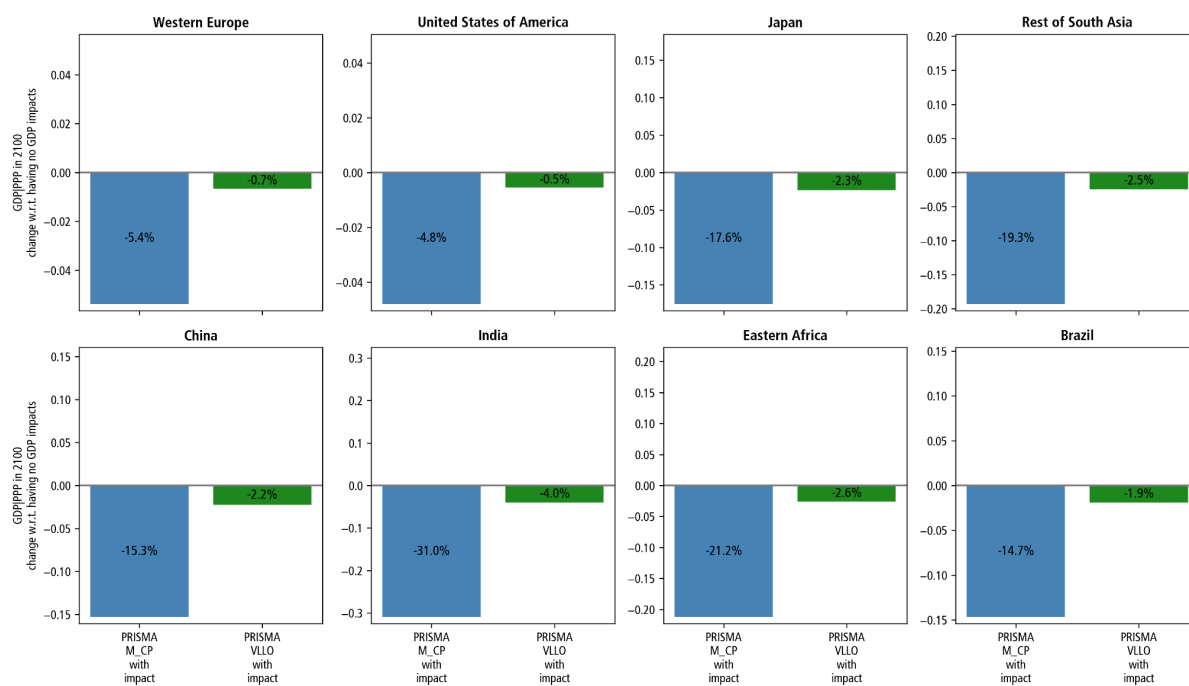


Figure 3.2.6c: Projected GDP (ppp) changes in key IMAGE regions in 2100, for the reference (CP = Current Policy) and mitigation (VLLO = very low emissions, roughly 50% of staying below 1.5dC) scenarios. Values represent relative changes in an impacted case, compared to the no impact case.



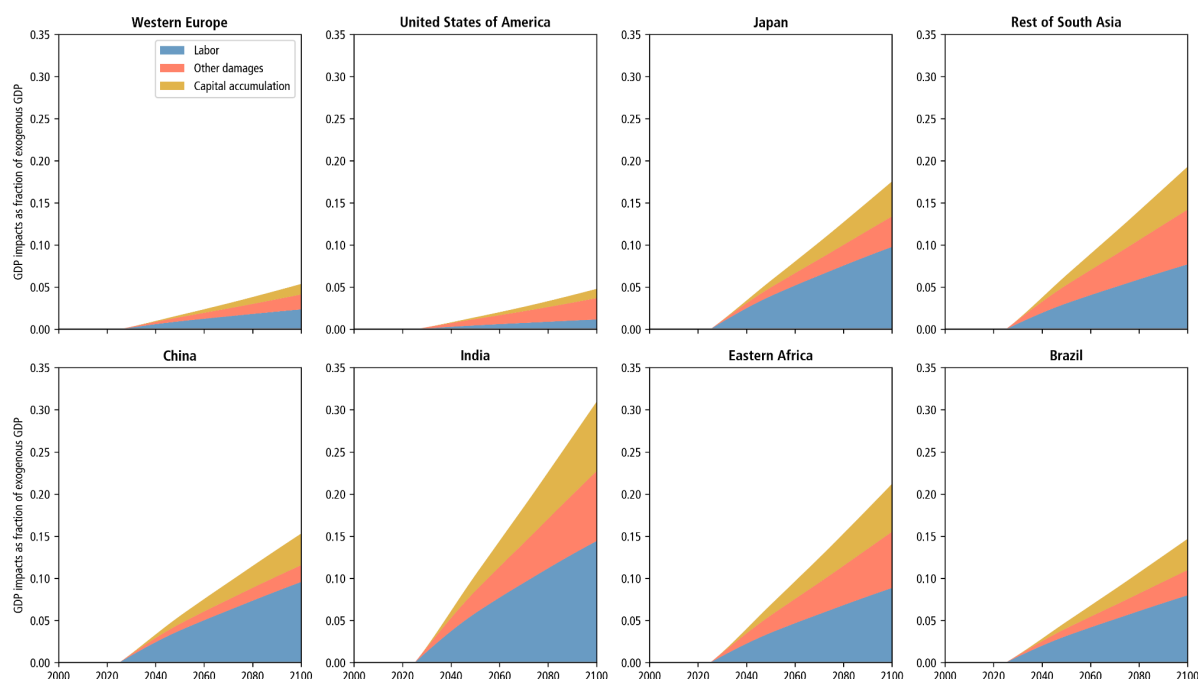


Figure 3.2.6d: Projected changes in the components of GDP (ppp) impacts (LP, other damages, capital accumulation), in key IMAGE regions until 2100, for the Current Policy scenario. Values represent relative changes in an impacted case, compared to the no impact case.



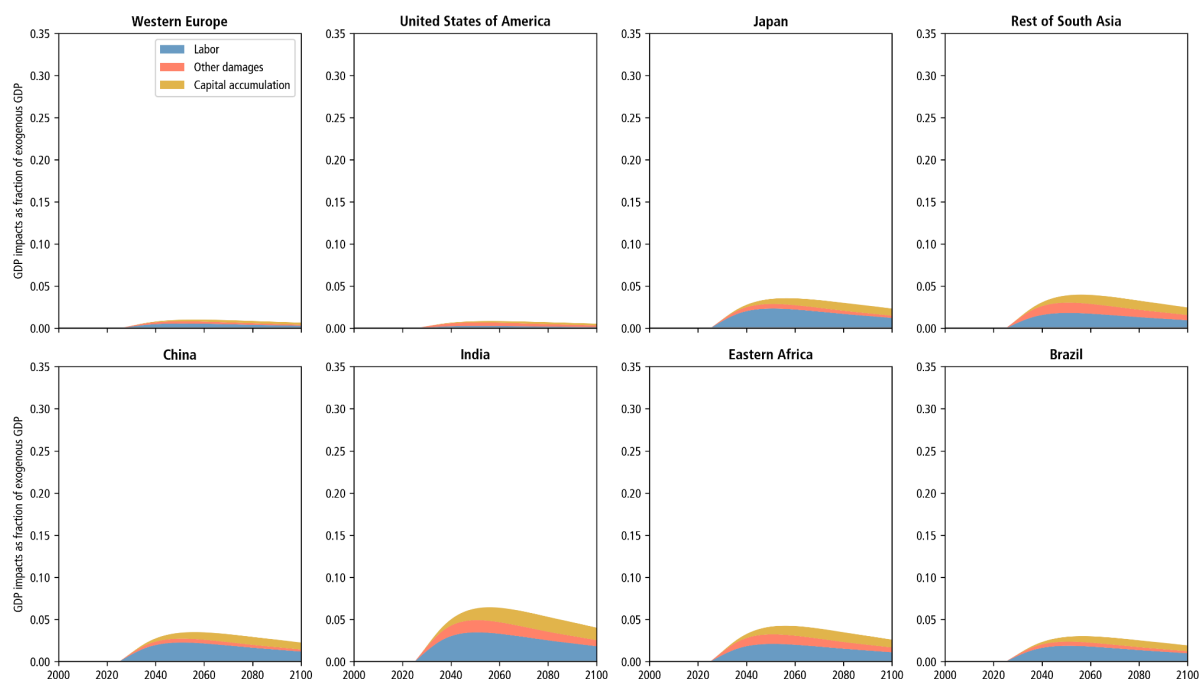


Figure 3.2.6e: Projected changes in the components of GDP (ppp) impacts (LP, other damages, capital accumulation), in key IMAGE regions until 2100, for the VLLO scenario (= very low emissions, roughly 50% of staying below 1.5dC). Values represent relative changes in an impacted case, compared to the no impact case.



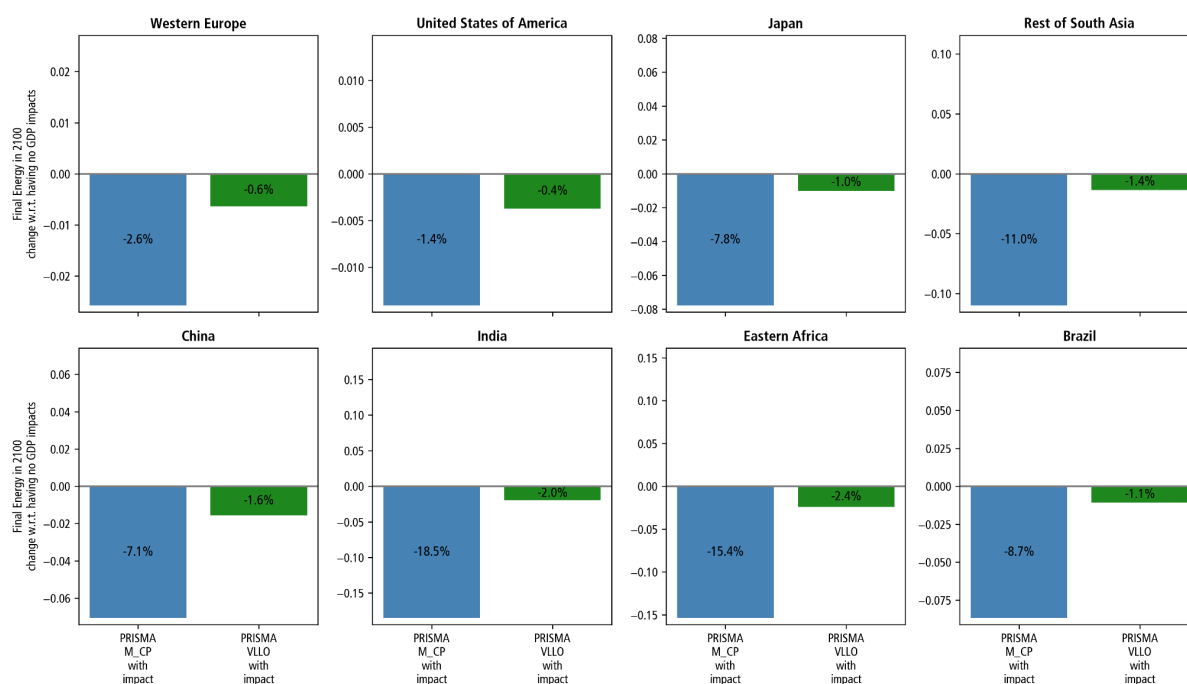


Figure 3.2.6f: Projected Final energy changes in key IMAGE regions in 2100, for the reference (CP = Current Policy) and mitigation (VLLO = very low emissions, roughly 50% of staying below 1.5dC) scenarios. Values represent relative changes in an impacted case, compared to the no impact case.

Opportunities for future work

The integration of LP and other economic damages in IMAGE paves the way for a range of future model improvements and assessments. One feature PBL is currently working on, is to link the economic damages to human health (morbidity, mortality). Further, after consistently integrating the “economic damages option” throughout the model (e.g. IMAGE-land will need to be updated with this new feature), one key goal is to link sectoral damages to sectoral processes in the model. The Dasgupta et al. LP damage functions can be

split up into high exposure (agriculture, construction, forestry, fishing, mining and quarrying) and low-exposure (manufacturing and service) sectors, allowing for implementing more sector-specific impacts. Similarly, this can be done for other GDP impacts. Another key improvement is to add a comparison between (avoided) damages, (possibly) adaptation and mitigation costs, allowing for cost-benefit type analyses. One option is to integrate (parts of) the MIMOSA model in IMAGE.

In terms of research options, these developments will expand the applications of the model, by e.g. allow for (better) assessing: cost-optimality, climate impacts in all existing and earlier produced scenarios, distributional impacts (how this trickles down to low-income deciles) and regional CC differentiation (impacting e.g. investment, risk, cost of capital).

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Annex I to section 3.1.2: Climate change impacts on economic inequality

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ENVIRONMENTAL RESEARCH LETTERS

TOPICAL REVIEW

Climate change impacts increase economic inequality: evidence from a systematic literature review

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Abstract

While it is widely assumed that poor countries will suffer more from climate change, and that climate change will exacerbate inequalities within countries, systematic and large-scale evidence on this issue has been limited. In this systematic literature review, we examine and synthesize the evidence from the literature. Drawing from 127 individual papers, we find robust evidence that climate change impacts indeed increase economic inequality and disproportionately affect the poor, both globally and within countries on all continents. This result is valid across a wide range of physical impacts, types of economic inequality, economic sectors, and assessment methods. Furthermore, we highlight the channels through which climate change increases economic inequality. While the diversity of different approaches and metrics in the existing literature base precludes extracting a universal quantitative relation between climate change and economic inequality for use in future modelling, our systematic analysis provides an important stepping stone in that direction.

1. Introduction

Since the late 1980s, global economic inequalities have been decreasing according to most metrics [1, 2]. This has been driven by decreasing inequalities between countries, due to rapid economic growth in Asia, and has occurred despite increasing inequalities within a number of countries [3, 4]. However, this trend could be reversed depending on the extent of climate change impacts, and how those are distributed globally [5]. Indeed, the Intergovernmental Panel on Climate Change (IPCC) [6] reports with high confidence that losses and damages attributed to climate change will be strongly concentrated, and disproportionately affect the poorest and vulnerable populations in the Global South. Climate change affects the economy, as biophysical impacts translate into economic damages in various ways [7]. These economic impacts are expected to be shared unequally between regions, countries, households and individuals. Indeed, different groups may be impacted differently according to geographic location and socio-economic characteristics, and future economic inequality will depend on relative adaptive capacities [8]. Distributive justice calls for a fair distribution of the costs, benefits, and risks associated with climate change. If we accept the moral imperative of ensuring that the burden of climate change does not fall disproportionately on the most vulnerable, a comprehensive analysis of the role of climate change in driving economic inequality is a first necessary step to enable a just transition. A large and growing body of literature explores the impact of climate-related events on inequalities between and within countries. While it is widely assumed that poor countries will suffer more from climate change [9], and that climate change will exacerbate inequalities within countries [10], systematic and robust evidence on a large scale is lacking on the issue. This is despite the fact that some authors have provided reviews on the links between poverty and natural disasters [11], between livelihood resilience and climate change [12], and some

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systematic mappings of the literature on justice and climate change adaptation [13]. This paper fills this gap, and provides a systematic review of the effect of climate change on economic inequalities from the existing literature. Although climate change will evidently affect inequalities between generations, we focus here on inequalities within a generation. We gather evidence on whether, where and how climate change exacerbates economic inequalities. In doing so, we provide a reproducible and transparent, hence reliable knowledge base to inform policy-making and practice [14]. We first present the methods used for the systematic review, including publication selection and data extraction (section 2), then the results across geographical scopes, physical impacts, economic sectors, types of economic inequality, and assessment methods (section 3). We finally reflect on the implications of our results for policy-making and future research (section 4).

2. Methods

We provide a systematic review of the effect of climate change on economic inequalities from the existing literature, focusing on its distributive dimension across and within countries. For that purpose, we conducted queries on paper titles and abstracts in the Web of Science and Scopus literature databases in February 2023. This section presents the publication selection and data extraction. The final corpus includes 127 papers, listed in the Extended Data section, where bibliometric information is also presented (figure 7).

2.1. Publication selection

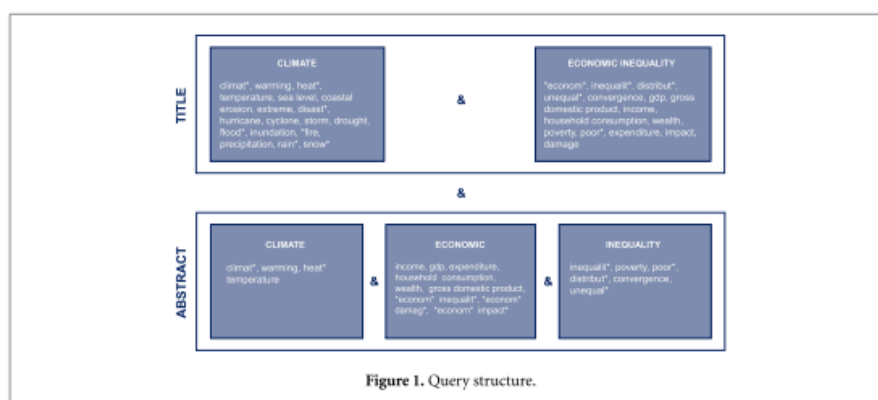
We conducted queries on titles and abstracts in the Web of Science and Scopus literature databases in February 2023. We used groups of keywords connected with Boolean operators, filtering for peer-reviewed papers on climate change impacts and their distributive implications. Books, book chapters and working papers were excluded from the results. We aimed for our method to be reproducible, and as transparent as possible. A balance thus needed to be found between explicitly excluding terms from the queries (with the risk of excluding relevant papers), and reaching a large enough corpus. The issue is that all-encompassing queries may include too many irrelevant papers, which should be then screened by hand, with the risk of losing transparency and reproducibility. Abstracts are bound to include a wider diversity of terms than titles. Therefore, we ran different queries for titles and abstracts. We used a smaller, more restrictive set of terms for titles (we included a smaller number of generic terms), and a larger set of more specific terms for abstracts. For titles, the query was organised into two blocks: the first one pertains to climate change and its physical impacts, the

second relates to the economic and inequality dimension. For abstracts, the query was organised into three blocks: the first one pertains to climate change and its physical impacts, the second relates to the economic dimension, and the third relates to inequality. All the sets of terms were linked by an AND Boolean. Those two sub-queries were linked by an AND Boolean in the overall query (see schematic representation on figure 1). We ran queries on 6 February 2023, returning 1066 items in the case of Scopus, and 825 items in the case of Web of Science. The query is summarised on figure 1, and the exact queries are presented in the Extended Data section. After merging the results and removing the 768 duplicates, the list of papers contained 1072 items, also after excluding conference proceeding papers, erratums, books and book chapters.

Each paper was then screened by two members of the author team using the *abstrackr* tool (<http://abstrackr.cebm.brown.edu/>). *Abstrackr* allows to organize and screen abstracts for systematic literature reviews. We did not use exclusion terms during the screening process. Papers were considered out of scope when they did not provide an assessment of the impact of climate change on income or consumption inequality. The following categories were used to tag the excluded papers: out-of-scope discipline (e.g. electrical engineering, chemistry, etc), irrelevant type of paper or method (e.g. purely theoretical paper, perspective paper), absence of clear link to climate change (e.g. focus on natural disasters disconnected from climate change), absence of economic variable, paper focused on mitigation and not on impacts, no mention of inequality, paper centered on adaptation. The grading system consisted of three labels: include, reject, unsure. The double screening process led to a small number of items that were not concurrently rejected or included by both reviewers. Those cases were then discussed individually within the author team. We retained 199 papers after the abstract screening process, which were then closely read by one member of the author team. The following information was extracted for all selected papers [15]:

- *bibliographic information*: journal, title, abstract, authors, year of publication, doi
- *general scoping information*: scope (global, regional, multi-regional, multi-national, national, sub-national); country or region of interest (if applicable); granularity (region, country, county, district, city, household, sub-national, sub-regional, urban-rural); type of inequality considered (income, consumption, GDP, welfare); method (econometric, surveys, or simulation based including integrated assessment model, computable general equilibrium model or microsimulation); type of physical impact (temperature, precipitation, extreme events, sea level rise, droughts, floods); specific sector; channel of impacts (e.g. labour productivity,





impact on infrastructure); whether the study is backward-looking (i.e. based on historical data only), forward looking (i.e. simulation scenarios), or both; whether the results only relate to exposure to climate change; whether the effects are strongly or only weakly related to climate change.

- **results:** whether the paper provides a quantitative estimate of the effect of climate change on economic inequality; the type of inequality metric and its value and unit (if applicable); the sign of the effect of climate change on economic inequality (increase, decrease, neutral, no conclusion, mixed, increase of poverty); the most impacted social group (neutral between poor and rich, no conclusion, mixed, the poor, the rich, the urban, the rural); a key quote from the paper; caveats or limitations highlighted by the authors.

When gathering evidence, we were careful to not over-interpret the results of the papers of the corpus, and to hold on to the wording used in those. For instance, if a paper concluded that 'climate change mainly affects the poor', without explicitly stating that inequalities increase, we refrained from concluding that the paper gave the result that 'climate change increases inequalities', as that result may depend on the effect of climate change on the middle of the income distribution. We did not use a preset definition of the term *poor* (e.g. people with income below a given level), but relied on the definition used by the authors of the papers of the corpus. This definition may thus vary from one case to the other. After careful review, 72 papers were excluded, because one or several of the following categories applied: (i) literature review, meta-analysis of existing papers, or purely theoretical paper, (ii) absence of a mention of distribution issues, (iii) absence of sentence linking climate change to the frequency or intensity of the studied physical manifestation of climate change, (iv) paper centered on adaptation, (v) paper centered on mitigation, (vi) inequality treated as a driver of another variable of interest,

not as an outcome, (vii) focus on energy poverty only. The final corpus contains 127 papers (listed in the Extended Data section), published between 1998 and 2023 (figure 7(a) of the Extended Data section), mainly within the fields of Environmental Sciences & Ecology and Business & Economics (figure 7(b) of the Extended Data section). We note a rapid recent increase in the number of relevant papers, trebling between 2020 and 2022. Also note that while a large body of literature studies the effect of climate policies (such as carbon pricing) on economic inequalities globally [16], in low and middle income countries [17], or in the case of the European Union [18], this is not the focus of this paper.

2.2. Data extraction: main dimensions

Here we present the dimensions we focus on in the data extraction process, and some descriptive statistics from the corpus. We devised six categories to analyse the corpus along its various dimensions (namely, geographical scope, granularity, physical impact, type of inequality, economic sector, assessment method). In each case, we counted the number of occurrences according to the statements made by papers on the impact of climate change on inequalities and on the nature of the most impacted group (cf categories described in table 1). Further descriptive statistics of the corpus are presented in the Extended data section (figures 8 and 9).

2.2.1. Scope and granularity

We consider the impact of climate change on inequalities within and between countries, and therefore include papers that provide global results, and papers on specific countries or regions. Scope is defined as the geographical perimeter of the study. Granularity refers to the geographical perimeter or social groups considered when assessing economic inequality within the geographical scope. In the global, regional, multi-regional, and multi-national studies, inequalities are mostly assessed at the country



Table 1. Outcome categories.

Outcome category	paper statements
regressive effect	• inequalities increase due to climate change, <i>or</i> • poverty increases due to climate change, <i>or</i> • the poor are more impacted by climate change
mixed effect	• mixed results in terms of the impact of climate change on inequalities, <i>or</i> • mixed results in terms of which social group is more impacted
neutral effect	• climate change does not affect inequalities
progressive effect	• inequalities decrease due to climate change, <i>or</i> • the rich are more impacted by climate change
no conclusion	• no explicit conclusion on the effect of climate change on inequality, <i>and</i> • no explicit conclusion on which social group is most impacted
other	• no explicit conclusion on the effect of climate change on inequality, <i>and</i> • a particular non-income related group is identified as being most impacted

or regional level. Papers assess inequalities at the household level, or at other sub-national social groups or geographical entities (e.g. urban vs. rural, cities, counties, districts, farms). The majority of studies have either a global (35%) or national (32%) scope. The most studied single countries are China (9 papers), Brazil (6 papers), and South Africa (5 papers). There are 67 country-specific papers covering every continent. In terms of geographical distribution, 31 papers focus on Africa, 24 on Asia, 13 on South America, 8 on North America, 4 on Oceania, and 4 on Europe. Figure 8 shows the geographical distribution of the country and multi-country studies of the corpus.

