Economic implications of climate overshoot

Global consequences of climate overshoot pathways: Annex 3

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CS-NOW

Climate services for a net zero resilient world

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Key messages from this report

1. Overshooting 1.5 °C is likely to have adverse global economic consequences

Overshooting is likely to have much higher overall global costs than keeping the global temperature below 1.5 °C. The increase in climate damage and adaptation action costs and the loss of mitigation co-benefits are both likely to be higher than the change in mitigation action costs. Scenarios in which overshooting is lower cost, which assume very low damage costs, no co-benefits and a high future discount rate, are highly unlikely.

2. All regions of the world could benefit economically from earlier decarbonisation

Taking the necessary actions to avoid overshooting could lead to higher global economic growth over the period 2020–2050 as a result of earlier investment in increased energy and material efficiencies that have positive long-term benefits for economies across the world.

3. Damage costs are highly uncertain

Damage costs based on observed weather changes as the climate has warmed are far higher than previously projected using models. Moreover, even observed damages could underestimate the substantial damages caused by some earth system tipping points.

About this report

The “Global consequences of climate overshoot pathways” study has examined the natural and human system consequences of the world overshooting 1.5 °C, but then using carbon dioxide removal technologies to return the global temperature to 1.5 °C by 2100.

The final report summarises the findings from the study. Six annexes present the technical evidence that underpin the final report:

- Annex 1: Development of overshoot pathways.
- Annex 2: The feasibility of deploying CDR at the rate required for overshoot pathways.
- Annex 3: Economic implications of climate overshoot.
- Annex 4: Hysteresis and tipping points analysis using the UK Earth System Model.
- Annex 5: Natural system impacts of overshoot pathways.
- Annex 6: Human system impacts of overshoot pathways.

Around 40 scientists have contributed to these annexes and more than 900 literature sources are cited.

This annex, Annex 3, presents technical evidence from the analysis of the economic implications of overshoot. It builds on the pathway development in Annex 1 and the CO_2 removal feasibility in Annex 2, and contributes to the analysis of energy system impacts in Annex 6.

About CS-N0W

Commissioned by the UK Department for Energy Security & Net Zero (DESNZ), Climate Services for a Net Zero Resilient World (CS-N0W) is a 4-year, £5 million research programme, that uses the latest scientific knowledge to inform UK climate policy and help us meet our global decarbonisation and resilience ambitions.

CS-N0W enhances the scientific understanding of climate impacts, decarbonisation and climate action, and improves accessibility to the UK's climate data. It contributes to evidence-based climate policy in the UK and internationally, and strengthens the climate resilience of UK infrastructure, housing and communities.

The programme is delivered by a consortium of world leading research institutions from across the UK, on behalf of DESNZ. The CS-N0W consortium is led by Ricardo and includes research **partners Tyndall Centre for Climate Change Research**, including the Universities of East Anglia (UEA), Manchester (UoM) and Newcastle (NU); institutes supported by the **Natural Environment Research Council (NERC)**, including the British Antarctic Survey (BAS), British Geological Survey (BGS), National Centre for Atmospheric Science (NCAS), National Centre for Earth Observation (NCEO), National Oceanography Centre (NOC), Plymouth Marine Laboratory (PML) and UK Centre for Ecology & Hydrology (UKCEH); and **University College London (UCL)**.

Contents

List of Figures

List of Tables

Acronyms

AR5	IPCC's Fifth Assessment Report (2013-2014)
AR6	IPCC's Sixth Assessment Report (2021-2022)
CCC	Committee on Climate Change
CDR	Carbon Dioxide Removal
CGE	Computable General Equilibrium
DESNZ	Department for Energy Security and Net Zero
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GWP	Global Warming Potential
HMG	His Majesty's Government
HO	"High Overshoot" pathway
IAM	Integrated assessment models
IPCC	Intergovernmental Panel on Climate Change
LO	"Low Overshoot" pathway
NDC	Nationally Determined Contribution (emission reduction)
NO	"No Overshoot" pathway
PgC	Petagrams of carbon
RCP	Representative Concentration Pathway
SDG	Sustainable Development Goal
SLCP	Short-lived Climate Pollutant
SSP	Shared Socioeconomic Pathway
TFP	Total Factor Productivity
VHO	"Very High Overshoot" pathway