2.2.2. Physical impacts

The scope of this review encompasses all manifestations of climate change. A large body of literature focuses on the impact of natural disasters on inequalities and the distribution of income without a clear focus on the possible links between those events and climate change. While that literature relates to our study, it is outside of its specific scope, and has been reviewed extensively elsewhere [19, 20]. The direct physical impacts of climate change can range from changes in the frequency or intensity of extreme events, such as hurricanes, floods, droughts, or heatwaves, to slower processes such as coastal erosion and changes in average climate conditions. These may lead to a wide variety of impacts, from reduced availability of fresh water and reduced crop yields, to changes in the incidence of vector-borne diseases, depletion of fisheries, mass coral bleaching, wildfires, and more. The main drivers of these

impacts include the warming trend (i.e. the evolution of global and regional average temperatures), extreme temperatures, the evolution of precipitation (and its spatial distribution), extreme precipitation, and sea level rise [21]. The types of physical impacts assessed in the corpus overwhelmingly relate to temperature increase (whether mean surface temperature or extreme heat) and precipitation (whether mean precipitation, increased variability of precipitation, or extreme precipitation), amounting to 197 occurrences (some papers may represent several types of impacts). The fact that most papers relate to temperature increase may be partly due to the large number of global studies, to the fact that temperature is easiest to project into the future, and to the difficulty to assess more specific physical impacts at the global scale.

2.2.3. Types of inequalities

We focus on the distributive dimension of economic inequality, i.e. how different dimensions of well-being are distributed within society, and how they may be affected by climate change⁴. Although these dimensions can be both monetary (such as income, wealth) and non-monetary (e.g. health, education), we understand here economic inequality as inequality with regard to income and consumption. Other dimensions can however affect individuals' well-being [22–25], notably health, leisure, the quality of social relations and the natural environment, but are not the focus of this paper. Heterogeneity in individual environmental, social, cultural conditions

⁴ We exclude here considerations of procedural justice, which concerns the processes by which achievements (such as being well-nourished or healthy) are distributed.



influence what is accessible to individuals at a given income level. Still, income can be spent to improve achievements and expand capabilities. It can be a strong driver of the sensitivity to climate change impacts, as it often determines other factors that impact sensitivity to climate impacts, such as access to technology (e.g. irrigation, air conditioning), insurance, and health services. In poor countries especially, low-income households often lack appropriate assets that may provide protection against extreme climate events, for instance adequate housing, and sufficient livestock in the case of the rural poor. Besides income, another way to measure economic inequality is to look at disparities in terms of wealth (i.e. the value of owned assets such as housing, cattle, cash or stocks). Wealth is a key dimension of well-being, as it generates income, i.e. it accounts for potential income that could be derived from assets, and can be associated with increased opportunities [26]. In summary, our search queries do not include the following specific categories: health, mortality, food, energy access, and energy use, although those dimensions can be linked to income and consumption, and may appear in the analysis provided by the selected papers. We do not include those terms in the query to avoid selecting papers that would adopt a narrow scope, and would for instance solely focus on a specific component of consumption, while neglecting others. Further, the review aims at assessing the impacts of climate change on economic inequality beyond pure exposure. The papers which report only on the distribution of exposure across different groups are not formally excluded, but are assigned to a specific category in the review.

2.2.4. Assessment methods

The scope of this review encompasses all possible methods to assess the impact of climate change on economic inequality. These include econometric studies, often relying on household surveys, which are required to study income or consumption inequality across households, either at the level of individual countries [27], or at the level of subgroups within countries [28, 29]. Simulation approaches are also relevant. Computable general equilibrium (CGE) models capture the impacts of climate change (in some particular cases, the impacts on agricultural productivity) at the level of large world regions with representative agents. They are sometimes coupled with a microsimulation model, which is based on the modeling of agents and can capture effects on heterogeneous households. The advantages of CGE models are their sectoral detail and their ability to capture trade effects in particular. Integrated assessment models are used to study the interplay of socioeconomic conditions, climate, energy and land use in the context of future scenarios and on a global scale. They can capture inter-regional inequality, as they mostly operate

at the level of large world regions, but usually miss sub-regional inequality, as they typically consider a single representative agent by region. However, recent efforts have led to a better representation of intra-regional inequality in those models [18, 30], although inequalities are not always related to climate change impacts. In the NICE model [30], climate damages are distributed across regional income quintiles using an elasticity parameter which is not empirically based.

2.2.5. Outcome categories

A majority of studies shows differential impacts across regions and social groups, but their authors do not always explicitly discuss the consequences of those on inequality, nor provide quantitative estimates of standard economic inequality metrics. Further, inequality metrics, when available, are bound to widely differ in nature across papers. We therefore mainly provide a qualitative rather than quantitative assessment, and simply examine whether inequalities increase or decrease within and between countries due to climate change impacts. We use the outcome categories presented in table 1 to analyse the effect of climate change on economic inequalities.

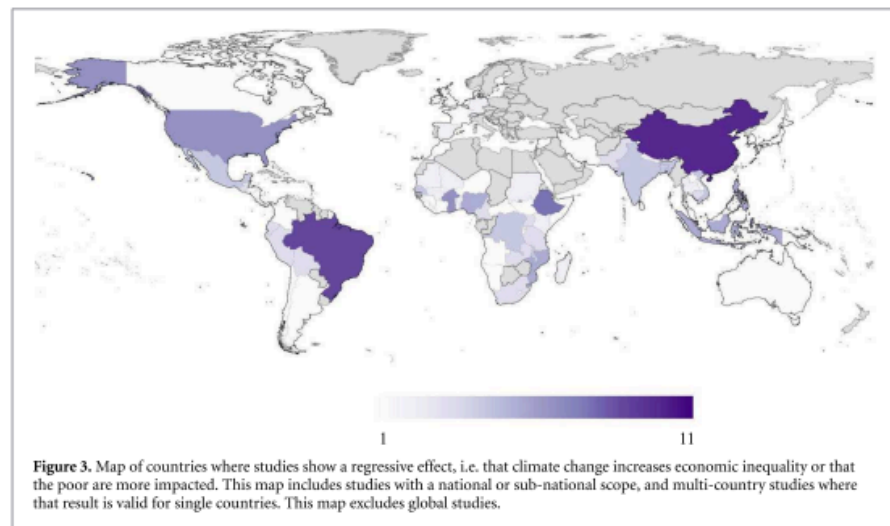
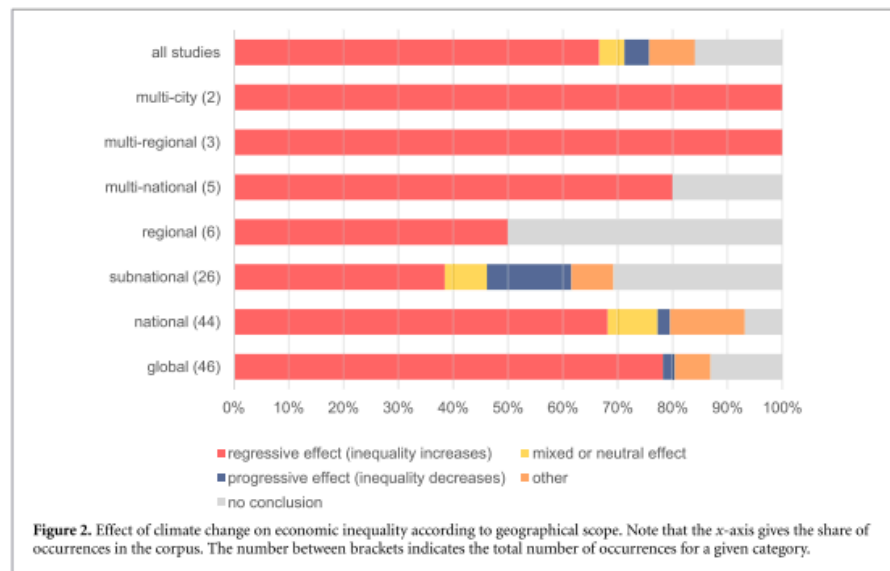
2.2.6. Agreement indicator

We use an agreement indicator developed in other systematic reviews [31] to summarize the level of agreement regarding the direction of the impact of climate change on economic inequality along all dimensions. This indicator is calculated as $H = \sum_{i=1}^3 s_i^2$, where i is the possible outcome (regressive effect, progressive effect, mixed or neutral effect), and s_i is the share of each outcome for the given category (e.g. geographical scope). By design, the index can range from 0.33 (a full level of disagreement regarding the effect of climate change on inequalities) to 1.00 (a full level of agreement, indicating that 100% of the papers are, for instance, pointing to a regressive effect of climate change on inequalities). For example, if, for a given category, 80% of the papers find a regressive effect, 10% report a progressive effect, and 10% find a mixed or neutral effect, the level of agreement equals $0.64 + 0.01 + 0.01 = 0.66$, which indicates broadly consistent although not universal evidence of a regressive effect of climate change on inequalities for that given category.

3. Results and synthesis

We present the main findings and analysis of the reviewed literature. We synthesize these according to the main relevant dimensions presented above. The result that inequality increases due to climate change or that the poor are more impacted is obtained across a diversity of geographical scopes (figures 2 and 3), physical impacts, economic sectors, channels,



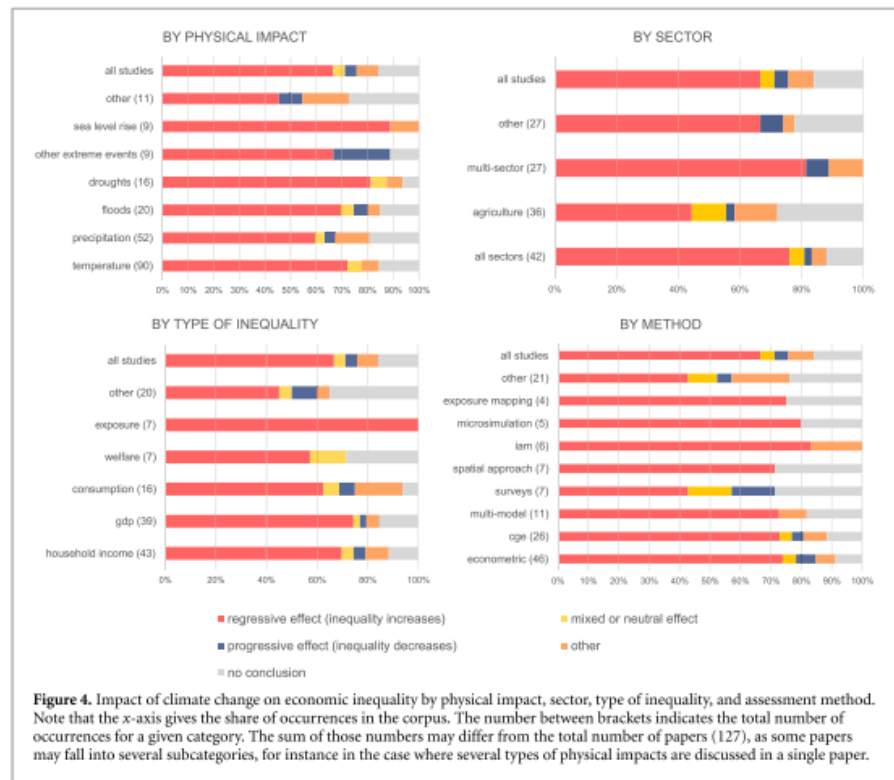


types of economic inequality and assessment methods (figures 4–6).

3.1. Climate change increases inequalities, both globally and within countries on all continents

While the majority of papers (75 out of 127) do not explicitly conclude on the effect of climate change on inequality, most of those papers still identify the poor as being the most impacted (55%), while four papers identify the rich (households [32, 33], countries [34], or countries [35]) as being the most impacted. Three of the those four papers focus on very local

situations: one in the particular case of tropical cyclone Bulbul in Bangladesh, where rich shrimp farmers incurred higher losses (explained by the larger size of their farms) [32], one in the case of wildfires in the US, where owners of high-value properties also incurred higher losses [34], and one focusing on the Ethiopian Awash basin, where poor households were found to benefit more from additional rainfall, and suffer less from a decrease in rainfall than non-poor households [33]. One paper with a global scope finds that rich countries are most impacted by climate change, in the particular case of extreme

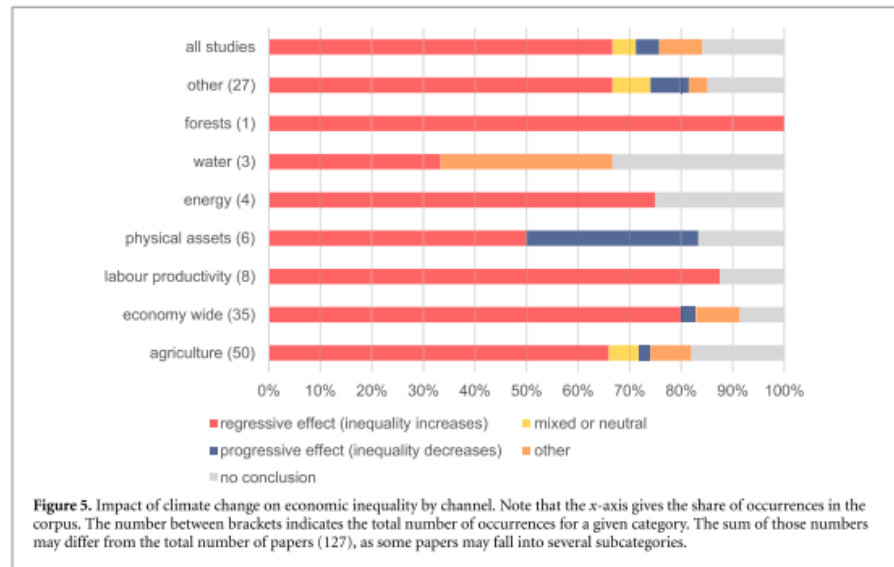


precipitation [35]. This econometric study looks at four different rainfall measures, and finds a greater sensitivity of rich countries to daily rainfall only. The authors explain this last result by the smaller dependence on agriculture and greater dependence on services of rich countries compared to poorer countries. Almost all global studies conclude that climate change increases inequalities or that the poor are more impacted (36 papers, i.e. 78% of global studies, figure 2). Some papers (12) identify other groups as being most impacted by climate change, without indication of income group, e.g. rural, urban, women, particular regions or countries, particular sectors or economic activities. Overall, a minority of papers does not conclude on either dimensions (17%), i.e. on both the effect of climate change on inequalities and on which group is most impacted.

Among the 52 papers which provide a conclusion on the impact of climate change on economic inequality, 35 papers find an increase in inequality due to climate change. Only two papers show a decrease in inequality due to climate change, both of which focus on very specific local circumstances:

floods in Pakistan [36], which is however associated with a decrease in income in the affected regions, and inequality of prices between fishers and traders in Mexico [37]. A majority of studies thus concludes that climate change either increases economic inequalities, or has more impact on the poor, or both (69% of the corpus, 83% of the papers which conclude on either dimension). In general, we find that the papers which conclude that climate change increases economic inequalities or that the poor are more impacted cover a much wider range of subcategories (e.g. types of physical impacts, assessment methods, etc) than those that conclude otherwise (figure 10).

We find that the results presented above can vary slightly according to whether one only considers within or between country inequalities. The result that climate change increases inequality mostly holds for national studies, as 68% of those conclude that climate change increases inequalities or that the poor are more impacted (30 papers). Studies comparing the effect of climate change across countries overwhelmingly find that inequalities between



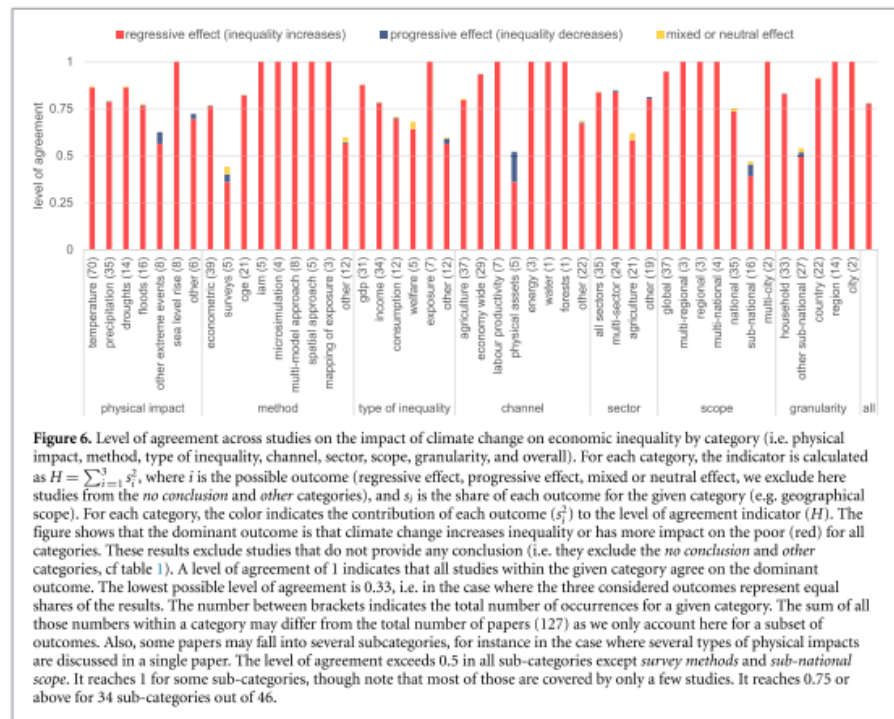
countries increase or that poor countries are more impacted (79% of all occurrences, figure 12). The share of papers focusing on within country inequality and giving the same conclusion is lower (64% of all occurrences, figure 12). The results show that climate change increases economic inequalities and disproportionately affects the poor holds in all world regions (figure 3). The countries with the highest number of studies (more than 5) showing that climate change increases inequality or has more impact on the poor are China, Brazil, Ethiopia and the US. Only 5 country-level or sub-national studies conclude that climate change decreases inequality or that the rich are more impacted, in Bangladesh, Ethiopia, Mexico, Pakistan, and Western USA.

Among all national, sub-national, multi-national and multi-regional studies, 41 studies focusing on the Global South (75% of such studies which provide a conclusion on either dimension) show that climate change increases inequality or that the poor are more impacted. This includes 15 studies that show that climate change increases inequalities, but do not necessarily provide a conclusion on whether the poor are more impacted, notably in Brazil, Lebanon, India, China, the Philippines, Iran, and African countries such as Burkina Faso, Ethiopia, Malawi, Ghana, Tanzania. These include studies with a national and sub-national scope. Among studies focusing on the Global North, 8 provide the same conclusion (in Europe and the US), i.e. 89% of Global North studies which provide a conclusion on either dimension. We thus conclude that this general result is valid across the Global South and the Global North.

3.2. All types of physical impacts increase economic inequalities, through several channels

The share of papers that find that a particular physical impact increases inequality or has more impact on the poor (figure 4 top left, in red) ranges from 60% (precipitation) to 89% (sea level rise), depending on the type of physical impact. Most papers (90) focus on the impact of temperature. In those cases, 72% of papers conclude that temperature change increases inequality or impacts the poor the most. The same biophysical impacts can lead to different damages across groups due to different sensitivities, i.e. different propensities to be adversely affected by a given climate change impact.

Most papers look at impacts on the whole economy or on multiple sectors, and the most studied single sector is agriculture (figure 4 top right). When all or multiple sectors are concerned, 78% of papers conclude that inequalities increase or that the poor are most impacted. That result is weaker for papers focusing on agriculture (44%), as a large share of papers do not provide any conclusion (28%), or identify other groups as being most impacted (e.g. particular agro-ecological zones [38], fruit producers [39], urban households [40], wheat importing regions [41]). How climate change may affect inequalities through its impact on agriculture is not straightforward. Food price hikes may be triggered by reduced agricultural productivity in most regions exposed to climate change. The impact on inequality can depend on the share of household income spent on food (which tends to decrease with income), and on the share of agricultural revenues



in total household income. Agricultural productivity and prices, through their consequences on the income of farmers, are still identified by some authors as the main channel through which climate change may increase poverty [42], hence inequality.

Several channels translate climate change impacts into effects on economic inequality. In order to understand how climate change may affect economic inequalities, we report on the impact channels identified in each paper, when those are specified by the authors (figure 5). Those channels include economy wide effects affecting all sectors, agricultural revenues (through decreasing crop yields, livestock revenues, or agricultural total factor productivity), decreasing labour productivity, infrastructure and physical assets, energy demand, water availability, and forests. We find that papers that identify labour productivity (8 papers) or energy (4 papers) as the main channels through which climate change affects economic inequalities overwhelmingly conclude that economic inequalities increase or that the poor are more impacted. A decrease in labour productivity may indeed increase inequality if it reduces the income of low-skilled workers more than the income of high-skilled workers. In particular, outdoor workers, and indoor workers in workplaces without air conditioning may be impacted more. We note that a

large share of the papers for which physical assets are identified as the main channel show that inequalities are decreasing due to climate change or that the rich are more impacted. Those correspond to the previously highlighted papers where rich agents incur a higher loss due to the higher value of their property [32, 34]. This is consistent with empirical evidence gathered elsewhere that richer households can also be vulnerable to climate-related shocks because they have a high concentration of capital assets [43], for instance in the case of livestock [44].

3.3. Climate change increases both household and national income inequalities

We categorise studies according to the type of inequalities considered, i.e. the variable that was used to compare social or geographical groups (figure 4 bottom left). The majority of studies considers household or individual income, followed by GDP, and household consumption. The studies focusing on national income (GDP), mostly with a global scope, do not generally provide details on the mechanisms at play at the sectoral level. While some global studies may only refer to GDP, several sectors and mechanisms can be included in the modelling, although those are not explicitly mentioned in the text. Finally, although our review primarily focuses on income



and consumption inequality per se, some papers also specifically look at disparities using the normative concept of welfare, which is derived from consumption. In that case, welfare is typically an isoelastic function of consumption, so that changes at the bottom of the distribution are given a greater weight than those at the top of the distribution. Again, we find rather homogeneous results across the types of inequality considered, with a slightly higher share of papers finding that climate change increases economic inequality or has more impact on the poor in the case of GDP (74%, those papers mostly have a global or national scope).

Different indicators have been proposed to give an overall measure of income or consumption inequality [45]. The most commonly used indicator is the Gini index, which measures the gap between the actual distribution of income or consumption and a perfectly egalitarian distribution, i.e. a distribution where every individual would receive the same income or consumption. Other indices focus on both ends of the distribution, for instance the Palma Ratio, which compares the income or consumption of the top 10% of the population with that of the bottom 40% [46]. The Theil index [47] derives from information theory, and offers interesting decomposition properties, because it allows breaking down inequalities between and within different groups. A total of 60 papers of the corpus provide a quantitative analysis. From those, 16 papers quantify results in terms of an inequality index (income Gini, consumption Gini or Theil index), and 12 papers look at specific income groups like deciles. The others conduct other types of analysis without explicit inequality metrics, but sometimes provide a measure of the impact of climate change on a specific income decile. Most of the latter (18 papers) do not conclude regarding the effect of climate change on inequality, though 9 of these still find a larger effect on the poor (including poor countries or cities). Among the 16 papers providing an inequality index (Theil or Gini), 10 papers find an increase of inequality, 3 papers find mixed results, while only one study finds that climate change leads to a decrease in inequality, one concludes that climate change is distributionally neutral, and one does not provide any explicit conclusion. All of the papers quantifying effects on income deciles find a higher effect of climate change on the poor, though most do not draw conclusions on inequality, since their analysis mostly focuses on the lowest income group. They are mostly conducted at the national or sub-national level, and a majority focuses on agriculture as the impact channel. The studies providing an inequality index are very different in scope (spatial, impact channel) and focus (forward/backward looking analysis, method and range

of future projection, etc). Therefore, it is impossible to draw more universal quantitative conclusions from the reported changes in the inequality index. The categorization of outcome provided in table 1 is used to bypass the lack of consistent and comparable income and consumption inequality metrics across papers.

3.4. Climate change increases economic inequality across the main assessment methods

The two main methodological approaches used to quantify the linkages between climate change impacts and economic inequality are econometric methods and simulation-based approaches. Econometric methods are used to study the relationship between selected past weather and climate and socioeconomic outcomes related to inequality. They constitute a large share of the literature on that issue, and the most common single method of our corpus (figure 4, bottom right). The four main single simulation approaches appearing in the corpus are general equilibrium modelling, multi-model approaches, integrated assessment models, and microsimulation. The result that climate change increases inequality or has more impact on the poor is robust across econometric and simulation based approaches (over 70% of the whole corpus in each case, over 80% of studies providing a conclusion on either dimension, figure 4 bottom right). We provide separate results for studies based on historical data (backward-looking) and for studies showing prospective scenarios (forward-looking) in the *Extended Data* section. Those subsets of studies show similar results to those of the whole corpus (figure 12, see also figures 13–16 for more detailed results).

Finally, using the indicator described in the methods section, we find that there is an agreement on the fact that climate change increases economic inequality or has more impact on the poor for all categories: in each case, that outcome is identified as the dominant one (figure 6, in red). In the case of surveys for instance, the level of agreement is rather low (0.44) compared to other categories of papers. The dominant color is red, meaning that those particular papers still point to a regressive effect of climate change on inequalities, although the level of agreement on that outcome is weaker than for other categories of studies. The overall level of agreement (for all studies providing a conclusion) is 0.79.

4. Discussion

An overwhelming majority of studies find that climate change increases economic inequalities or has more impact on the poor. This result is valid across all



regions, physical impacts, sectors, types of inequalities and assessment methods, and is particularly salient in studies comparing the effect of climate change across countries. Due to our conservative approach to paper classification, this result does not rely on studies which show differential impacts of climate change across regions or social groups without explicitly concluding on their effect on inequality. For that reason, the evidence for climate change impacts increasing economic inequality may be even stronger than indicated by our assessment. Indeed, this conservative approach might have led us to under-report the evidence of the regressive effect of climate change on economic inequality because of our decision not to categorise studies that did not make explicit statements on those effects. In the final list of papers, only two studies conclude that climate change decreases inequality, both of which focus on very specific local circumstances [36, 37], and four papers identify the rich, either households [32, 33], counties [34], or countries [35], as being more impacted by climate change, again mostly in very specific settings. The main exceptions are found to be a few studies where rich agents incur higher losses due to the higher size or value of owned physical assets. These papers represent less than 5% of the corpus.

We acknowledge limitations in our methodology. First, there are possible pitfalls related to the choice of keywords in the title and abstract queries. As already mentioned, we aimed to reach a balance between using keywords that bring out the most important papers, while at the same time avoiding the selection of unrelated papers, with the risk of possibly omitting papers that might have been relevant. While we aimed for maximum reproducibility and transparency of the methodology used, several steps along the process of paper screening and selection have involved decisions by the team of authors: some papers were excluded from the final list, for instance if it appeared that they did not present a strong enough link to climate change (cf list of categories presented in section 2). One avenue to possibly address this limitation would be to survey the results using machine learning tools [48]. Machine learning systematic reviews are easily scalable, and exclude human interference, but bring their own intrinsic biases. Those relate in particular to the selection of data used to train the algorithm. The question remains also whether these methods would perform better on all the paper selection criteria, which sometimes are rather subtle and involve expert knowledge beyond text mining. A second limitation of our work relates to the lack of consistent reporting of inequality measures across papers, which means that we are unable to provide a quantitative assessment of

the size of the effect of climate change on economic inequality.

This review has been motivated by the need to better understand the distributional dimension of climate change impacts, in order to provide the other side of the coin of the widely discussed distributional effects of climate change mitigation. From a public policy perspective, our analysis calls the attention of policy-makers on the issue of inequality, in particular when designing adaptation plans to climate change. Our results clearly show that climate change impacts are regressive across countries, therefore calling for appropriate and targeted compensatory mechanisms at the international level, in particular through international adaptation finance. This issue is strongly linked to the debate surrounding the implementation of a loss and damage fund, as discussed at COP27. Regarding within country inequalities, national policy-makers need to ensure that adaptation and loss and damage funding is actually directed to low-income households to reduce their vulnerability and improve their resilience to climate change impacts. Addressing future climate change impacts on economic inequalities will require considerable policy change and the deployment of financial resources. The results from this study can help policy-makers better integrate climate risk management components into the design of 'climate-proof' social intervention programs in poor regions, which is particularly vital for achieving climate justice goals. Such social intervention programs can be the provision of insurance for smallholders and other primary sector producers. Labour market interventions such as re-skilling or re-training can also achieve additional resilience to climate risks through the enhancement of the productivity and employability of workers in highly exposed sectors.

To help decision-makers achieve this, future research must provide a more robust quantitative assessment of the effect of climate change on inequality. Our analysis provides a first basis to construct an empirical understanding of the interactions between climate change and global inequality. However, it would need to be complemented in several ways to provide comprehensive and robust quantitative estimates with a global scope, which are needed to eventually include inequality in all of its aspects into integrated assessment modelling, and thus make the link between impacts, adaptation and mitigation to inform policy-making. First, and most importantly, researchers need to systematically provide a clear and explicit assessment of their results in terms of inequality, and compute inequality metrics whenever appropriate, in order to provide a more robust quantitative assessment on the effect of climate change on



inequality. Indeed, while the existing case studies reviewed here paint a fairly clear qualitative picture, what is currently lacking is a robust quantification across impact sectors and with global coverage. Such a quantification is needed to put future modelling efforts onto a solid empirical foundation, and as such a robust empirical assessment of the incidence of climate damages on different income groups is a key task in future work. It is also important to understand what the underlying drivers for this heterogeneity are, and if there are other socio-economic characteristics besides income that are key determinants, such as governance, institutions, education, and gender. Second, as our results show that the impacts of climate change increase economic inequalities or are concentrated on the poorest, measuring the impacts of climate change in terms of aggregate dollars hides their actual effect on welfare. Therefore, our analysis calls for using welfare indicators more widely in impact assessments. Third, our review is limited to the economic dimension of inequality, and complementary reviews would be needed to gather a better understanding of the impact of climate change on other dimensions of inequality, such as health, education and access to basic services. There is a need for more representation of social heterogeneity, especially in country-level studies. The lack of such representation could partly explain why a large share of the literature offers no explicit and quantified conclusion on the effect of climate change on inequality. Fourth, we note that only a very small number of studies focus on the Middle-East and Eastern Europe. There is thus a clear need for future research to examine the question of the impact of climate change on economic inequality in these regions. Fifth, further systematic studies would also be needed to complement our understanding on the role of adaptation actions and policies in their possibility to alter the effect of climate change impacts on inequality. The same biophysical impacts affect social groups differently depending on their adaptive capacities, and on the implementation of adaptation. It is important to account for how adaptation may mitigate the effects of climate change on inequality, or on the contrary in which conditions adaptation would exacerbate them, as was documented in cases of maladaptation [49]. Finally, there is a need to link to other areas of economics and social sciences studying inequality, as climate-related inequality interacts with other pre-existing inequalities. This is key to be able to design efficient and equitable policies. The research avenues outlined above could pave the way to a more robust and quantitative understanding of the interactions between climate change and global inequality. As such, it would help to tackle these two challenges together in an integrated and targeted way, and provide a basis to design policies that ensure climate justice for all.

Data availability statement

The data that support the findings of this study are openly available at the following URL/DOI: <https://doi.org/10.5281/zenodo.10894327>.

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Conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix. Extended data

A.1. Queries

The Scopus query is presented below (also summarised on figure 1):

```
TITLE (climat* OR warming OR temperature OR heat* OR "sea level" OR "coastal erosion" OR extreme OR disast* OR hurricane OR cyclone OR storm OR drought OR flood* OR inundation OR *fire OR precipitation OR rain* OR snow* AND (inequalit* OR distribut* OR unequal* OR convergence OR *econom* OR gdp OR "gross domestic product" OR income OR (household W/2 consumption) OR expenditure OR wealth OR poverty OR impact)) AND ABS (climat* OR warming OR temperature OR heat* AND (inequalit* OR distribut* OR unequal* OR convergence ) AND ( ( household W/2 consumption ) OR income OR expenditure OR wealth OR gdp OR "gross domestic product" OR (economic W/1 inequalit*) OR (economic W/1 damage)))
```

The following analogous query was run on Web of Science in February 2023 also:

```
TI = (climat* OR warming OR temperature OR heat* OR "sea level" OR "coastal erosion" OR extreme OR disast* OR hurricane OR cyclone OR storm OR drought OR flood* OR inundation OR *fire OR precipitation OR rain* OR snow*) AND
```



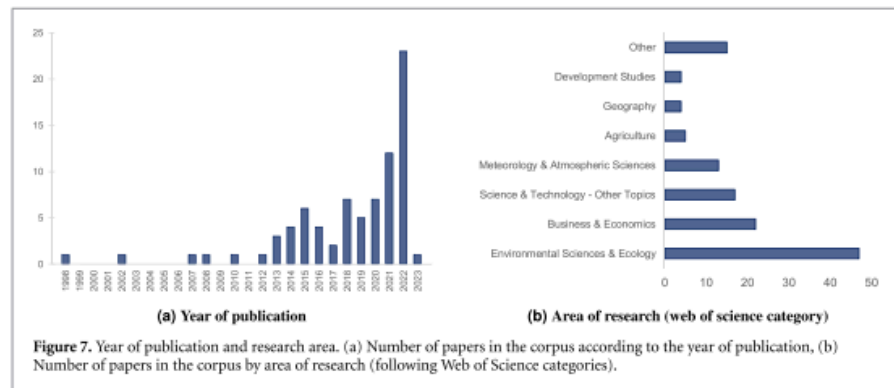
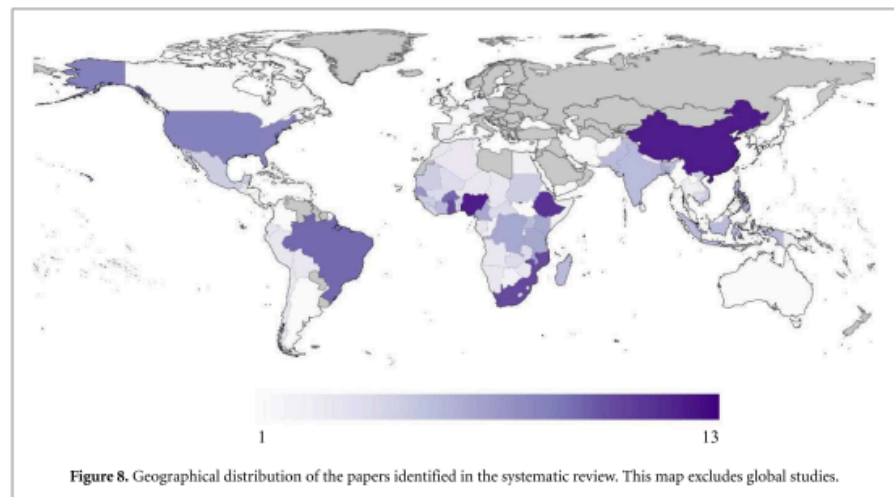


Figure 7. Year of publication and research area. (a) Number of papers in the corpus according to the year of publication, (b) Number of papers in the corpus by area of research (following Web of Science categories).



TI = (inequalit* OR distribut* OR unequal* OR convergence OR *econom* OR gdp OR "gross domestic product" OR income OR (household NEAR/2 consumption) OR expenditure OR wealth OR poverty OR impact) AND AB = (climat* OR warming OR temperature OR heat*) AND AB = (inequalit* OR distribut* OR unequal* OR convergence) AND AB = ((household NEAR/2 consumption) OR income OR expenditure OR wealth OR gdp OR "gross domestic product" OR (economic NEAR/1 inequalit*) OR (economic NEAR/1 damage))

A.2. Bibliometric information

Figure 7 presents the years of publication and the areas of research of the papers of the corpus.

A.3. Geographical distribution of the corpus

Figure 8 presents the geographical distribution of the country and multi-country studies of the corpus. We note that very few papers focus on the Middle-East and Eastern Europe.

A.4. Descriptive statistics

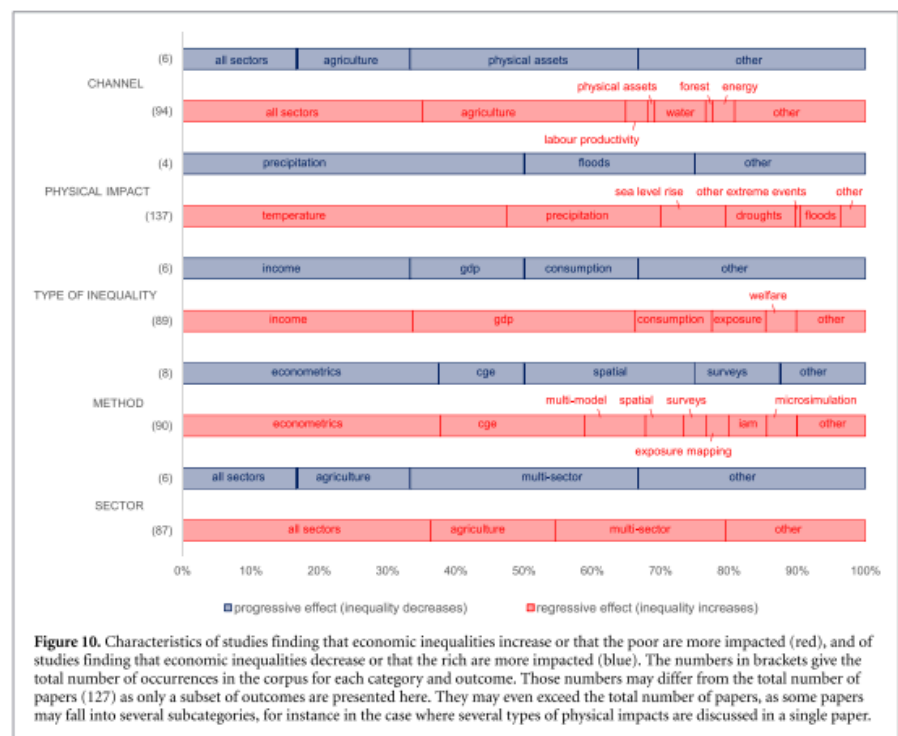
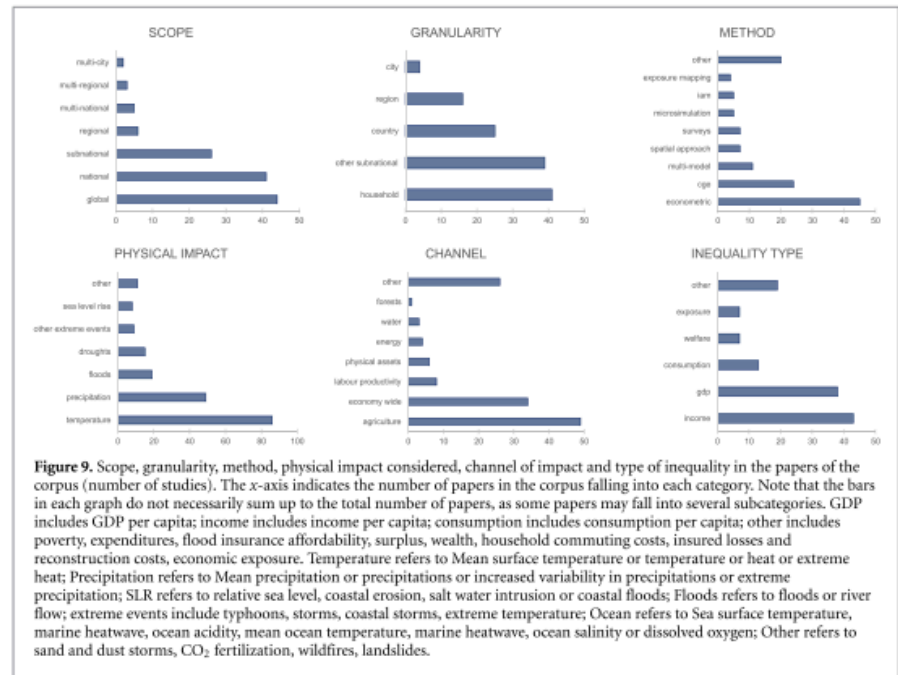
Figure 9 presents the scope, granularity, method, physical impact, channel of impact and type of inequality in the papers of the corpus.

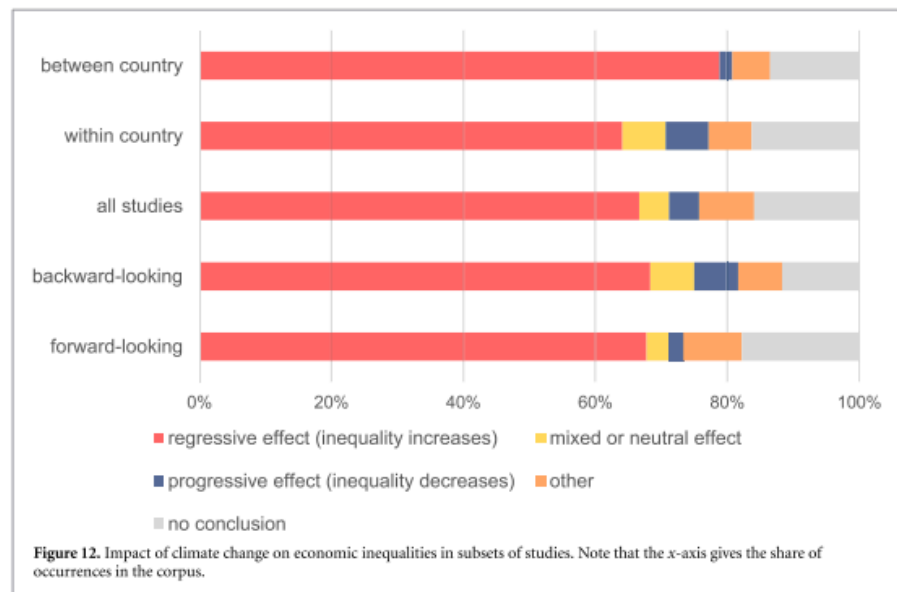
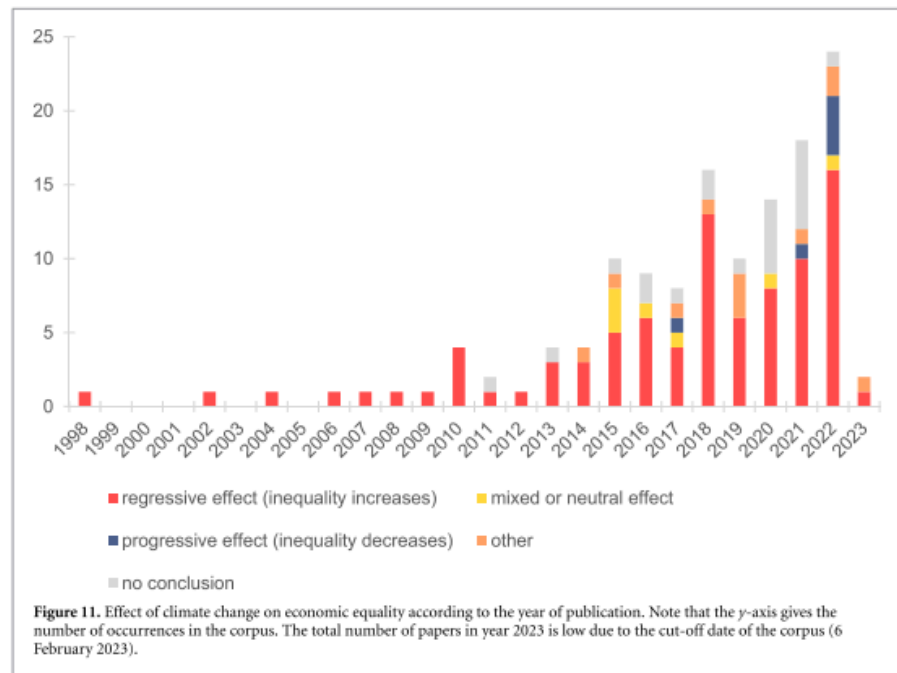
A.5. Summary results

Figure 10 gives the characteristics of the studies that conclude that climate change increases economic inequalities or that the poor are more impacted, and those of the studies that conclude that climate change decreases inequalities or that the rich are more impacted.

Figure 11 gives the the evolution of the dominant effect of climate change on economic inequality according to the year of publication. The type of







conclusion has become diverse over time, as the number of published papers has increased. Nevertheless, the conclusion that climate change has a regressive effect on economic inequality has remained dominant across time, and even more so if one excludes the papers that provide no conclusion.

A.6. Results for subsets of studies

Figures 12–16 give the detailed results of the impact of climate change on inequalities for four subsets of studies, namely backward-looking studies, forward-looking studies, studies focusing on inequalities within countries, and studies focusing on inequalities



Figure 13. Impact of climate change on economic inequality according to geographical scope.