Executive Summary

Climate change benefit-cost analyses underpin the development of effective and proportionate climate polices. Many studies have focused on mitigation costs for energy systems, with some also examining the impact of mitigation actions on the wider economy. The negative impacts found by many (but not all) of these studies have been used to argue for slowing or not undertaking mitigation actions. But a more appropriate approach, taken by other studies, is a benefit-cost analysis that compares mitigation costs with the costs of any adaptation actions to reduce those climate change damages and the costs of (residual) damages. This approach accounts for the costs of climate change caused by not taking mitigation actions. Such benefit-cost analyses could be further improved by adding co-benefits of mitigation, such as improved health from better air quality and diet, but few studies have attempted this to date as co-benefits are difficult to monetise.

This annex presents a benefit-cost comparison of the three overshoot pathways developed in this project, in which the global surface average temperature rises to between 1.6 °C and 1.9 °C mid-century before being returned to 1.5 °C by the year 2100, against the counterfactual "No Overshoot" pathway in which this temperature does not exceed 1.5 °C. We include damage costs and co-benefits in our benefit-cost analysis.

Economic damage from climate change is substantial but with uncertain magnitude

Estimates of future climate change damages vary widely. At least part of the variation stems from the methods used. Future projections of damages based on econometric analyses of the impact of climate change to date are substantially higher than projections from detailed sectoral models that have traditionally been used.

Integrated Assessment Models (IAMs) are used to assess the impacts of climate change. IAMs link the economic system and the climate system into a unified framework. Many IAMs have emerged with differences in regional settings, climate factors, damage coverage categories, and consequently damages attributable to climate change. For a temperature increase of 1.5 °C to 2 °C, projected damages from the most used IAMs (DICE, PAGE, and FUND) range from about -1% to +1% of GDP. Varying damage functions, which are core equations in IAMs that link temperatures with economic losses, appear to be the most likely cause of these differences between models.

Computable General Equilibrium (CGE) models can estimate the overall economic costs of several climate change impacts and their wider economic implications. Estimates of climate change costs generally rise as global temperature increases. The wide variation in estimates in the literature is at least partly caused by variations in the coverage of impacts and the scope of each model (geographic; sectoral; period).

More recently, empirical studies have provided impact evaluations of climate change from various perspectives. There is consensus in the literature that climate change adversely affects the whole economic system, in terms of aggregate economic output, agriculture, industrial output, and services output. Agriculture experiences large losses as productivity is directly affected by weather. Moreover, industry and service sectors are negatively affected by climate change through reductions in labour productivity. Climate change also has negative effects on health and mortality.

Impacts on low-income countries are projected to be much higher than on high-income countries. Projections of the long-term impact of climate change on GDP vary widely. The lowest are close to projections from IAMS (e.g. 1%–3% reduction). Yet several studies project GDP reductions in 2100 in an RCP8.5 scenario of 7%–23%, and 60% in one study. Projected impacts are higher for studies than consider changes in extreme weather and that assume that GDP losses will compound over time. All of the studies make conservative assumptions in some ways, and none examine all climate change impacts (e.g. sea-level rise tends to not be considered), so losses could be higher than projected.

There are three predominant reasons for the differences in damage cost projections between these methods. First, empirical methods identify ex-post impacts of climate change based on observational data, while modelling studies estimate future climate change damages using climate and economic projections. Second, empirical studies usually only capture direct climate change impacts and assume the relationship between climate and the economy can be extrapolated to future losses. On the other hand, structural economic models can capture indirect impacts of climate impacts and allow dynamic interactions between sectors. Finally, there is no consensus about the future importance of adaptation in empirical studies, and few modelling studies consider adaptation thoroughly.