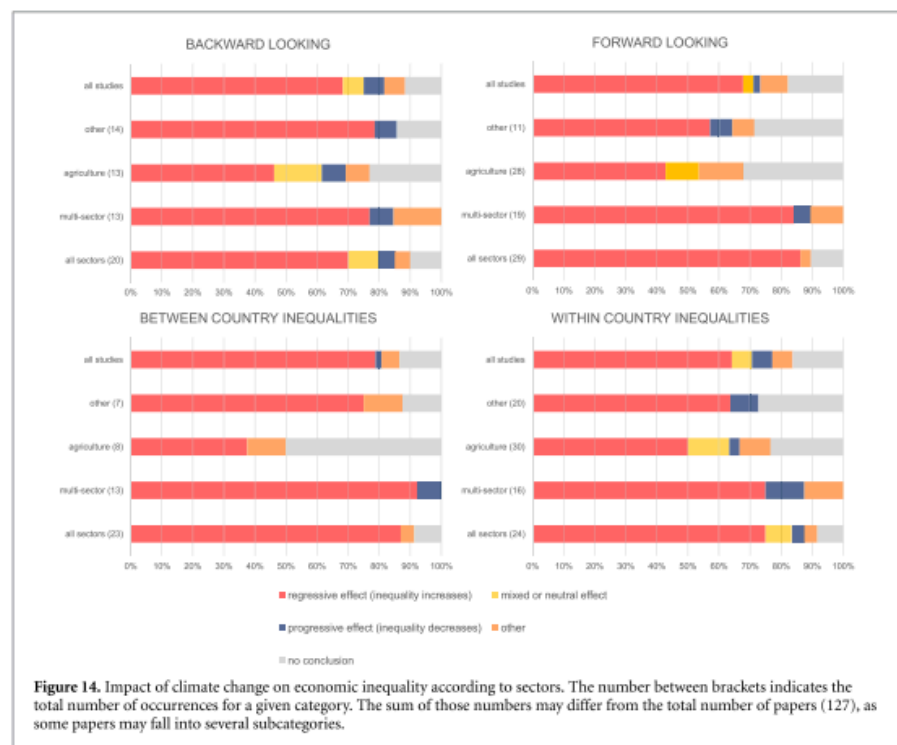
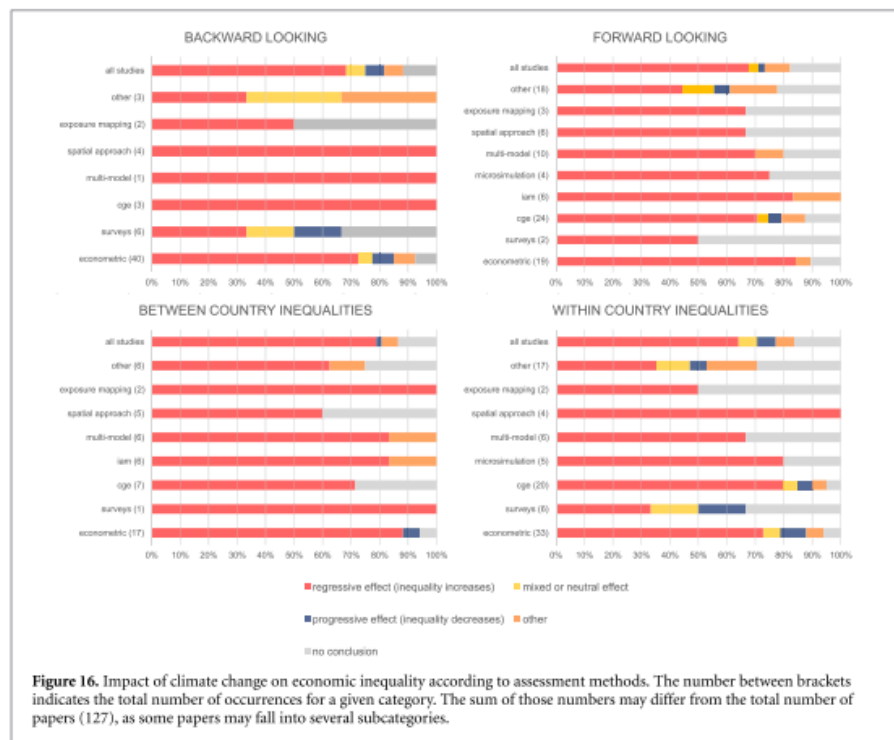
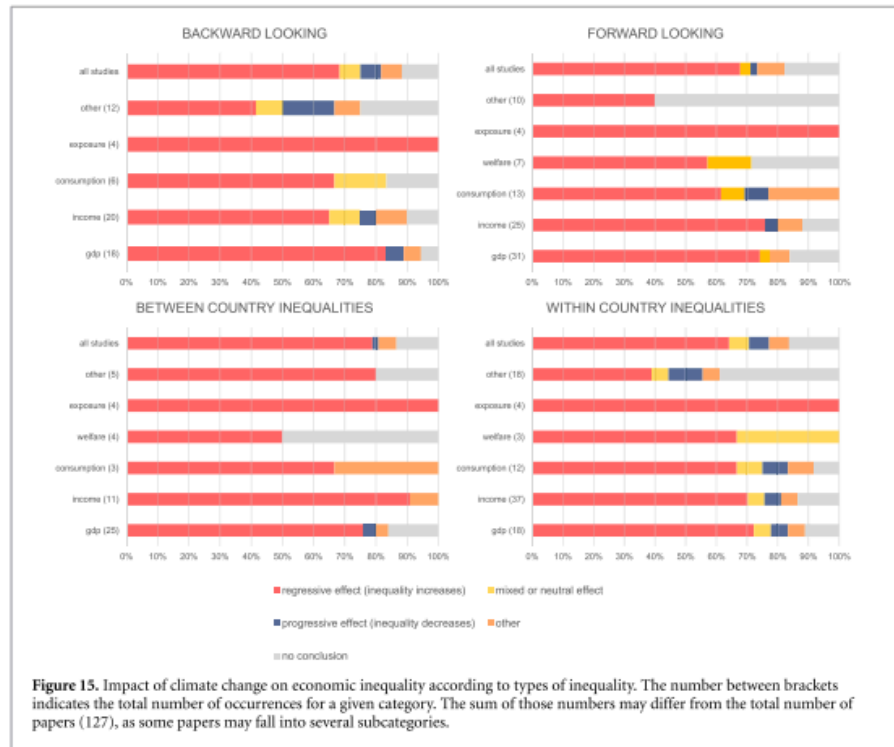


Figure 14. Impact of climate change on economic inequality according to sectors. The number between brackets indicates the total number of occurrences for a given category. The sum of those numbers may differ from the total number of papers (127), as some papers may fall into several subcategories.





between countries. Note that some papers examine both within and between country inequalities at the global level (10 papers), 7 of which conclude that climate change increases inequality or that the poor are more impacted, while 2 papers provide no conclusion, and one paper concludes that inequality increases or that the rich are more impacted.

The results for studies based on historical data (backward-looking) and for studies showing prospective scenarios (forward-looking) are very similar to those of the whole corpus (figure 12). There is a larger share of progressive effect results (i.e. decreasing inequalities) in backward-looking studies than in forward-looking studies. However, evidence still points to the fact that climate change has increased economic inequalities in the past or that the poor have been more impacted (68% of all backward-looking studies, 79% of backward-looking studies which provide a conclusion), and that climate change is expected to increase economic inequalities in the future or that the poor will be more impacted (68% of all forward-looking studies, 87% of forward-looking studies which provide a conclusion).

A.7. Corpus

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Annex II to section 3.2.1: Macroeconomic amplification of climate change damages: modeling the role of socioeconomic drivers

ABSTRACT

The long-run economic impacts of climate change depend not only on direct productivity losses but also on macroeconomic feedbacks. Here we introduce a representation of the macroeconomic impact of climate change within a process-based integrated assessment model, *IMACLIM-R World*. We analyze the macroeconomic conditions that may amplify damages over time through reduced capital accumulation, assessing six key drivers: saving rates, population, labor productivity, openness of international financial flows, fossil fuel availability, and energy intensity. Using the Shared Socioeconomic Pathways (SSP) framework, we contrast these drivers across three no-climate-policy scenarios (SSP1, SSP2, SSP3). We distinguish direct impacts, prescribed by a damage function, from total impacts that incorporate amplification via reduced investment and slower capital accumulation. Our results show that in 2100, indirect impacts could account for 25–50 % of global total losses and up to 80 % in some regions. Sensitivity analysis reveals that economies with low savings, rapid population or labor productivity growth, or constrained financial flows face stronger investment shortages and higher total impacts. Macroeconomic amplification can even reverse the ranking of regional damages, highlighting that total climate costs, and their distribution across regions, cannot be inferred from damage functions alone. These findings demonstrate the importance of integrating capital accumulation dynamics and socio-economic assumptions into climate-economy models.

1 - Introduction

The effects of anthropogenic climate change are being increasingly felt in all regions of the world, resulting in economic losses and biophysical damages (Calvin *et al* 2023). Therefore, it is important to understand how these losses and damages may translate into macroeconomic losses along future development and emissions pathways.

The macroeconomic impacts of climate change are generally quantified as a decline in economic activity resulting from changes in the statistical distribution of climate variables,



such as local or global annual mean temperatures, average precipitation, and the variability of temperature and precipitation. Various methods have been developed to relate future levels of warming to the subsequent economic losses (Piontek *et al* 2021). These include expert assessment surveys, statistical approaches, and biophysical modeling. The results can then be aggregated through bottom-up enumeration, computable general equilibrium (CGE) modeling, or estimated directly via top-down panel-based or cross-sectional studies. This diverse methodological landscape produces a wide range of outcomes, often represented by damage functions relating the decline in gross domestic product (GDP) to the level of global warming. These functions facilitate comparison across approaches (Howard and Sterner 2025, Tol 2024).

However, the scope of each damage assessment depends on which system feedbacks are considered and included. Therefore, the literature on the economic impacts of climate change often distinguishes between “direct” and “indirect” impacts, albeit using different terms and definitions, highlighting that their magnitude depends on the scope considered. For instance, Bosello and Parado (2020) define direct costs as the physical losses multiplied by their prices, whereas the indirect costs account for the economic adjustments triggered by the shock, and typically captured by changes in GDP. Piontek *et al.* (2021), meanwhile, distinguish between the direct impacts, defined as the sum of the impacts affecting each sector, assessed in isolation, and the final impacts, which account for macroeconomic adjustments, such as the amplification of damages through propagation across the economy or the mitigation of damages through adaptation to climate change. Similarly, Fankhauser and Tol (2005) contrast the direct impacts with the indirect effects due to horizontal and dynamic interlinkages: horizontal linkages are across sectors and regions, and may lead the final GDP loss after inter-sectoral readjustments to differ from the sum of the sectoral impact, while dynamic interlinkages happen over time, leading to a gap between the static relationship conveyed by damage functions and the final GDP loss (Estrada *et al* 2015). As outlined in the two aforementioned studies, dynamic effects predominantly occur through capital accumulation: reduced output in a given year may result in lower investment, thereby reducing capital accumulation and production in the long run.

This paper aims to explore and quantify this dynamic amplification of direct climate impacts transmitted through capital accumulation via endogenous investment responses. This amplification mechanism has been identified and quantified in several previous studies



(Estrada *et al* 2015, Fankhauser and S.J. Tol 2005, Dellink *et al* 2019, Kalkuhl and Edenhofer 2016, Bilal and Känzig 2024, Piontek *et al* 2019, Willner *et al* 2021). Using an endogenous neoclassical growth model, Fankhauser and S.J. Tol (2005) have reported that these indirect impacts due to investment deficit could exceed the direct impacts. In their model, direct impacts correspond to the damage function applied to production by reducing total factor productivity, while indirect impacts correspond to the difference between direct impacts and the total loss of GDP per capita compared to a scenario without impacts. Kalkuhl & Edenhofer (2016) have shown analytically that in a one sector neoclassical growth model at equilibrium, the indirect impacts due to capital accumulation slowdown would represent a share $\frac{\alpha}{1-\alpha}$ of the total loss of GDP, where α is the capital income share of the economy (typically equal to $\frac{1}{3}$). Using a damage function in IAMs, Van der Wijst *et al.* (2023) estimated that indirect impacts from reduced capital accumulation account for a smaller share of total impacts, representing 13–25% in 2100. Casey *et al.* (2023) calibrated climate-related productivity losses on panel data and applied them to future projections in a Solow growth model, finding a comparable share of indirect impacts from capital accumulation of about 23% in 2100. Using a multisectorial computable general equilibrium (CGE) model that captures different channels through which climate impacts affect different sectors, Dellink *et al.* (2019) report that the indirect impacts caused by reduced capital accumulation represent half of the total economic impacts. Using a DICE model in which climate damages reduce the economy's growth rate, Willner *et al.* (2021) find that reduced investment accounts for 40% of the total GDP loss.

The present paper contributes to this literature by further examining the macroeconomic drivers that shape the conditions under which climate change impacts are amplified through capital accumulation. For instance, a decline in output may reduce savings, but the subsequent impact on future output depends on the response of regional investment to regional savings (assuming that investments either come from domestic savings or from abroad). It depends also on the rate of capacity utilisation, as overcapacities may reduce the vulnerability to a decline in investment. We analyse these mechanisms, by assessing the role of six plausible macroeconomic drivers: saving rates, population, labor productivity, openness of international financial flows, the price and availability of fossil fuels, and the energy intensity of production. Using the Shared Socio-economic Pathways (SSP) framework (Riahi *et al* 2017), we contrast these drivers across three scenarios (SSP1, SSP2, SSP3). We



simulate the corresponding economic pathways throughout the twenty-first century using IMACLIM-R World, a multi-sector, recursive-dynamic global computable general equilibrium model, with climate impacts derived from an aggregated damage function (Van Der Wijst *et al* 2023).

The role of socio-economic development trajectories in determining regional vulnerability to climate change impacts has been highlighted by (Takakura *et al* 2019): exploring a set of 5 SSPs along 4 emissions pathways, they reported that emissions trajectories are the primary determinant of economic damages, while differences across SSPs for a given emissions trajectory become increasingly significant as global temperatures rise. We complement this analysis by explicitly analyzing the difference between the direct impacts, as determined by the damage function, and the total impacts, which incorporate additional losses resulting from reduced capital accumulation. Furthermore, while their model integrates SSP features within sectoral impact modules, our approach highlights the importance of SSPs at the macroeconomic and financial levels, providing a complementary perspective on how socio-economic pathways affect climate-related economic outcomes.

The rest of the paper is structured as follows. First, we present the model, paying particular attention to the non-neoclassical mechanisms that link economic growth and capital accumulation, as well as the scenarios used in the analysis. Second, we present our results. Third, we conduct a sensitivity analysis of the contribution of each socio-economic assumption defining the SSP. Finally, we discuss the implications of our results for the modelling community working on climate damage assessment.

2 - Modelling Framework

2.1 The IMACLIM-R World Model



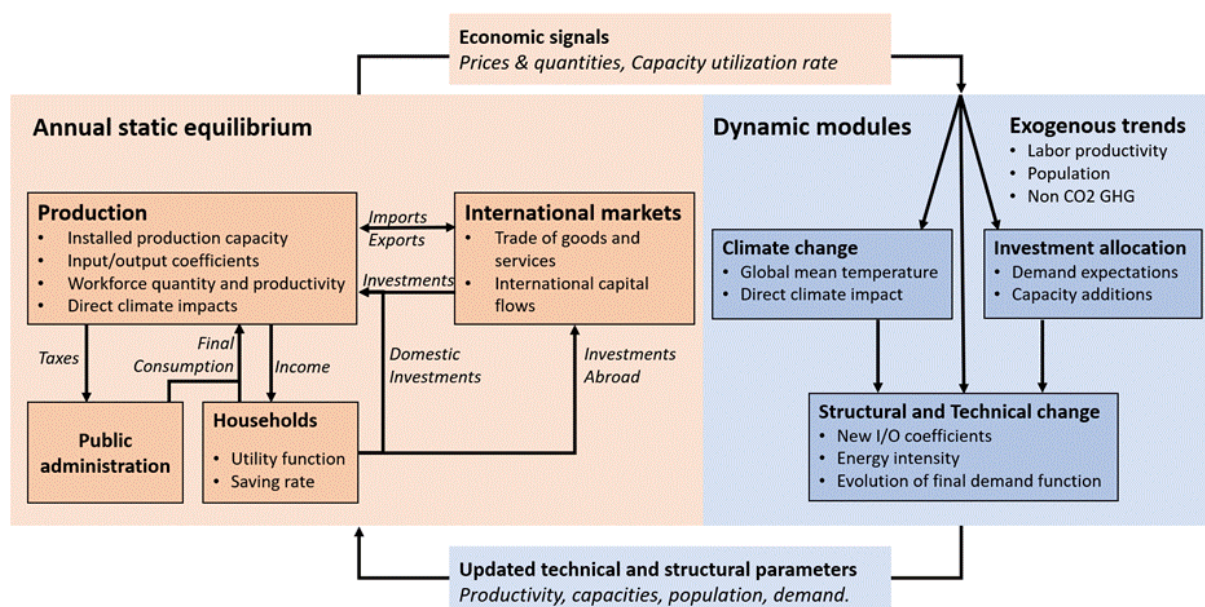


Figure 1. Structure of the IMACLIM-R World model. At each timestep, dynamic modules are fed with economic signals from the previous annual static equilibrium, and update the parameters and the constraints under which the next annual static equilibrium is determined.

IMACLIM-R World is a dynamic-recursive general equilibrium model of the global economy, disaggregated into 12 sectors and 12 regions in the version we used (Sassi *et al* 2010, Waisman *et al* 2012a, Briera and Lefèvre 2024). It relies on a hybrid accounting framework that ensures a consistent representation of both material and financial flows, and describes growth pathways in a second-best world, featuring market imperfections, partial uses of production factors and imperfect expectations. At each yearly time step, short-term macroeconomic adjustments are determined by a static equilibrium, constrained by available technologies and production capacities (Figure 1). Technological change is introduced between each static equilibrium through dynamic sectoral modules, representing energy sectors, transports, construction, industry, agriculture and services. In these modules, technological choices and changes in production capacity are made, as is the allocation of resources between sectors, according to semi-myopic forecasts, and driven by economic

signals calculated in the previous static equilibria, such as wages, relative prices, capacity utilization and physical flows. Sectoral modules update the sectoral production capacities and the input–output coefficients in sectoral production functions, leading to an evolution of sectoral productivities. In static equilibria, the proportions of intermediate inputs and labor used in production are determined by these coefficients, with no possibility of substitution, *à la* Leontief. Production operates under diminishing returns, as on the one hand, labor costs diverge as capacity utilization (load factor) approaches its maximum level. On the other hand, under imperfect labor market conditions, wages rise when the unemployment rate falls, consistently with the wage-setting curve theory (Guivarch *et al* 2011). Therefore, a distinctive feature of IMACLIM-R World, in contrast with neo-classical models, is that it does not assume full employment of production capacities or the labor force: market clearing conditions can lead to a partial utilization of production capacities. The load factor ultimately reflects the capital–labor ratio, that is to say the balance between the available labor supply and its productivity, on the one hand (measured in terms of annual working hours and output per hour), and the productive capacity, on the other (expressed as the maximum annual output in each sector). A low load factor indicates excess capacity and limited sensitivity of output to changes in production capacity. Conversely, a high load factor indicates capital scarcity and a high responsiveness of output to changes in production capacity.

In this framework, sectoral output levels result from the interaction between consumers' utility maximization and rising production costs as both capacity utilization rates and employment rates increase. Economic growth is made possible by exogenous improvements in labor productivity and population growth, as well as by endogenous structural change that shifts demand to more productive sectors (industry, then services) as per capita income rises (Lefevre *et al* 2022). Realized economic growth may depart from the exogenous labor productivity and population trends due to imperfect labor market, imperfect foresight of investment allocation and possibly investment shortage.

2.2 Climate impacts on economic activity

At each time step, the model calculates CO₂ emissions from fossil fuel use and industrial activities. CO₂ emissions from land-use change, as well as emissions of other greenhouse



gases, are treated as exogenous and follow the RCP4.5 in the scenarios considered in this article. The model also computes the evolution of global temperature driven by these emissions, using an embedded reproduction of the FAIR v1.6.3 model (Millar *et al* 2017). Rising temperatures reduce factor productivity, which in turn lowers output.

A damage function at the regional scale based on (Van Der Wijst *et al* 2023) is used to parameterize the regional level-effect GDP loss associated with a given level of global warming. This damage function was chosen because it features damages at the national level, allowing for regional specification of impacts. Furthermore, the implementation in IMACLIM-R World is straightforward as the damages depend only on global temperature change and not on other climate variables, contrarily to recent econometric assessments (Waidelich *et al* 2024), and a wide uncertainty range is available, which encompasses most of the existing damage assessments, offering flexibility for sensitivity analyses. However, the choice of the damage function is rather illustrative here, as we focus on the gap between direct and total impacts, rather than on the magnitude of impacts, and alternative damage functions could also be implemented in our modelling framework.

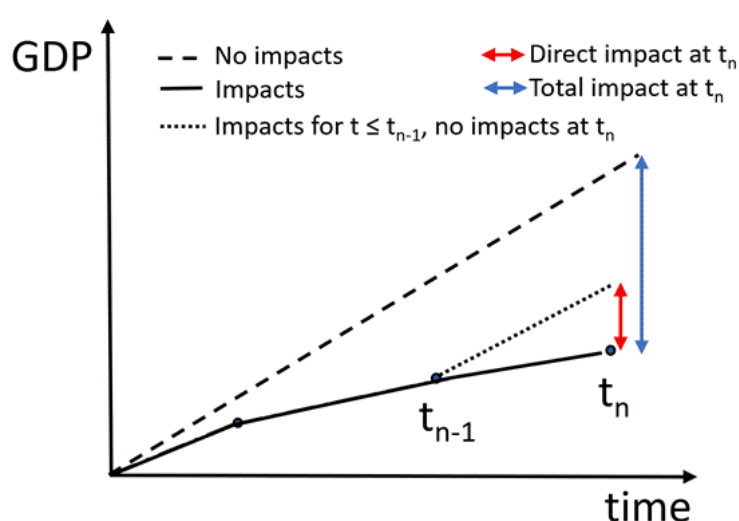


Figure 2. Schematic illustration of total and direct impacts of climate change.

The *direct impact* at time t is defined as the GDP loss at time t relative to a counterfactual economy in which productivity is unaffected by climate change in year t but otherwise evolves identically with climate impacts until year $t-1$ (Figure 2). At each time step, in each region, the factor productivity loss due to climate change is calibrated in order to equalize the direct impact and the damage function. Because we use an economy-wide aggregated damage function, we assume that the productivity loss is identical across all non-energy sectors and affects all production factors equally, analogous to a reduction in total factor productivity (TFP) in a neoclassical production function. More precisely, labor productivity, production capacity, and the efficiency of input conversion into output, are reduced in the same proportions. The *total impact* is then measured as the difference in GDP relative to a counterfactual economy that would have no climate-related damages. We consistently refer to the indirect impact as the difference between the direct impact and the total impact.

2.3 Impact on investment

Total investments are calculated in static equilibria. Gross regional savings are computed as a share of regional output, with a saving rate initially calibrated on GTAP data (Aguiar *et al* 2019) and that evolves exogenously (see Appendix). The amount of investment allocated to each region is calculated from gross regional savings minus a proportion X_c that feeds an international capital market, and adding a proportion M_c imported from the capital present on that market. X_c and M_c are calibrated on GTAP data, and their evolutions depend on the SSP scenario. The allocation of investment across sectors and the addition of new production capacities depend on imperfect sectoral expectations, which are formed in the sectoral modules, typically through the extrapolation of past trends in outputs and prices.

Because the drivers of investment (domestic saving rates and international capital flows) are exogenous to demographic dynamics and labor productivity growth, structural imbalances in the capital–labor ratio may emerge. When national savings plus net foreign capital inflows are insufficient relative to the rate of labor force expansion, capital deepening fails to keep pace, resulting in capital scarcity and depressed productivity growth. Capital scarcity can create persistent development traps rooted in the disequilibrium between capital formation and labor supply growth. Conversely, when savings or capital inflows are comparatively high, the economy may experience excess capacity and underutilization of capital, reflecting a



mismatch between factor accumulation and effective demand.

Climate damage compounds these dynamics: the drop in production reduces gross savings and ultimately investment, generating a cumulative effect on production capacity. The impact of reduced investment is therefore not uniform across sectors and regions as it depends on the capital-labor ratio and the resulting capacity utilization rates. Where excess capacity prevails, the marginal productivity of capital is nearly zero, so a fall in investment has little effect on output. By contrast, in contexts of capital scarcity, where production capacity is over-utilized, the higher marginal productivity of capital makes economies more sensitive to variations in investment. In this case, productivity losses translate into amplified GDP losses over time, as the accumulation of the investment deficit widens the gap between direct impact and total impact.

2.4 Scenarios and assumptions

The availability of investment and the utilization rate of production capacities are therefore crucial determinants of the level of indirect impacts. Their evolution is strongly dependent on a set of exogenous and uncertain parameters, including the labor supply, which depends on labor productivity and demographic growth, the international flows of capital, and the saving rates. We explore the uncertainty in the future evolution of these parameters by contrasting three scenarios consistently with the Shared Socio-economic pathways framework: SSP1, sustainable development; SSP2, middle-of-the-road; SSP3, regional rivalry. We only assess no-climate policy scenarios because we focus on climate change impacts. We contrast these scenarios along five dimensions which are expected to influence the magnitude of total impacts, through (i) their role in the investment dynamics, such as international capital flows, (ii) their influence on capital scarcity relative to labor supply, such as population growth and labor productivity, and (iii) in the magnitude of climate impacts due to different emissions pathways, such as fossil fuel availability and energy efficiency (Table 1).

The population growth is obtained from the SSP scenario explorer hosted by IIASA (KC *et al* 2024). In the central projection (SSP2), the global population peaks in 2080. In SSP1, the global population growth is slower than in the baseline, in particular in the developing world, and the global population peaks in 2060 before declining up to 2100. Conversely, in SSP3, the



global population keeps increasing until 2100, in particular in developing countries.

Labor productivity trends are calibrated to match the updated SSP growth drivers (Dellink *et al* 2017, 2024) for runs without climate impacts. The GDP is the highest in SSP1, intermediate in SSP2, and the lowest in SSP3, especially in developing countries. Variations between SSPs are summarised in the table below.

International capital flows are designed consistently with the narratives of each SSP. In SSP1, we assume stronger international cooperation and reduced investment risks in emerging economies. It causes the regional share M_c of international capital to evolve endogenously. Investment is therefore directed toward regions where capital scarcity imposes the highest additional labor costs, that is, where the marginal productivity of capital is greatest. Meanwhile, the exported share of capital X_c remains constant. In the SSP2, M_c and X_c are held constant. In SSP3, the assumption of increased regional rivalry and reduced cooperation leads to a progressive closure of international capital flows: the share of exported capital X_c decreases tenfold from 2020 to 2100 in all regions.

Fossil fuel use and the energy intensity of development pathways also differ across SSPs: SSP1 is more energy-efficient, with fossil fuels being less abundant and more expensive; SSP3 is the opposite, while SSP2 adopts intermediate assumptions (cf Appendix B & C).

Finally, the role of saving rates is assessed independently of the SSP framework, by analyzing variations of +/- 20 % from their baseline evolution.

In the following, we first look at the results of the six scenarios (3 SPPs with and without damages, keeping the saving rate identical), and then analyze the sensitivity of the results to each of the five factors and to the level of saving rates.

Socio-economic assumption	Corresponding parameters	SSP1	SSP2	SSP3



Population	Active population, total population. Source: SSP scenario explorer hosted by IIASA (KC <i>et al</i> 2024)	Global population 2050: 9.1 Bn 2100: 8.0 Bn	Global population 2050: 9.6 Bn 2100: 9.9 Bn	Global population 2050: 10 Bn 2100: 13 Bn
labor productivity	labor input per input of production. Source: SSP scenario explorer hosted by IIASA (Dellink <i>et al</i> 2024)	Strong increase of productivity in developing countries.	Moderate increase of productivity in developing countries.	Lower increase of productivity in developing countries, and in developed countries (with the exception of the USA).
International capital flows	X_C : Share of gross domestic savings exported. M_C: Imports of international capital.	X_C is kept fixed, M_C evolves to channel financial flows in regions with capacity shortages.	X_C is kept fixed, M_C is kept fixed.	X_C decreases exponentially to 0 with a decline rate of 2.8 % per year (X_C is divided by 2 over 25 years), M_C is kept fixed.



Fossil fuels	Availability of fossil fuel resources and cartel strategy of OPEC. (Waisman <i>et al</i> 2012b)	Low fossil fuel resources, OPEC targets a high price (\$100/bbl)	Medium fossil fuel resources, OPEC targets a high price (\$100/bbl)	High fossil fuel resources, OPEC targets a low price (\$40/bbl)
Energy efficiency	Autonomous and endogenous energy efficiency improvement cf. (Bibas <i>et al</i> 2015).	Fast convergence of energy efficiency towards the leader country, fast improvement of the leader's energy efficiency	Slow convergence of energy efficiency towards the leader country, slow improvement of the leader's energy efficiency	No energy efficiency improvement.

Table 1. Implementation of the shared socio-economic pathways in IMACLIM-R World.

3 - Scenario results

In counterfactual scenarios without climate impacts, economic activity is projected to expand substantially through the end of the century. In SSP1 and SSP2, global GDP increases sixfold, while CO₂ emissions rise by 50% in SSP2 but decline by 25% in SSP1 thanks to improvements in energy efficiency. In SSP3, GDP triples and emissions increase by 25% (Figure 3). All three no-policy scenarios exceed the 2°C threshold around 2050, with global



temperatures reaching 2.9°C, 3.3°C, and 3.2°C in 2100 under SSP1, SSP2, and SSP3, respectively. When climate impacts are incorporated, economic activity is reduced, and global GDP in 2100 is 8%, 17%, and 16% lower than without impacts in SSP1, SSP2, and SSP3, respectively. Although this does not halt absolute growth, global GDP per capita stagnates in SSP3 from 2090 onward. These results are obtained with the medium damage quantile from the COACCH damage function, and higher (or lower) losses would emerge with higher (or lower) damage quantile (Van Der Wijst *et al* 2023).

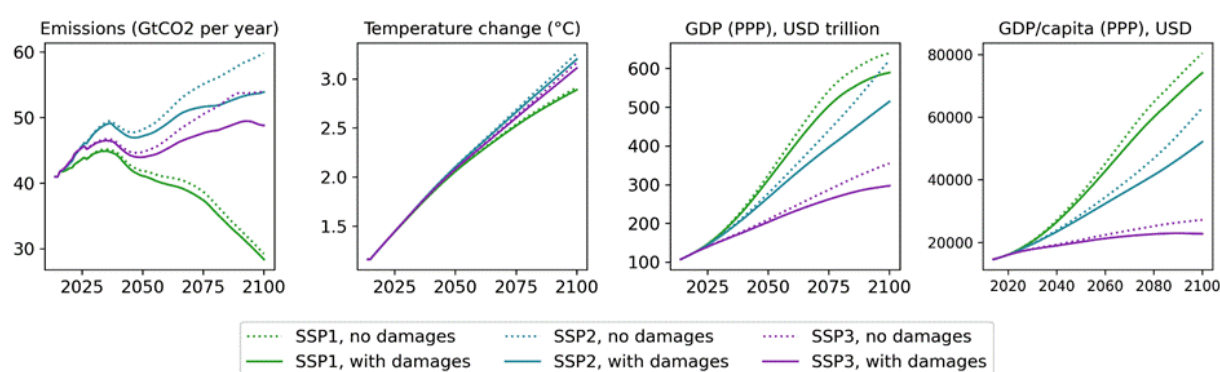


Figure 3. CO₂ emissions, global temperature change, global GDP and GDP per capita of the SSP scenarios with and without climate change impacts.

Direct GDP losses expressed as a function of global temperature change vary only modestly across scenarios, as differences mainly reflect the changes in the relative economic weights of regions that experience unequal levels of direct impact (Figure 4). By contrast, indirect impacts, and consequently total impacts, are highly scenario-dependent: for a global average warming of 2.85°C, direct GDP losses amount to roughly 6% in all scenarios, while total losses reach 8% in SSP1 and 12% in both SSP2 and SSP3 (Figure 4), twice more than direct GDP losses. Accordingly, indirect impacts account for between 25% and 50% of total GDP losses (depending on the SSP) compared to a no-damage scenario.

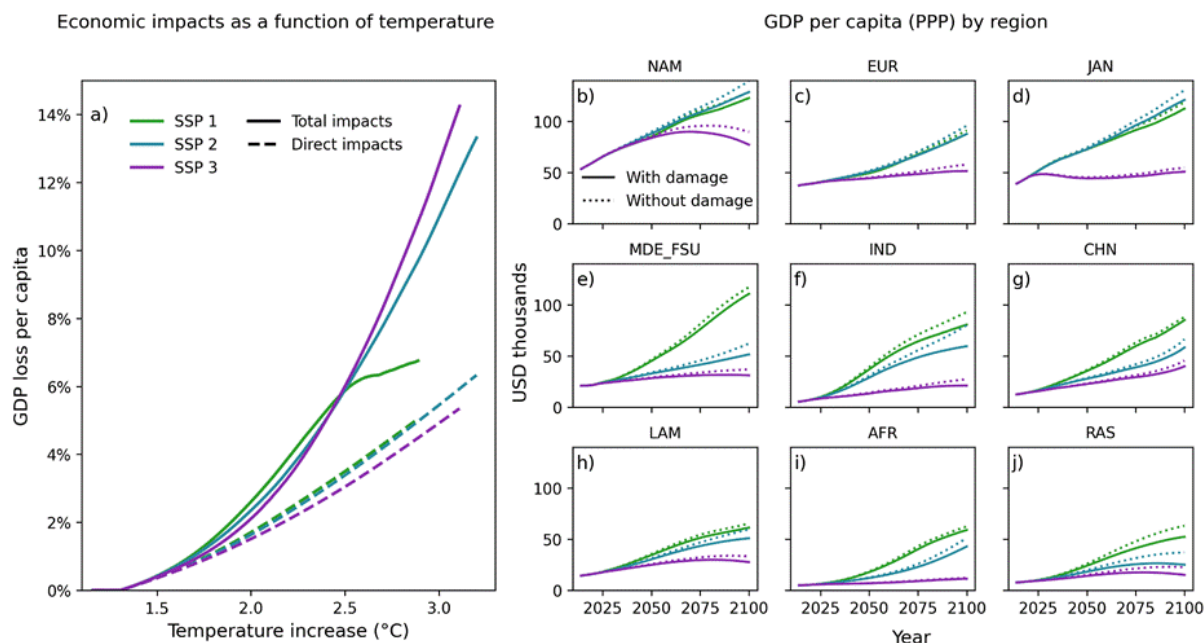


Figure 4. a) Global economic impacts, expressed in GDP loss, as a function of global mean temperature increase. b-j) GDP per capita pathways with and without damages in nine macro-regions, for each SSP. The nine macro-regions are Northern America (NAM), Europe (EUR), Japan, Australia and New-Zealand (JAN), Middle-East and the former Soviet Union (MDE FSU), India (IND), China (CHN), Latin America (LAM), Africa (AFR) and the rest of Asia (RAS).

At the regional level, the picture is more heterogeneous (Figure 4). In scenarios without climate impacts, GDP per capita decreases by the end of the century in several regions, particularly under SSP3. The inclusion of climate impacts amplifies these declines, especially in the Americas (both North and South) and in the “rest of Asia” region. The magnitude of total climate change impacts, measured here as the loss of GDP in 2100 relative to a no-damage baseline, (Figure 5) is generally larger than direct impacts: 4 times larger in China under SSP2 and 3.5 times larger in the former Soviet Union and the Middle East under SSP2 and SSP3. The distribution of total impacts also varies substantially across SSPs. For example, China is the least affected region under SSP1, yet becomes the sixth most affected under

SSP3. Similarly, Africa is heavily impacted in SSP2 but much less so in SSP1 and SSP3. In the latter case, it is the region experiencing the smallest total GDP loss, even though it ranks third in terms of direct impacts. It should be noted that the variations of regional damages across SSPs are not in agreement with those reported in (Takakura *et al* 2019) because our implementation of the SSPs contrasts macroeconomic and financial drivers while theirs is focused on the sectoral impact modules.

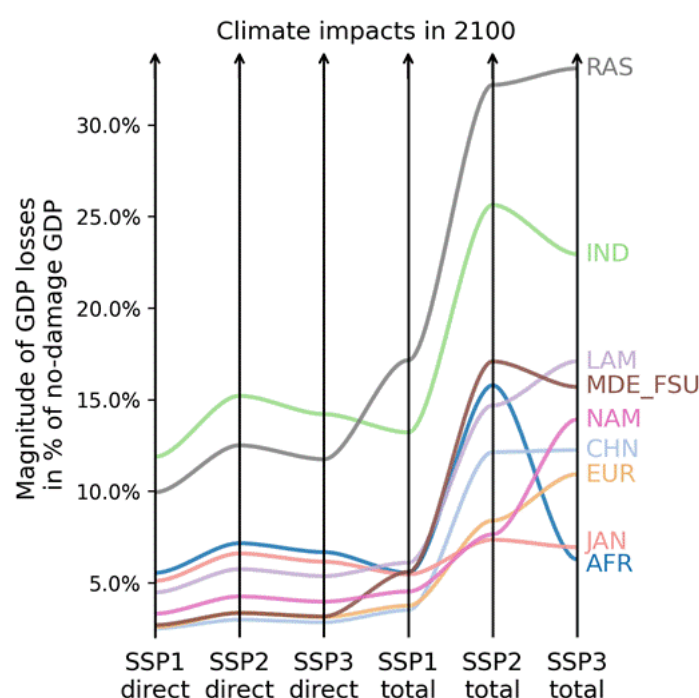


Figure 5. Direct and total climate impact in 2100, for each SSP, expressed as a loss of GDP compared to a no-damage scenario, for each region. The nine macro-regions are Northern America (NAM), Europe (EUR), Japan, Australia and New-Zealand (JAN), Middle-East and the former Soviet Union (MDE FSU), India (IND), China (CHN), Latin America (LAM), Africa (AFR) and the rest of Asia (RAS).

The numerical values of these results should be considered illustrative, first because of the

large uncertainty surrounding the magnitude of direct impacts, and second because the results are sensitive to parameters that are difficult to calibrate due to a lack of data (e.g., the cost of production capacities; see the discussion for more details) or subject to uncertainties (e.g., saving rates). However, it is noteworthy that both the magnitude and the geographical distribution of the total economic effects of climate change differ markedly from those that would be inferred directly from the damage function. The source of this discrepancy lies in the differentiated vulnerabilities to the capital shortages resulting from reduced investments, as described in the Methods section. Countries experiencing capital shortages face a higher marginal productivity of investment, making them more vulnerable to investment variability following output losses due to climate change. In IMACLIM-R World, the gap between total and direct impacts can be entirely attributed to reduced investment, as relaxing investment constraints, for example, by increasing investment capacities by several orders of magnitude, eliminates the discrepancy entirely (as shown in supplementary figure F3). This mechanism is also valid under standard neoclassical growth assumptions. With diminishing returns to capital and constant returns to scale in labor and capital, the further the economy is from its steady state, the higher the marginal productivity of capital. Furthermore, this marginal productivity increases with both labor supply and total factor productivity. However, it is clear that the gap between direct and total impacts here can be much larger than those reported using neoclassical growth models and previously discussed (Fankhauser and S.J. Tol 2005, Kalkuhl and Edenhofer 2016, Casey *et al* 2023, Van Der Wijst *et al* 2023, Dellink *et al* 2019). While the latter report that indirect impacts due to capital accumulation slowdown represent between 13% and 50% of the total impacts, in our SSP3 scenario the indirect impacts range from 0% of the total impacts in Africa to 80% in the Middle East and former Soviet Union. The difference between the results of IMACLIM-R World and those of neoclassical growth models lies in their production functions. In IMACLIM-R World, output cannot exceed installed capacities. On the contrary, neoclassical growth models typically allow substitution between labor and capital, such as in a Cobb–Douglas specification, where output is proportional to labor supply raised to the power $1-\alpha$, with α denoting the capital income share.

The contrasted results across SSPs thus highlight how underlying assumptions shape the magnitude of total impacts. All regions experience lower total impacts in 2100 under SSP1 than under SSP2. This is partly because direct impacts are lower in SSP1. Emissions are lower



despite stronger growth, thanks to improved energy efficiency and reduced fossil fuel availability, which lead to a smaller temperature increase. The amplification of direct impacts into total impacts is also lower in SSP1 because capital shortages are mitigated by several factors: international financial flows reduce capital scarcity, and slower population growth limits imbalances between capital and labor. Higher productivity in SSP1 acts in the opposite direction but is not strong enough to offset these effects. Ultimately, total impacts are much lower in SSP1.

The difference of total impacts between SSP2 and SSP3 varies more across regions: total impacts decrease in some regions and increase in others, even though direct impacts decrease everywhere because end-of-century temperatures are lower. The reduction in international financial flows in SSP3 raises total impacts in countries that were net capital importers under SSP2 and lowers them in net capital exporters. Lower productivity in SSP3 tends to reduce total losses relative to SSP2, but higher population growth, in particular in developing economies, pushes them upward. Reduced energy efficiency increases both direct and total losses. Finally, whether total regional impacts ultimately rise or fall between SSP2 and SSP3 depends on which effects dominate.

Overall, total economic losses from climate change may substantially exceed direct damages, and their magnitude and regional distribution are strongly shaped by socioeconomic conditions and investment constraints. This highlights the need for sensitivity analysis to disentangle the contribution of each factor to regional and scenario-specific variations, which is undertaken in the following section.

4 - Sensitivity Analysis

The SSP scenarios are contrasted along five dimensions that vary simultaneously. To assess the contribution of each dimension to climate impacts, we conduct a sensitivity analysis following the method of Marangoni et al. (2017). This approach decomposes the effect of each factor into three components: its individual effect, its total effect, and its interaction effect with the other factors. To obtain the individual effect of a factor X on output Y between SSP2 and SSP1, we calculate the change of output Y resulting from a switch of factor X from SSP2 to SSP1, while all other factors are fixed as in SSP2. To obtain the total effect of a factor X on output Y between SSP2 and SSP1, we calculate the change of output Y



resulting from a switch of factor X from SSP2 to SSP1, while all other factors are fixed as in SSP1. The interaction effect is then given by the difference between the total effect and the individual effect. A large interaction effect indicates that the influence of a factor strongly depends on the levels of the other factors. For example, figure 6 can be read as follows: if the output considered is the total climate impact in 2100 and the factor in question is labor productivity, then the individual effect of switching labor productivity from SSP2 to SSP3 (where productivity is lower) is a reduction of total impacts by 4.7 percentage points of GDP, and the total effect is a reduction of 5.4 percentage points of GDP.

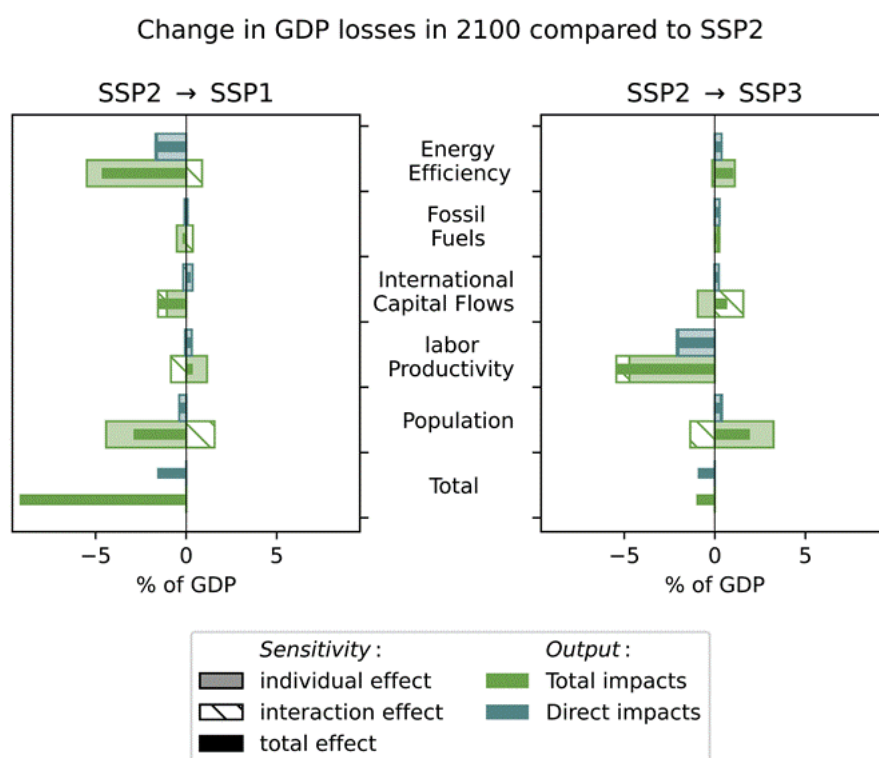


Figure 6. Sensitivity of the direct climate impacts in 2100 to scenario factors. Variations in total and direct losses are expressed as the difference, in percentage points, between the total and direct impacts (expressed in GDP percentages) across the SSPs.

The sensitivity analysis clarifies the influence of each scenario assumption on direct climate impacts and on total climate impacts at both global and regional scales.

First, end-of-century direct climate impacts depend on the temperature anomaly and therefore on the trajectory of CO₂ emissions over the century. CO₂ emissions are determined by the product of the carbon intensity of GDP and the level of GDP. In these scenarios, which assume no climate policies, the carbon intensity of GDP declines when energy efficiency improves and fossil fuel availability decreases, as observed when moving from SSP2 to SSP1, while the contrary is observed when moving from SSP2 to SSP3. Other drivers shape GDP, and thereby emissions. Global GDP increases with higher productivity, larger population, and the redirection of international capital flows toward capital-scarce regions. These mechanisms imply higher direct impacts when population rises and lower direct impacts when productivity falls, as occurs when shifting from SSP2 to SSP3, while the contrary is observed when moving from SSP1 to SSP2. Redirecting capital flows to regions where capital is most productive raises GDP, emissions, and hence direct impacts, as in the shift from SSP2 to SSP1. Conversely, reducing net international capital flows in SSP3 produces a similar effect, because many net capital exporters in SSP2 are themselves capital-scarce (net capital flows are displayed in supplementary figure F2). Overall, direct impacts are lower in SSP1 than in SSP2, mostly because of the improved energy efficiency, and lower in SSP3 than in SSP2, mostly because of the lower productivity.

Second, the amplification of direct impacts into total impacts depends on the balance between capital availability and labor supply. Total impacts decrease if capital availability increases compared to labor supply, as in the case when capital flows are rebalanced toward capital-scarce regions (while keeping other factors unchanged) when moving from SSP2 to SSP1: by reducing capital scarcity, it reduces total impacts despite increasing direct impacts. The individual effect of moving the international capital flows from SSP2 to SSP3 is a reduction of total climate impacts, while its total effect is an increase of total climate impacts. This is because whether a given allocation of capital across regions improves or worsens overall capital-labor balances ultimately depends on the assumptions about population and labor productivity. In this case (from SSP2 to SSP3), the interaction of reduced capital flows with a lower labor supply worsens climate impacts. Regionally, total impacts decrease in areas benefiting from additional inflows or reduced outflows, while impacts increase in regions which were net capital importers in SSP2, typically high-income



economies. The higher energy efficiency and lower fossil fuel availability significantly reduce total impacts of climate change in SSP1 compared to SSP2 while the lack of energy efficiency improvement and higher availability of fossil fuels in SSP3 (w.r.t. SSP2) worsen them. Higher labor productivity strongly increases total impacts when moving from SSP3 to SSP2 and from SSP2 to SSP1, because it increases the relative capital scarcity, and also because it increases direct impacts. Conversely, the lower population when moving from SSP3 to SSP2 and from SSP2 to SSP1 reduces total impacts. Productivity effects dominate over population effects at the global scale, but this is not always the case at the regional scale (cf Appendix).

Total loss is also highly sensitive to the saving rate, the primary driver of investment. Figure 7 presents the ratio of total impacts to direct impacts for alternative saving rates, progressively varying from 20% below to 20% above the reference rate. The figure demonstrates that changes in saving rates lead to markedly different damage amplification. Within each SSP, scenarios with lower saving rates exhibit higher ratios of total to direct impacts than those using the reference rate. Moreover, all scenarios with low saving rates show greater amplification than scenarios at the reference rate, regardless of the SSP. Saving rates are thus a critical determinant of damage amplification.

The IMACLIM-R World simulations and sensitivity analysis thus show that total climate impacts can diverge substantially from the direct impacts specified by the damage function. Regional socio-economic assumptions are a key determinant of macroeconomic outcomes, as vulnerability depends on capital accumulation, investment, and savings dynamics.



Ratio of total impacts to direct impacts, for different saving rates

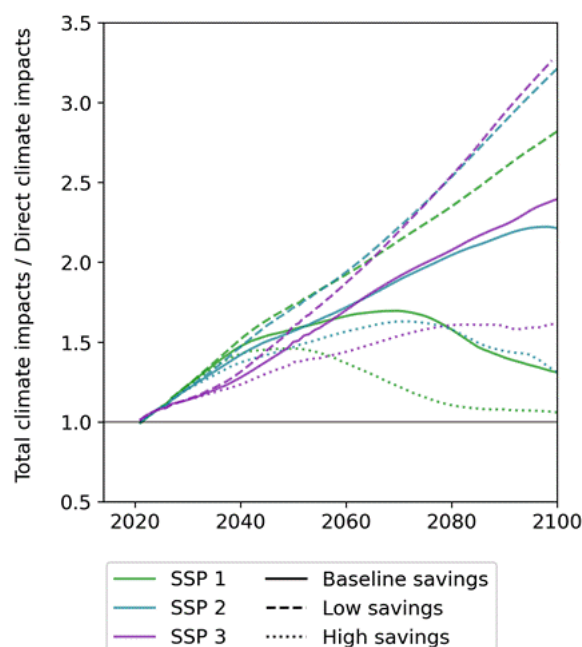


Figure 7. Ratio of total to direct impacts across regions for each SSP, under three savings pathways: (i) a reference saving rate path equivalent to the one used throughout the paper, (ii) a high saving rate that increases linearly relative to the baseline, reaching 20% above it by 2100, and (iii) a low saving rate that decreases linearly relative to the baseline, reaching 20% below it by 2100.

5 - Discussion & Conclusion

Our simulations find that total impacts from climate change can be significantly larger than the direct impacts prescribed by the damage function. It is due to the accumulation of investment losses over time, which amplify aggregate GDP declines relative to a counterfactual without climate damages. These findings are consistent with the earlier studies aforementioned. It should however be noted that others have suggested that the response of capital accumulation could mitigate the direct negative climate impacts. First, the anticipation of future impacts may lead to increased savings in the short run as specified



in Ramsey growth model (Piontek *et al* 2019) when climate damages are non-persistent, although this is deemed insignificant in (Fankhauser and S.J. Tol 2005). However, saving rates may also be reduced due to lower expected returns in investments, as reported by Willner *et al.*, (2021): in Ramsey-type growth models, when damages are assumed to directly affect the economy's growth rate, reduced savings account for half of the additional GDP losses caused by the reduced investments. In IMACLIM-R World, the saving rate is exogenous which prevents this kind of effect. Second, as illustrated in a CGE where endogenous rates of return on capital determine international capital flows, damages could be mitigated if interest rates on capital rise in regions affected by climate change, increasing the inflow of international capital (Eboli *et al* 2010). In our model, financial flows respond to capital scarcity only in SSP1, which significantly mitigates the overall impact. However, this mitigation is not sufficient to reduce the overall impact below the direct impact. This is partly due to the fact that all regions experience climate impacts, which reduces the overall investment capacity. Empirically, climate risks have been reported to lead to capital outflows (Ferriani *et al* 2023), which may further increase capital scarcity and amplify total impacts. Overall, our results largely depend on how investment dynamics are represented. IMACLIM assumes, in line with neoclassical theory, that investment is constrained by savings. Other modelling paradigms, such as post-Keynesian non-equilibrium approaches where investment is created through debt (Mercure *et al* 2019), would likely yield different intertemporal amplifications of impacts.

Our results reinforce the view that the dynamics of capital accumulation are central to understanding the long-run macroeconomic consequences of climate change. The analysis presented here extends these insights by highlighting the role of certain macroeconomic characteristics in shaping vulnerability. Economies with relative excess capacity, or with financing conditions that allow investment to match labor force and productivity growth, appear better positioned to absorb climate-related shocks. By contrast, economies where investment is constrained are more vulnerable, as output losses translate into tighter investment capacity, reinforcing the downward spiral in growth. It should be noted that our estimation of the gap between total and direct impacts in IMACLIM-R World depends on our model calibration assumptions: production capacities are derived from each sector's output, with no undercapacity or overcapacity assumed during the calibration period (2014–2020). The costs of production capacities are then set to align production growth with investment



flows and capital depreciation. Existing overcapacities might therefore distort the calibration, leading to underestimation of capital stocks and overestimation of production capacity costs, while existing undercapacities have the opposite effect. Furthermore, assuming an initial capital–labor balance implies that the capital scarcity that amplifies indirect impacts takes time to emerge.

We have also shown that saving rates play a key role in amplifying damages, as lower savings exacerbate capital scarcity. Because we employed a reference saving rate pathway for each SSP, this approach prevents us from assessing the contribution of savings to differences in impacts across SSPs. However, econometric studies (Fontagné *et al* 2022, Fouré *et al* 2013) have estimated the relationship between savings, demographic structure, and GDP per capita, and used it to project savings rates under the SSP scenarios. Their projections give higher savings in SSP3 than in SSP2, and higher in SSP2 than in SSP1, consistent with lower demographic growth leading to an older population. Combined with SSP demographic trajectories, this would imply stronger macroeconomic amplification of climate impacts through investment constraints in scenarios with lower demographic growth, such as SSP1 and SSP5, even though these scenarios are supposed to represent a lower degree of vulnerability.

In theory, the scope of the mechanism governing damage amplification is not limited to the issue of climate change, but more generally concerns any economy that suffers a loss of production (due to an exogenous shock, for example) likely to lead to a drop in investment. Thus, the factors determining vulnerability to exogenous shocks should be the same as those determining the amplification of the impacts of climate change. Empirically, capital accumulation has been put forward as an explanation for the persistence of output shocks observed in GDP timeseries by (Estrada *et al* 2015), although the degree of persistence of shocks is difficult to estimate econometrically. The impossibility to disentangle direct weather impacts on TFP from the intertemporal effects due to capital dynamics is also reported in Kalkuhl and Wenz (2020). In addition, other socio-economic factors may explain vulnerability to shocks, such as latent domestic social conflicts (Rodrik 1998).

Taken together, these results show the importance of integrating macro-financial constraints, demographic dynamics, and structural vulnerabilities into assessments of the economic impacts of climate change. Direct and total impacts may differ substantially, implying that the



way the damage function is integrated with the macroeconomic model plays an important role. In particular, ex-post calculation of damages such as in (Taconet *et al* 2020) or (Drouet *et al* 2021) could yield strongly different results from integrated modules that compute damage endogenously. Therefore, modelling teams should make explicit their modelling choices and the feedback channels from climate impacts to the economy they represent. Second, total impacts are highly sensitive to macroeconomic mechanisms that have not historically been a primary focus of integrated assessment models developers, which means that these models are not yet fully suited for this type of analysis. In a broader sense, the macroeconomic mechanisms emphasised in this study have the potential to exacerbate future damages due to climate change, surpassing current projections and extending the already considerable uncertainty surrounding the magnitude of these damages.

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Appendix



A - Climate impact module

The productivity loss is calibrated in order to equalize direct impacts and the value returned by the damage function in each region. The labor productivity (measured as units of output per working hour), production capacity, and the efficiency of input conversion into output from region r at time t are all multiplied by a productivity decline factor $1 - \omega_{r,t}$, with $0 < \omega_{r,t} < 1$ if productivity decreases. A decline in productivity increases unit production costs, thereby reducing output. The direct GDP loss is thus the difference between two GDPs computed from two static equilibriums sharing the same parameters, except that they have different productivity decline factors: $1 - \omega_{r,t}$ for the economy affected by climate impacts at time t , and 1 for the one which is not affected at time t .

However, the relative drop in GDP is not equal to the productivity decline factor $1 - \omega_{r,t}$. This is partly because lower input conversion efficiency compounds the effect of higher input costs, and most sectors are either their own customers or the customers of their customers. As a result, the higher the share of intermediate inputs in production costs, the greater the GDP loss relative to $\omega_{r,t}$. The gap between $\omega_{r,t}$ and GDP loss therefore depends on each region's economic structure and evolves over time. To capture this, regional productivity losses are re-calibrated at each time step using a Newton-like iterative scheme, adjusting productivity until the resulting GDP change matches the value predicted by the damage function. This approach accounts for sectoral interdependencies and ensures a consistent mapping from productivity shocks to economic impacts.

B - Fossil Fuels

The oil supply module is comprehensively described in (Waisman *et al* 2012b). OPEC producers can reduce or increase oil extraction to stabilize world oil prices around their target. In SSP1 and SSP2, they target a high price of \$100/bbl, in SSP3 they target a lower price of \$40/bbl. The oil extraction dynamics are endogenous and follow hubbert curves,



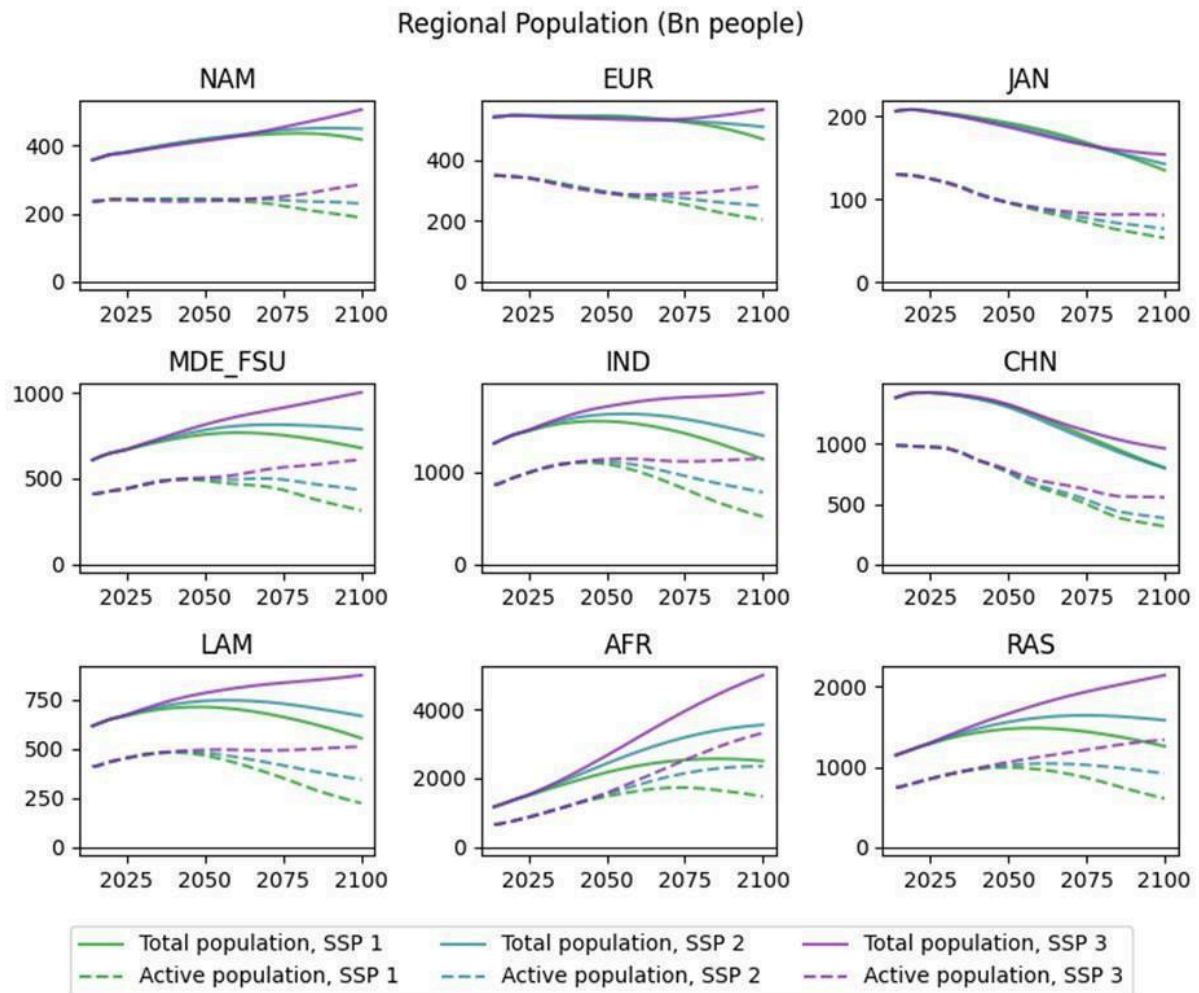
with a progressive increase of production followed by a decline. We contrast three cases about future oil resources. **Low oil resource** (SSP1): Production starts to decline when 50% of reserves remain, the deployment of production capacities is slow. **Medium oil resources** (SSP2): Production starts to decline when 25% of reserves remain, the deployment of production capacities is slow. **High oil resources** (SSP3): Production starts to decline when 25% of reserves remain, the deployment of production capacities is faster.

C - Energy Efficiency

The energy efficiency module is described in (Bibas *et al* 2015). The maximum annual rate of price-driven energy efficiency improvement is 50% higher in SSP1 than in SSP2, and the convergence is complete in SSP1, meaning that countries converge towards the energy efficiency level of the most efficient country in each sector (the “leader”), while in SSP2 they only converge towards 90% of this level. The convergence speed towards this targeted level is also much faster in SSP1 than in SSP2. More precisely, the price index of energy defines a characteristic timescale of convergence (the higher the price index, the faster the technology spillover, and thus the faster the convergence and the lower this characteristic timescale). After this timescale, the energy efficiency gap between leader and followers is divided by 2 in SSP2, and by 100 in SSP1, ensuring complete convergence. Furthermore, the energy efficiency of the leader improves 4 times faster in SSP1 than in SSP2. In SSP3, there is no energy efficiency improvement.

D- Population

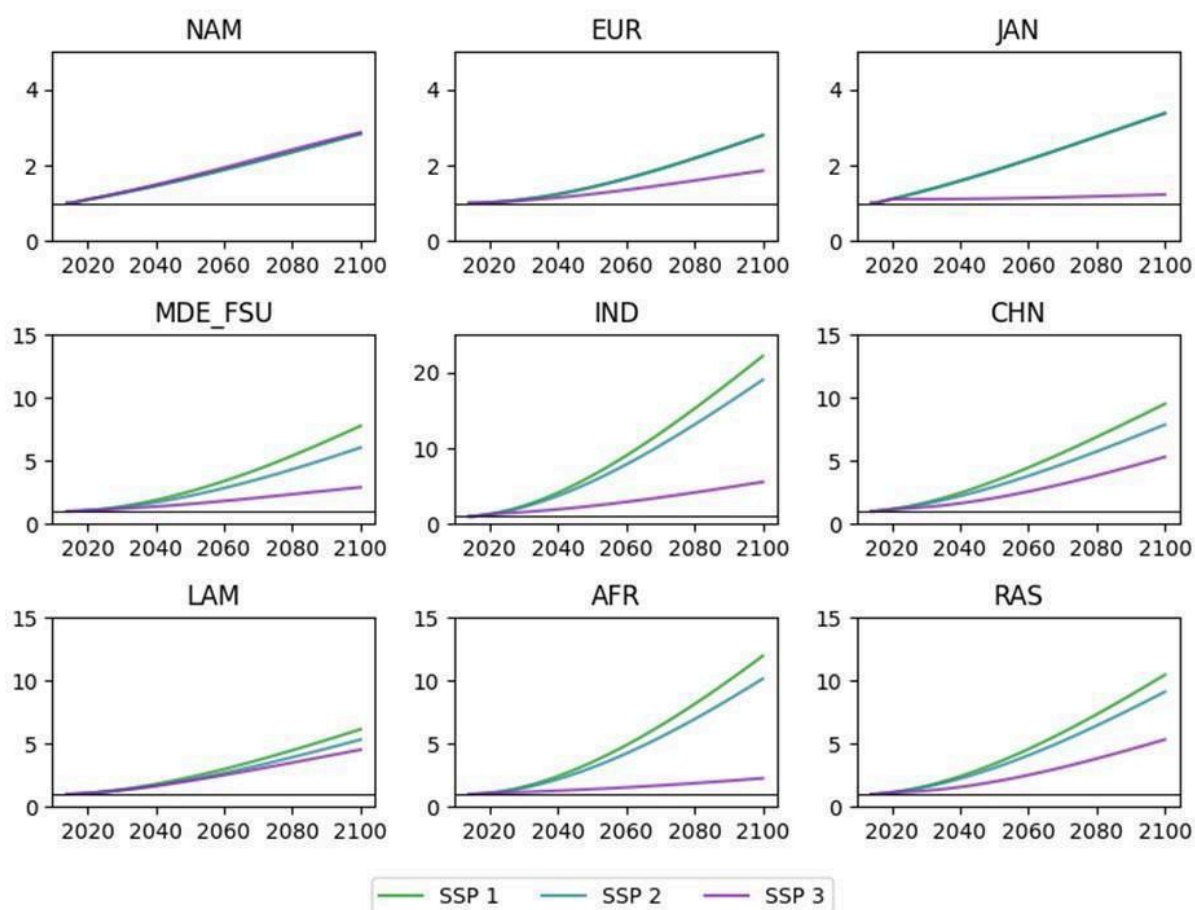




E - Labor productivity

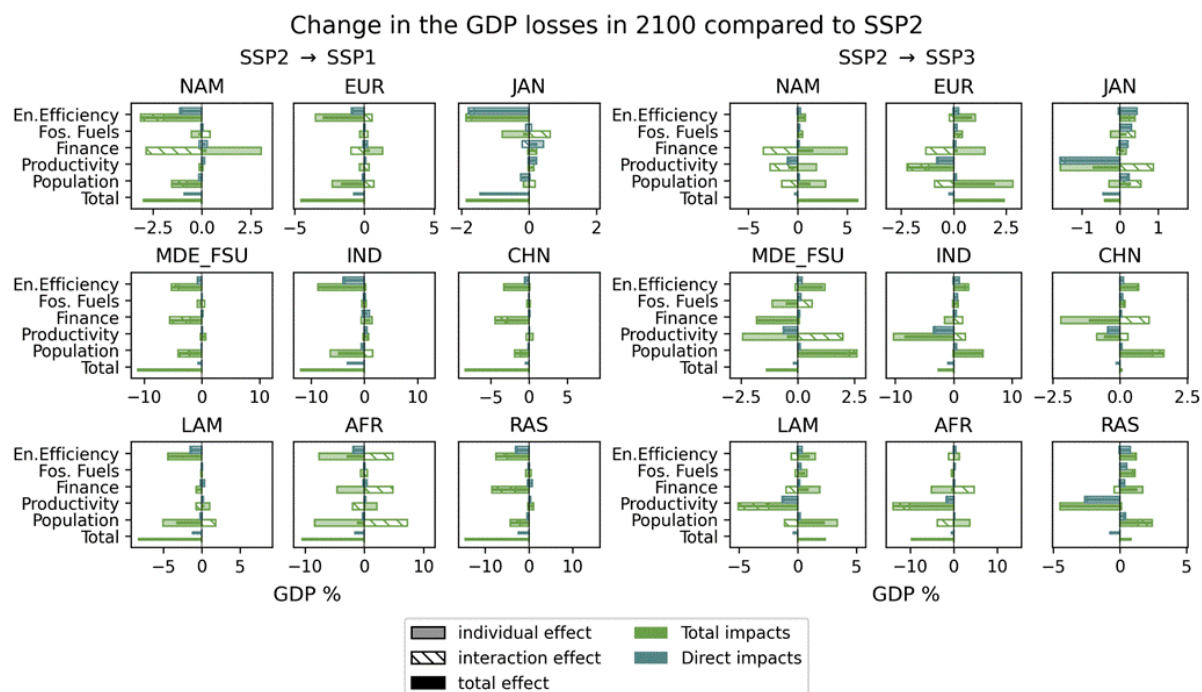


Labour productivity evolution (1 in 2014)

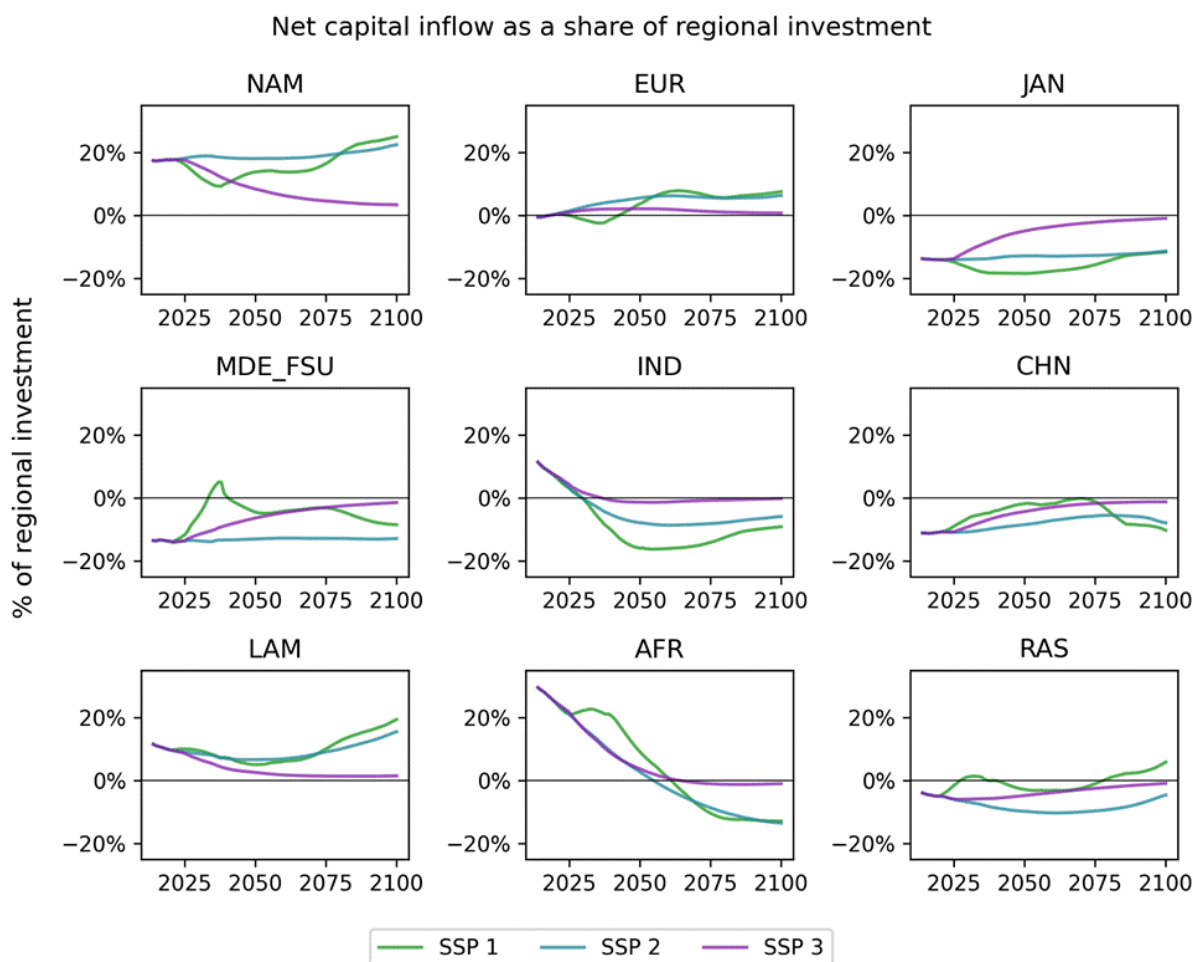


F - Supplementary figures

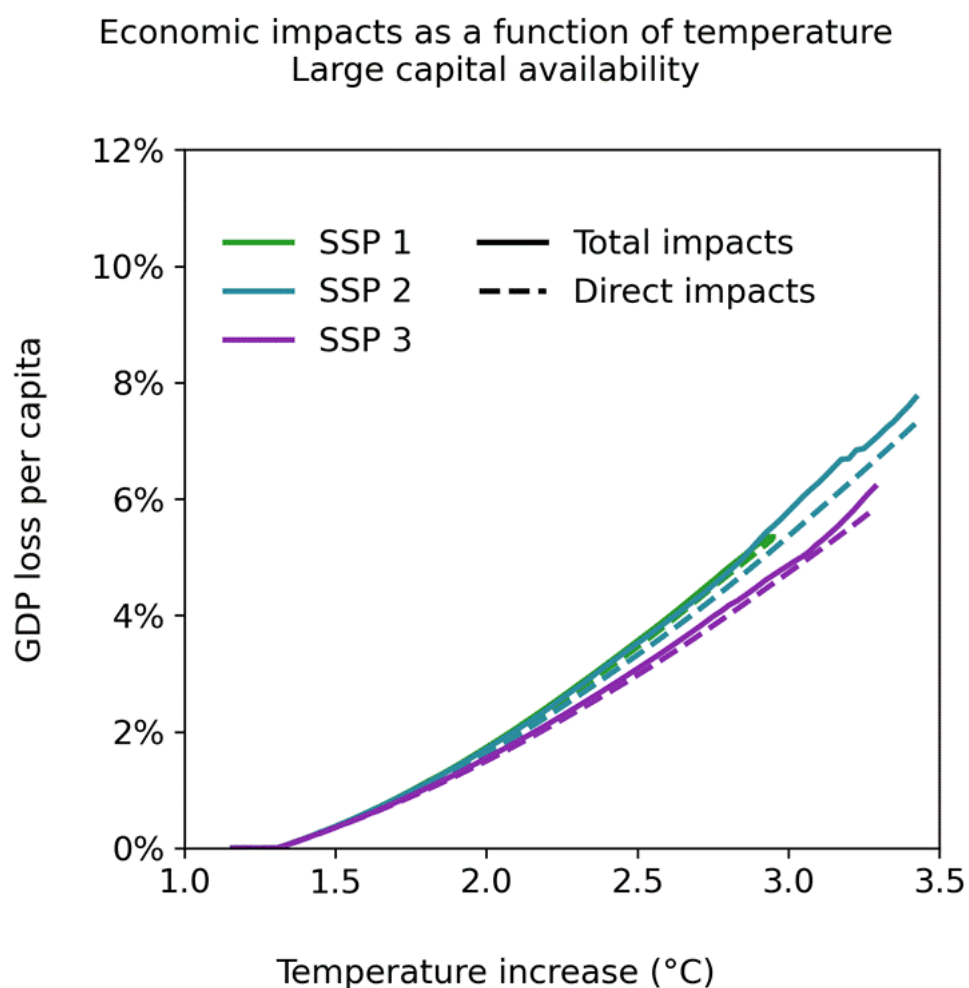




Supplementary figure F1. Sensitivity of the total and direct GDP losses in 2100 to scenario factors. Variations in total and direct losses are expressed as the difference, in percentage points, between the total and direct impacts (expressed in GDP percentages) across the SSP.



Supplementary figure F2. Net capital inflows in each region, expressed as a percentage of regional investment, for each SSP.



Supplementary figure F3. Large capital availability case: investments are multiplied by 10 at each timestep. Global economic impacts, expressed in GDP loss, as a function of global mean temperature increase.

Annex III to section 3.2.5: Comparing Economic Impacts of Net-Zero Transition with Climate Damage Uncertainties

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Comparing economic impacts of net-zero transition with climate damage uncertainties using a dual-model approach

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Abstract

This study conducts a scenario analysis of global net-zero emissions by 2050 using two macroeconomic models with distinct theoretical foundations: E3ME (non-equilibrium) and GEM-E3 (equilibrium). The analysis quantifies the economic impacts of increasing climate policy ambition to meet the global 1.5 °C warming target and highlights key differences between the models in projecting GDP, employment, and sectoral transitions. The findings indicate that while economic outcomes of decarbonization may vary depending on the model paradigm used, the uncertainties in climate damage projections far exceed those of mitigation costs. By comparing the economic impacts of mitigation with potential losses from climate damages, the study finds that the costs of mitigation are lower and more predictable than the potential climate damage costs. Limiting warming to 1.5 °C yields net economic gains in almost all countries examined, while a 3 °C trajectory could trigger widespread losses. The study reinforces the need for decisive and immediate global mitigation efforts.

1. Introduction

A shift in the discourse surrounding the trade-offs between transitional risks and climate damages is evident. Recent estimates of climate-related damages indicate a significant escalation in projected GDP impacts, even as early as 2050 (Bilal and Känzig 2024, Kotz *et al* 2024), especially if global emissions stay at current levels. Even in the medium-term throughout the next decades, economic losses attributable to climate-related damages are anticipated to be substantial, exceeding the costs associated with an early and orderly transition (Russel *et al* 2022). Over the longer horizon, by 2050 and beyond, physical risk losses are projected to reach their peak even under a net-zero emissions scenario, compatible with a temperature increase of well-below 2 °C, while escalating considerably in scenarios characterized by higher global emissions and temperature increases (NGFS 2024). At COP 28 in 2023, the first global stocktake under the Paris Agreement showed slow progress in scaling-up climate action, but countries agreed to accelerate efforts, urging a faster transition from fossil fuels to renewable energy by adopting specific targets for renewable capacity expansion and energy efficiency improvements by 2030 (UNFCCC 2023).

Researchers have used various methods to estimate economic losses from climate-related damages, with projections ranging from under 2% to over 40% of global GDP at 3 °C of warming (NGFS 2024). Key approaches include impact enumeration (Nordhaus 1994), surveys (Howard and Sylvan 2020), computable general-equilibrium (CGE) models (Kompas *et al* 2018), econometrics (Burke *et al* 2015, Kalkuhl and Wenz 2020, Kotz *et al* 2024), and meta-analyses of several studies (Nordhaus and Moffat 2017), each with unique strengths. Recent studies, such as Kalkuhl and Wenz (2020) and Kotz *et al* (2024), often use econometric

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methods like panel regressions to estimate the so-called damage functions. Damage functions vary widely in their coverage of impacts (e.g. temperature, precipitation, extreme weather events), assumptions about non-linear damage escalation, and whether climate shocks affect economic levels or growth rates, contributing to ongoing uncertainty in long-term projections.

To mitigate the risk of potentially severe economic and environmental losses associated with climate change, it is imperative for the global community to reduce greenhouse gas (GHG) emissions and transition toward a net-zero emissions trajectory. Net-zero pathway analysis supports ambitious emissions reduction targets by identifying specific actions, strategies, and interventions across various sectors (Fragkos *et al* 2020, DeAngelo *et al* 2021, Pollitt and Chyong 2021, Van Soest *et al* 2021, Dafnomilis *et al* 2023). This helps prioritize measures such as renewable energy adoption, energy efficiency improvements, transport electrification, and industrial decarbonization. By assessing the impacts, feasibility and trade-offs of net-zero pathways, stakeholders can make informed decisions about efficient and equitable pathways to net-zero emissions, fostering collaboration and consensus among governments, businesses, and civil society.

However, climate damages are rarely included in these analyses and therefore it is difficult to assess the trade-offs between transition risks and climate damages. Transition risks arise from the regulatory and structural changes in moving our economic and energy systems towards net-zero emissions; however, if global warming keeps increasing to more than 3 °C, it is likely that the world will face severe economic losses from the physical risks of climate change.

The wider macroeconomic impacts of net-zero pathways are commonly assessed using different approaches and models and developing alternative scenarios. Here, we use the E3ME (macroeconomic non-equilibrium model) and GEM-E3 (CGE equilibrium model) multi-sectoral macroeconomic models to cover a range of probable economic outcomes, as they are characterized by disparate theoretical underpinnings. The GEM-E3 equilibrium model assumes that the economies use their resources efficiently and are in a state of equilibrium (E3-Modelling 2017). Specific climate policy (e.g. a carbon price) is represented as an external shock to the economy, leading to some degree of crowding-out of investment from other productive sectors. On the other hand, a non-equilibrium model allows for the possibility of inefficient economic systems. E3ME is an example of this, following the post-Keynesian school of economics emphasizing the growth potential of additional investment instead of the crowding-out mechanism (Cambridge Econometrics 2022).

Fankhauser *et al* (2022) highlight the urgency of reaching a common academic agreement to equip policymakers with practical tools for mitigation. Stern *et al* (2022) argue that non-equilibrium models are better suited for long-term economic transformations and should be the primary tool for environmental economic impact assessment. However, most integrated assessment models (IAMs) like DICE (Nordhaus 1993), REMIND (Baumstark *et al* 2021), or MESSAGEix-GLOBIOM (Krey *et al* 2020) are equilibrium models. Mercure *et al* (2019) examined how the two model types differ in their scenario projections, highlighting patterns driven by fundamental differences in model assumptions and theoretical underpinnings. These differences stem from the envisioned process of how economic growth realizes in the economy but can also stem from distinct policy instruments for achieving net-zero emissions (Lynch *et al* 2024). We think that a dual-model approach gives us the opportunity to cover the range of most probable economic outcomes.

The paper contributes to existing literature in two ways. Firstly, by defining an innovative net-zero scenario where global emissions reach net-zero by 2050 and identifying the range of expected economic outcomes for policymaking using the dual-model approach. The second objective is to compare the expected costs and impacts of decarbonization with the economic benefits of avoiding potential climate damages that would result from inaction. We estimate the range of economic impacts from policies aimed at achieving net-zero emissions using global macroeconomic models based on different theoretical foundations. These results are then compared with estimates of climate damage costs drawn from the literature and calculated using a variety of methodological approaches. This unique comparison helps assess the uncertainties inherent in both sets of estimates and supports drawing conclusions based on multiple analysis approaches.

By adhering to an ambitious climate commitment that limits global temperature rise to 1.5 °C, the study shows that economic losses are considerably lower compared to scenarios with higher temperature increases. Under a high-emissions scenario, GDP losses due to climate change could reach 23% in some regions by 2050, with poorer countries suffering the most, whereas the net-zero scenario substantially lowers these risks. The study also highlights significant employment impacts, indicating that a net-zero transition could create numerous jobs in renewable energy sectors. Potential job losses in fossil fuel industries can be mitigated through targeted policies and retraining programs.

The results support the need for early and rapid climate action to avoid significant risks associated with climate damages of increasing temperatures, which outweigh those risks from the transition process. Additionally, comparing two modeling approaches provides policymakers with guidance on navigating



diverse economic impact assessments and understanding the overarching conclusions of the model-based study.

2. Climate damages

The economic impacts of decarbonization discussed in multiple studies (Fragkos 2020, DeAngelo *et al* 2021, Pollitt and Chyong 2021, Van Soest *et al* 2021, Dafnomilis *et al* 2023) pertain mostly to the transitional effects associated with achieving net-zero emissions. Nonetheless, we should note that by effectively limiting global warming and temperature increase, a significant reduction in the potential climate-related damages can be realized (IPCC 2023).

In recent years Climate research has concentrated on studying average temperature rises of 1.5 °C–2 °C (as specified in the Paris Agreement), which are viewed as an optimistic or even best-case scenario for the forthcoming years (Sharpe 2023). Consequently, a comprehensive examination of broader temperature escalations should consider scenarios with higher global temperature increases. Currently, temperature rises of 2.5 °C–3 °C are considered the most likely scenarios if current policies and trends continue by 2050 (IEA WEO 2024). Nevertheless, even less probable situations, such as temperature increases exceeding 4 °C in the longer term, should not be ruled out.

Burke *et al* (2015) establishes a key feature of damage functions that represent the feedback loops between emissions and economic development. The authors show that damage functions follow a highly non-linear pattern to temperature changes, which would result in 23% GDP losses in a high-emissions scenario relative to a scenario without climate change by 2100. Furthermore, even these estimates might underestimate the impacts if extreme outcomes, like significant sea level rise, occur at 2 °C or higher but not at 1.5 °C. Kotz *et al* (2024) find that the world economy will have to face a 11%–29% reduction in incomes even in a 2 °C warming scenario by 2100 relative to a baseline without climate impacts. Similarly, Bilal and Känzig (2024) estimate that the global macroeconomic damages resulting from rising temperatures would reduce global GDP by 12%. Burke *et al* (2018) suggest that limiting warming to 1.5 °C instead of 2 °C by the century's end not only reduces climate damages but also decreases global inequality, with poorer countries benefiting the most.

Keen (2021) has criticized economists' forecasts of climate change damages for being overly optimistic. Economists often underestimate damages due to assumptions that GDP remains unaffected, using current temperature-GDP relationships for future impacts, and diluting scientific warnings with optimistic expectations. Pindyck (2013) states that IAMs have flaws, including arbitrary input assumptions on discount rates and a lack of a consistent theory for capturing climate damages. Instead, they address the issue in an ad hoc manner. Correcting these errors suggests climate damages could be much worse. Lately, the 2023 temperature anomaly emerged unexpectedly, revealing a knowledge gap not seen since satellite data began offering real-time insights into Earth's climate system 40 years ago (Schmidt 2024). If the anomaly persists, it suggests global warming is altering the climate system sooner than expected casting doubt on past predictions for droughts and rainfall patterns.

3. Methodology

The E3ME and GEM-E3 models are widely used to assess the economic impacts of various policies, as well as their potential effects on the environment and society, aiming to develop sustainable development strategies (Fragkos *et al* 2023, Lynch *et al* 2024, Souffron and Jacques 2024). Both models are types of IAMs, with a particular emphasis on robust economic representation. Furthermore, both models are founded on Input–Output (IO) tables derived from the national accounts system. An IO-table consists of multiple sectors and captures the economic activity happening between those as well as the imports and exports by sector. Building on the initial information captured in the IO-tables, main macroeconomic indicators are derived, such as intermediate demand, consumption, capital formation, employment and compensation of employees, trade, etc. Both models capture the complex interlinkages between economy (based on the IO structure), energy system and environment, which are connected to the core economic representation through bottom–up representation of energy system dynamics (at the sector level, focusing on electricity supply, industries, transport and buildings) and emission calculations, the accumulation of which results in global warming. Recently, E3ME and GEM-E3, along with the IMAGE model, have been applied to assess the economic impacts on the Russian–Ukrainian war (Harmsen *et al* 2024). Furthermore, the two models have been utilized to examine the disparities and structural change that emerge within the economy through a net-zero transition (Lynch *et al* 2024).

While both models share similar fundamental principles, they differ significantly in how specific system elements are designed, leading to distinct modeling outcomes (see table 1). A key distinction is that GEM-E3



Table 1. Overview of the key macroeconomic model similarities and differences, data source: Mercure *et al* (2019).

	E3ME-FTT	GEM-E3
Model type	Macroeconometric (E3ME), hybrid with bottom-up evolutionary modules (FTT)	CGE model, hybrid with bottom-up modules
Macroeconomic theory branch	Non-equilibrium (Demand driven)	Equilibrium (Supply driven)
Technological change	Endogenous (power, road transport, domestic heat, and steel sectors)	Endogenous (power, road transport, heating)
Labor market representation	Imperfect and flexible labor markets	Imperfect and flexible labor markets, 5 skill levels are represented
Investment & Finance	No crowding out, no fixed limit on finance	Crowding-out and alternative financing options are available. Finance is constrained at the global level.
Sector coverage	43 (70 in the EU)	65
Regional coverage	71 countries and regions	46 countries and regions

is an equilibrium model, assuming that the economy remains in an optimal equilibrium in each scenario, whereas E3ME is a non-equilibrium model, acknowledging that the economy is not always in equilibrium (Mercure *et al* 2019).

Equilibrium models ensure a closed system approach that allows a consistent comparison across scenarios of different policy options and an explicit comprehension of system dynamics and long-term structural changes. While a new generation of hybrid equilibrium models, like GEM-E3, incorporate empirically estimated behaviors of markets, for example by featuring endogenous unemployment, decisions still comply optimization rules.

In terms of investment decisions and financing options, equilibrium models usually assume that all resources are fully utilized, meaning new investments or ventures displace existing activities and productive investment, leading to the so-called ‘crowding-out effect’. Conversely, non-equilibrium models consider the potential for more efficient resource allocation through money creation and investment without necessarily crowding out other activities (Pollitt and Mercure 2018). More recently, hybrid CGE models like GEM-E3, include different financing considerations, as described in Paroussos *et al* (2019), allowing for alternative financing options (e.g. bank behavior, risk premia, credit constraints) while always ensuring consistency of resource allocation and a globally constrained money supply. Still, differences in financial constraints can be considered as one of the main differences between the two models, as it is likely to lead to more pessimistic results in GEM-E3 (Souffron and Jacques 2024). However, crowding-out effects can diminish under favorable financing schemes even in equilibrium models, as demonstrated by Fragkos & Paroussos (2018), who show that when firms and households can borrow in capital markets without increasing unit funding costs, the GDP impacts of decarbonization for the EU are minimal or even positive in the short term.

This brings up one key aspect, which is the issue of money creation. In an equilibrium approach, supply of credit is a fixed amount, determined by central banks which is linked to real economic activities. On the other hand, in a non-equilibrium model there is potential for borrowing without limiting available resources of others (Lynch *et al* 2024). This leads to the conclusion that equilibrium models are supply-driven, whereas non-equilibrium models are demand-driven indicating the main driver of economic activity in the model.

Emissions abatement in the models is achieved through various options, including fuel substitution driven by carbon pricing, which raises the cost of fossil fuels and promotes the adoption of low-emission energy carriers and technologies; energy efficiency enhancements enabled by investments in advanced technologies and equipment; and production adjustments prompted by climate-related constraints, leading to reduced demand and emissions for carbon-intensive goods. Furthermore, climate policies incentivizing emissions abatement can be implemented through various mechanisms in both models, including:

- **Carbon taxes:** Exogenously (in E3ME) or endogenously (in GEM-E3) set to meet emission reduction targets.
- **Emission caps:** With the tax level endogenously determined to clear demand and supply for emission permits.
- **Market-based instruments:** Such as emissions trading systems (ETS) and subsidies for clean technologies.
- **Regulatory instruments:** Including energy efficiency standards, renewable energy targets, CO₂ standards for vehicles, and phase-out policies for high-emission technologies.
- **Trade-related policies:** Like the Carbon Border Adjustment Mechanism and industrial tariff adjustments to mitigate competitiveness impacts on trade-exposed sectors.



3.1. E3ME model

The E3ME model is a tool designed to analyze the interactions between the economy, energy systems, and the environment (Cambridge Econometrics 2022). Its primary purpose is to provide a quantitative framework for evaluating the effects of energy-environment-economy (E3) policies. E3ME is employed to assess a broad spectrum of policies, including taxation strategies, climate regulations, labor market reforms, and technological support measures such as initiatives for electric vehicles (EVs). It enables policymakers to understand the economic, environmental, and social implications of these policies.

E3ME examines energy consumption, emissions, and material use, incorporating technology-focused Future Technology Transformations (FTT) models in key sectors like energy (Mercure 2012) and transport (Mercure *et al* 2018). The FTT models are bottom-up simulation tools that analyze technology adoption and diffusion across key sectors. These models capture competition between technologies, influenced by factors like costs, policies, and market dynamics, to project transitions toward low-carbon technologies and assess their environmental and economic impacts (Mercure 2012). This integration aids in evaluating how technological advancements and policy interventions can shape environmental outcomes.

Rooted in the Cambridge (UK) tradition of macroeconomics and post-Keynesian economic thought (Eichner *et al* 1975), the E3ME model draws inspiration from John Maynard Keynes' work in *The General Theory* (Keynes 1936). The model's theoretical foundation relies on econometric techniques, offering a robust framework for simulating policy impacts. It captures the intricate interactions between economic sectors and environmental factors, providing a dynamic and detailed method for policy analysis. This econometric approach enables the estimation of how policies influence economic behavior and outcomes over time.

E3ME has been applied to analyze the economic, social, and environmental effects of Covid-19 recovery plans, helping policymakers craft measures that support immediate recovery while aligning with long-term sustainability objectives (Pollitt *et al* 2021). It has been used to evaluate the energy security and economic impacts of the war in Ukraine, which began in 2022 (Hartvig *et al* 2024). In addition, E3ME has explored the trade-offs between different pathways for reducing transport and heating emissions in Europe (Stenning *et al* 2021).

3.2. GEM-E3 model

The GEM-E3 model is a multi-sectoral, recursive dynamic CGE model representing 46 regions (including all EU countries) and 65 sectors/economic activities interconnected through bilateral trade (E3-Modelling 2017). It provides a detailed representation of the global economy, capturing the interplay between production, consumption, prices, trade, investment, capital and labor dynamics. By incorporating market-derived prices, the model evaluates the socioeconomic and distributional effects of various types of policies (including energy, climate, labor or tax policies) while maintaining general equilibrium in all scenarios simulated.

GEM-E3 employs a bottom-up approach for the electricity sector, where the GEM-E3-Power module (Polzin *et al* 2021) optimizes electricity investment and operation costs under constraints such as technology potential, resource availability, and policies like ETS prices and phase-out measures. The model also represents the transformation of the transport sector, simulating passenger and freight transport choices, public and private modes and technologies, including internal combustion engines, plug-in hybrids, and battery EVs (Karkatsoulis *et al* 2017).

The model incorporates low-carbon equipment manufacturing as distinct production sectors, linking clean innovation and decarbonization with the potential for green growth and industrial competitiveness. It consistently evaluates the effects of climate policies on economic growth, employment, income distribution, and welfare, considering social and distributional impacts across countries and income groups (Fragkos *et al* 2021). Additionally, GEM-E3 analyses the complex interactions between labor market, industrial policies, and decarbonization measures, providing insights into how climate policies can balance economic growth and environmental sustainability while ensuring a just transition.

4. Scenario design

Scenario analysis within an IAM model aims to explore future outcomes by simulating the environmental and socioeconomic impacts of climate policies. Initialized with current data and assumptions about key drivers like population growth, economic trends, climate and energy policies, and technology trends, the models provide a detailed set of results on the impact of alternative scenarios with different levels of climate ambition. Comparing scenario results across multiple indicators like GDP, employment and carbon emissions helps policymakers understand the impacts and trade-offs of different strategies, informing the design of robust policies to effectively address climate change while ensuring a just and sustainable transition.



Identifying the baseline scenario is crucial in the current modeling process as it determines the impact of net-zero scenarios by analyzing projected deviations from the baseline. The 'Current Policies' scenario simulates the continuation of historical trends and existing national climate policies, excluding unlegislated pledges like net-zero commitments. The scenario assumes that current climate policies will extend beyond their expiration around 2030, with carbon pricing extrapolated using the GDP growth rates from 2030 to 2050, maintaining 2030 levels of climate ambition in each country. The global average temperature rise in the Current Policies scenario is around 3 °C.

In the 'Net-zero' scenario, a global carbon price is introduced after 2025 progressively increasing to 2050, affecting all sectors aiming to ensure a cost-efficient global transition towards net-zero emissions by 2050. The scenario includes additional ambitious climate policies including energy taxes, biofuel mandates, investments in clean technologies, and CO₂ standards and regulations on vehicles and boilers. The scenario also integrates major climate policies like the European Green Deal 2021 (European Commission 2020) and the U.S. Inflation Reduction Act (Dennis 2022).

Further policy measures in the net-zero scenario include caps on new fossil fuel capacities, a phase-out of unabated coal power by 2050, and afforestation investments. Biofuel blending rates are set to reach 100% by 2050, and substantial subsidies are used to support decarbonizing industrial processes through electricity, hydrogen, and CCS technologies. These coordinated efforts aim to significantly reduce emissions and achieve the average temperature rise of 1.5 °C, while transitioning to a sustainable, low-carbon future. More detailed description of the scenario design is provided in appendix A.

5. Results

We analyze the net-zero scenario versus the Current Policies scenario using two E3 models, focusing on nine major economies to evaluate the potentially diverse socioeconomic impacts. Leading global GHG emitters are China, the USA, India, and the EU.

5.1. Reaching net-zero emissions

In the Current Policies scenario, global emissions remain high, especially in developing economies like India, driven by economic growth and rising living standards. However, in case of committing to the global net-zero scenario, these high emitting countries also achieve significant emission reductions to reach global net-zero targets (figure 1).

The net-zero scenario achieves global net-zero CO₂ emissions by 2050, with large emissions reductions achieved already by 2035 to meet the Paris Agreement's 1.5 °C goal. Mitigation efforts can vary by region, with some regions achieving net-negative emissions by 2050 to offset residual emissions elsewhere. Brazil, for example, achieves negative emissions through afforestation and bioenergy with carbon capture and storage, while India continues to use fossil fuels to meet its increasing energy needs (UNFCCC 2015). Appendix B provides a brief discussion of primary energy demand in both models and scenarios.

5.2. Socioeconomic impacts of net-zero

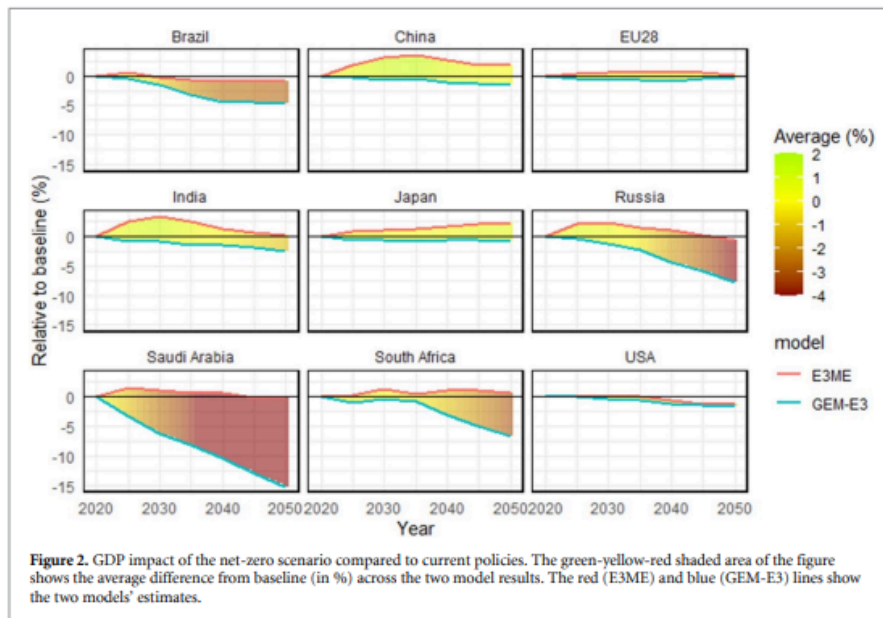
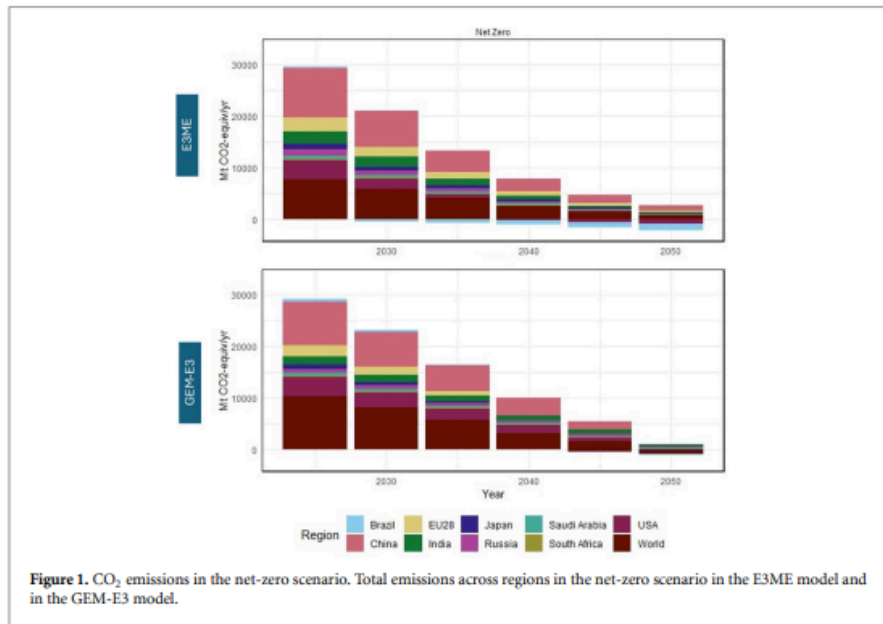
A key feature of both models is their ability to estimate the socioeconomic impacts of decarbonization endogenously. While results vary due to differences in model design and assumptions (as described above), certain trends can be identified. The short- and long-term outcomes depend on how climate policies are integrated into economic systems. GEM-E3 projects an initial economic slowdown due to higher clean energy costs compared to the Current Policies scenario, followed by reduced economic activity by 2050, largely driven by the crowding-out effects of decarbonization investment, reducing the productive investment in other activities. In contrast, E3ME anticipates short-term growth driven by investment stimulus given its money creation assumption, followed by a period of slowdown during debt repayment, before stabilizing in the long run.

Economic development can be analyzed through GDP trends, which reflect the overall economic activity growth, while social impacts can be captured by sectoral employment shifts across countries and sectors.

GDP impacts vary across countries, with some benefiting from the net-zero transition while others face severe economic challenges, as shown in figure 2. The extent of these impacts depends on factors such as their energy costs, policy frameworks, and economic integration, while the regional economic impacts are massively influenced by the country's role in fossil fuel trade (importer/exporter) and by its carbon intensity, as shown in Lynch *et al* (2024).

Developed economies such as the EU, the USA, and Japan, which already have established climate policies and lower carbon intensity, generally experience more moderate economic impacts. In contrast, fossil fuel-exporting countries face greater uncertainty, with projections indicating lower GDP in the net-zero scenario by 2050, particularly for Brazil, Russia, and Saudi Arabia.





China, India and Japan exhibit the most favorable economic effects of the net-zero scenario, either showing the highest positive GDP impacts (E3ME) or the least negative effects (GEM-E3). China's proactive investment in reducing coal dependency and expanding renewable energy infrastructure plays a key role in this trend. E3ME projects a 3% GDP increase by 2035, stabilizing at 1.7% in 2050, while GEM-E3 anticipates a slight decline of economic activity, offset by higher exports of clean energy technologies such as solar PV, batteries, and EVs.



Unlike the EU, the USA faces small relative GDP losses according to both models due to its extensive shale oil industry that is hit by ambitious climate regulations. E3ME and GEM-E3 indicate a limited reduction in country's GDP as strict assumptions on oil phase-out affect the USA's oil export reliance. Europe, leading in climate action with the European Green Deal, shows initial GDP growth as a result of reduced fossil fuel imports. E3ME estimates a 0.7% increase in 2030, decreasing to 0.3% by 2050 due to debt repayment. GEM-E3 shows limited economic decline due to Europe's benefits from reduced fossil fuel imports and higher low-carbon technology export revenues.

Oil-exporting countries face the highest GDP risks, with Saudi Arabia experiencing significant economic impacts. E3ME shows Saudi Arabia's GDP growth of 1%–2% from its relative efficient oil production, though this falls short of baseline projections after 2040. GEM-E3 projects a large GDP reduction of more than 10% from the Current Policies scenario by 2050 due to reduced fossil fuel export revenues (more details on trade impacts are shown in appendix B). Research indicates petrostates will lose over half their expected oil and gas revenues in the context of energy transition, assuming deep decarbonization towards global net-zero, unless they are efficient producers like Saudi Arabia (Prince 2023). Zubair *et al* (2019), Zubair and Awan (2021) show the growth potential of developing solar energy industries through targeted investment in Saudi Arabia, which could be utilized to counterbalance the negative impact of net-zero scenario.

In summary, the model-based analysis indicates that certain countries benefit more than others from the energy transition assumed in the net-zero scenario. China, India, and Japan emerge as winners, showcasing favorable economic trajectories due to investments in renewable energy. In contrast, the USA faces relative GDP losses attributed to its shale oil industry, though existing climate policies mitigate the impact. According to both models, Europe experiences a marginal GDP impact. Oil-exporting countries, especially Saudi Arabia, face significant GDP risks, with substantial losses predicted from reduced fossil fuel export revenues.

Employment trends mirror GDP impacts, closely tied to economic output (see figure 3). Besides overall economic performance, sector-level employment impacts offer insights into the transformative impact of a net-zero scenario. Firstly, the overall trend of transitioning away from fossil fuel sectors to renewable energy sources and green electricity is evident. In addition to the energy-related sectors, the net-zero transition would have massive impacts also on other production sectors like manufacturing, services and agriculture which are indirectly impacted by decarbonization through supply chain effects captured appropriately by the macroeconomic models.

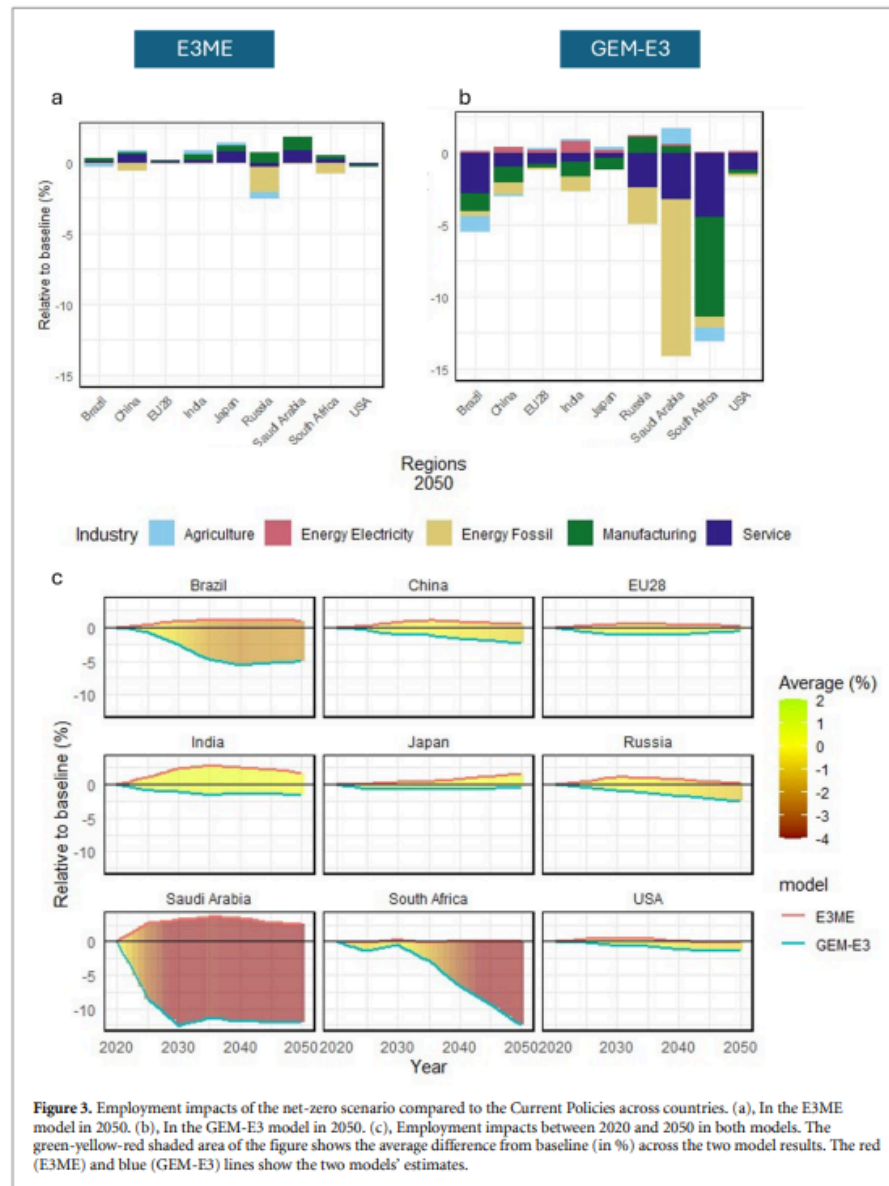
In E3ME, regions like China, India, and Japan expect employment growth due to higher economic activity, mainly in services and manufacturing sectors, starting before 2030 and remaining stable until 2050. In both models, Fossil energy sector jobs decrease due to reduced demand for fossil fuels. Conversely, the electricity sector sees job growth due to increased activity as electrification of heating, industrial and transport uses is a prominent strategy to achieve large emissions reductions towards net-zero (van Heerden *et al* 2025). Job losses in fossil fuel sectors and gains in the electricity sector are common across models, which however differ in their projections for employment impacts in the services sector that are largely driven by their GDP estimates (more negative in GEM-E3, positive for E3ME).

The mechanism explaining why the services sector has a high employment growth within E3ME results is that households spend less on energy products because of improved energy efficiency. The additional share of household income that is saved by lower energy spending is used for consumption across other sectors of the economy, which is mainly directed to spending in the services sector in E3ME. Besides increased consumption/production of the services sector, the remaining share of the energy savings is spent on increased production, thereby resulting in a secondary investment effect of the net-zero policies. Countries with high possible job impacts in E3ME, such as China, India and Japan, have the smallest employment fall in the GEM-E3 results, suggesting lower effects of displacing other activities. In sectoral terms, GEM-E3 shows that the services sector is negatively impacted by decarbonization due to supply chain indirect effects of the net-zero transition that are largely driven by the overall decline in GDP; however, in absolute numbers, job losses projected in the sector are significant as more than 50% of the global workforce is in the services sector. Job losses are also projected in industries driven by the reduced demand for carbon-intensive industrial products by consumers and firms coupled with a relocation of industrial activity across countries via trade.

Saudi Arabia shows varied results, with E3ME predicting a 2%–3% employment increase from service and manufacturing job growth, especially in solar power. However, GEM-E3 indicates significant job losses due to reduced fossil fuel revenue.

The US and Europe show moderate employment growth in E3ME, less than 1% higher than Current Policies by 2050. GEM-E3 shows slightly lower employment, aligning with its economic growth projections but in the opposite direction.





6. Comparison of economic impacts and climate damages

The estimated economic impacts presented in the previous chapter are based on a net-zero scenario, which keeps global average temperature increase at 1.5 °C by the end of the century compared to pre-industrial levels (Kikstra *et al* 2022). In contrast, the Current Policies scenario is projected to result in an approximate 3 °C average temperature increase by 2100. The economic, energy and emission trajectories of the baseline are in line with IEA (2024), which determine temperature outcomes. The macroeconomic impacts of the net-zero scenario represent the mitigation costs associated with implementing ambitious climate action measures. In this chapter, we compare these costs and benefits of mitigation with the cost of climate inaction. The models—in their current form—are unable to estimate this, therefore we rely on a comprehensive review of climate cost estimates.



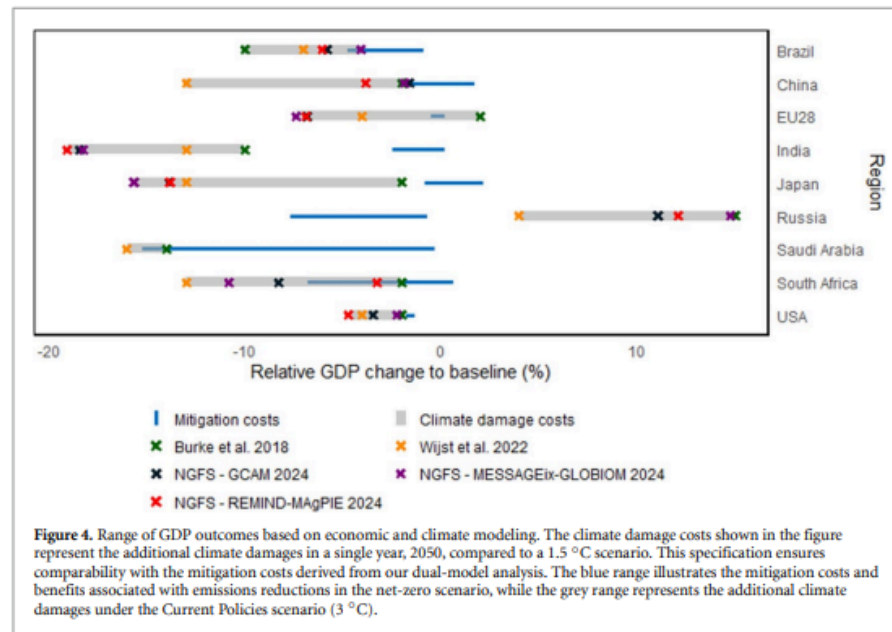


Figure 4. Range of GDP outcomes based on economic and climate modeling. The climate damage costs shown in the figure represent the additional climate damages in a single year, 2050, compared to a 1.5 °C scenario. This specification ensures comparability with the mitigation costs derived from our dual-model analysis. The blue range illustrates the mitigation costs and benefits associated with emissions reductions in the net-zero scenario, while the grey range represents the additional climate damages under the Current Policies scenario (3 °C).

Figure 4 presents a regional breakdown of the estimated economic impacts of climate change in 2050. Relative GDP change in percentage terms is shown on the x-axis for each region/country included in the analysis. The blue range shows the potential range of GDP impacts of mitigation that stem from the model-based results of a global net-zero scenario (presented in section 5.2). This uncertainty range of economic analysis is derived from the maximum and minimum GDP impacts of the presented dual-modal analysis for year 2050.

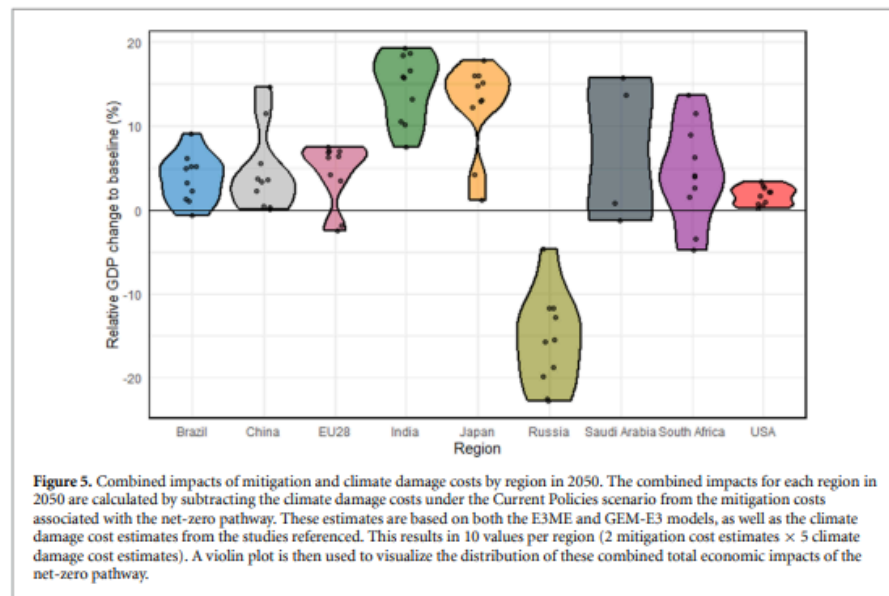
Given the limited availability of climate damage estimates for years beyond 2050, typically restricted to 2050 and 2100, and the E3ME model results extending only to 2050, our analysis necessarily focuses only on 2050. A review of the climate damage literature reveals consistent evidence that the costs of climate damages are expected to increase over time, largely irrespective of the level of climate action. This finding is further supported by recent NGFS short-term scenarios (NGFS 2025), which indicate substantial climate-related damages even in the near term. These short-term impacts stem from extreme regional weather events, such as droughts, floods, and storms, that lead to significant GDP losses and financial stress, with global repercussions through trade and financial linkages. Over the longer-term, climate damages are expected to intensify considerably. Bilal and Känzig (2024) and Kotz *et al* (2024) estimate global GDP losses of 19% and 14%, respectively, by 2050, increasing to 44% and 33% by 2100.

Furthermore, the figure shows point estimates of damage costs in the same year. The grey ranges, representing point estimates of climate damage costs under a 3 °C global warming scenario compared to a 1.5 °C global warming scenario, illustrate the potential variability in climate-related costs resulting from inaction. These costs reflect the estimated impacts of rising temperatures on regional GDP, based on the empirical methods employed in the referenced studies. The ranges presented are not intended to encompass a comprehensive meta-analysis of the climate damages literature but rather to illustrate comprehensive, scientifically robust, peer-reviewed and recent estimates of damages to reflect the potential costs of climate inaction.

The costs associated with lower climate ambition, as estimated using different climate damage functions, cover a much larger range than the mitigation costs derived from the dual-model analysis of the net-zero scenario in all regions. This indicates the much higher uncertainty of the potential economic damages from climate change compared to the potential economic impacts of a transition towards global net-zero.

However, the greater variability in damage cost estimates may, in part, be attributable to the broader and methodologically more diverse estimates on damage costs, in contrast to the mitigation cost estimates considered in this paper, which are derived from only two models.





A comparison with existing literature can provide context for the relative magnitudes of mitigation costs and climate damage costs. van de Ven *et al* (2025) report in the IPCC AR6 scenarios that mitigation costs are projected to be between 2%–4% of total GDP by 2050 which shows that the uncertainty surrounding these estimates is comparatively lower.

Our results fall at the lower end of the IPCC range, due to key mechanisms in our models differing from those in existing literature. van de Ven *et al* (2025) mainly use CGE models, which tend to predict more negative economic impacts than macroeconomic models like E3ME. Within CGE models, GEM-E3 (used here) incorporates endogenous technology learning, lowering clean technology and thus mitigation costs compared to other CGE models.

Besides the larger uncertainty in estimating climate damage costs, the current analysis indicates a higher average economic cost of climate damages compared to the estimated mitigation costs of the net-zero pathway in all countries except for Russia.

Wijst *et al* (2023) present relatively high GDP impact estimates from climate damages in multiple regions, such as China and South Africa compared to other studies. However, the MESSAGEix-GLOBIOM estimates indicate more severe economic losses for the EU and Japan, demonstrating that climate damages can be significant even in highly developed economies. The most negative outcome is projected for India, where its GDP could decline by (Burke *et al* 2015) nearly 20% by 2050 under a high-emissions scenario compared to estimates excluding climate change impacts. Similarly, Japan and Saudi Arabia are expected to experience GDP losses of 15%–16%.

On the other hand, some regions may see economic benefits from rising global temperatures. According to Burke *et al* (2018) and the NGFS scenarios (2024), Russia is projected to achieve a GDP increase of more than 10%, primarily due to the potential expansion of arable land in previously frozen regions. Canada may also experience similar effects. However, other studies on climate inaction costs estimate more moderate economic outcomes, reflecting differences in methodological and modeling approaches.

Figure 5 demonstrates the combined effects of mitigation costs and avoided climate damages in the net-zero scenario in comparison to the Current Policies scenario. When considering the avoided climate damages, most regions exhibit a positive impact across almost all estimated damages and mitigation costs. Specifically, some regions such as India and Japan may achieve close to 20% higher GDP, while the majority of regions experience GDP impact between 0%–15% compared to the baseline. Russia is an exception, as climatic changes are estimated to have a positive GDP impact, suggesting that higher average temperatures boost economic output. As a result, Russia appears on the negative side of the plot when avoided climate damages are considered.

These results highlight two key findings of the research. First, the range of uncertainty for the cost of avoided climate damages is significantly larger than that of the potential mitigation costs associated with an



orderly and early net-zero transition. Second, a comprehensive assessment of the net-zero transition must consider both mitigation costs and avoided climate damages. When accounting for the climate damages that would have occurred under a baseline scenario, the net-zero transition is expected to have a positive impact on GDP across most countries.

7. Conclusions

This study underscores the intricate relationship between economic growth, climate change, and policy responses. It highlights that immediate and ambitious climate action has a lower -and much less uncertain—cost compared to the pathway resulting from the current policies for all major economies analyzed (except for Russia). Various damage functions reveal potentially severe climate change damages in case of increasing global warming.

Ultimately, the dual-model analysis employed in this study highlights the varied economic impacts contingent on country-specific characteristics and model assumptions. To encompass the possible economic effects of the transition towards net-zero, both an equilibrium model (GEM-E3) and a non-equilibrium model (E3ME) have been utilized. For developed countries, the net-zero scenario suggests moderate socioeconomic impacts, whereas fossil fuel-exporting and developing nations would face a broader range of negative outcomes.

The economic impacts of climate damages across regions and models show significant discrepancies in the literature. For example, Saudi Arabia and India could face very high GDP losses of up to 50% and 37%, respectively, while Russia and Canada might see economic benefits under certain warming scenarios. Critiques highlight the optimism in economic forecasts of climate impacts, often neglecting future risks and the non-linear nature of climate damages. The accelerated pace of climate change further complicates predictability.

Comparing the economic impact of climate damages with the mitigation costs of committing to ambitious climate action indicates an economic advantage for the net-zero pathway. In contrast, failure to mitigate climate change results in significant negative socioeconomic and environmental consequences.

Limiting global warming to 1.5 °C could result in net global economic benefits, whereas a 3 °C increase—if current trends and policies do not intensify—could massively reduce GDP in most countries globally.

Global cooperation for climate action combined with tailored and ambitious policies in specific countries are essential for supporting the transition to net-zero emissions, especially for vulnerable economies. Immediate climate action, guided by comprehensive research and scenario analyses, is necessary to mitigate the very high climate damage risks and future economic losses and ensure sustainable development and a just transition.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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The Net Zero scenario modelled in E3ME is based on the ClimateMAPS Net-Zero scenario, developed by Cambridge Econometrics in co-operation with Ortec Finance.

Declaration of generative AI in scientific writing



During the preparation of this work the authors used Copilot and ChatGPT in order to improve readability. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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