As most empirical studies project greater economic impacts than assumed in IAMs, it is possible that damages have been underestimated, possibly by a substantial amount, in benefit-cost analyses produced by previous IAM studies. This would lead to the benefits of taking mitigation actions being underestimated. Yet the wide range of damage cost variations from empirical methods highlights the high uncertainty in climate change damage costs. For this reason, we examine two levels of damage costs in this study, based on IAM and empirical studies.

Benefit-cost analysis of overshooting 1.5 °C

We carried out a benefit-cost analysis of the implications of overshooting 1.5 °C that accounted for mitigation costs, climate change damage costs and co-benefits. Energy system mitigation costs were projected using the TIAM-UCL integrated assessment model. Given the wide variation in projected damage costs from different sources described above, we examined two damage cost scenarios for each overshoot pathway. One had low damage costs from an IAM ("PAGE09" – around 3% loss of GDP in 2100 for RCP8.5) and the other had relatively high projected economic damages from an empirical study ("Burke" – around 23% loss of GDP in 2100 for RCP8.5), so we examined both ends of the range from the literature. Both scenarios were implemented in the PAGE model and the costs and benefits of adaptation actions to reduce damages were separately assessed for each scenario. However, our confidence in the representation of adaptation in PAGE is low due to the simplistic representation of damages and old assumptions.

Burke estimates reduce over time for all of our pathways as many high-latitude countries are assumed to benefit slightly from a small increase in the global mean temperature. But the reduction is smaller for overshoot pathways so overshooting is projected to cause higher damage costs. This finding is consistent with a more recent paper by the same author, which concludes that limiting the global temperature rise to 1.5 °C would have around a 70% chance of net economic benefits compared to a 2 °C rise, with the benefits mostly realised in the Global South. It is not clear whether the convex Burke function would change shape to give higher future damages if changes in extreme weather were accounted for. Hence there are considerable uncertainties over the Burke scenario insights.

Finally, we incorporated co-benefits from improved air quality, improved diet and greater active travel into the analysis. These have not generally been included in previous benefit-cost analyses of mitigation actions. As co-benefits are difficult to assess and have high uncertainty, we considered scenarios both with and without these co-benefits.

The choice of the future global discount rate (the extent to which we believe future benefits and costs are less important than those today) is an ethical judgement that has been a key parameter affecting previous benefit-cost analyses. It is important because a low discount rate gives future damages and mitigation actions a much greater weight compared to mitigation investments today than a high discount rate. Overshoot pathways have delayed mitigation actions then require higher carbon dioxide removal (CDR) later in the century, and so have lower relative mitigation costs at higher discount rates. For this reason, our benefit-cost analysis considered a range of future discount rates.

Energy system costs from the TIAM-UCL integrated assessment model for each pathway were much larger than damage costs or co-benefits, at least from the year 2050. However, Figure ES1 shows that the *differences* in energy system costs between pathways, which are the variations in mitigation costs between pathways, were small compared to the differences in Burke damage costs and the differences in co-benefits between pathways. The “No Overshoot” pathway had the lowest mitigation cost if the future was not discounted because CDR costs were lower than for overshoot pathways. Overshoot pathway mitigation costs became cheaper than for the “No Overshoot” pathway when the discount rate was increased because the present value of overshoot pathways have lower near-term mitigation costs. As all four pathways do not exceed warming of 1.5 °C in 2100, they all have substantial mitigation costs compared to pathways with substantial climate change (but much lower damage costs).

Combining the mitigation action costs with damage costs and loss of co-benefits suggests that overshooting would have higher costs than the “No Overshoot” pathway for a range of discount rates, so the benefit-cost analysis is negative in each case in Figure ES1. For overshooting to be lower cost, it would be necessary to assume very low damage costs

(PAGE rather than Burke), no co-benefits, and a future discount rate of at least 3%. In reality, recent climatic experience suggests that damage costs will be higher than suggested by process models and there are likely to be at least some co-benefits. Based on this analysis, claims that overshooting might be lower-cost are not credible. In most scenarios we have examined, overshooting 1.5 °C then reducing the global mean temperature has substantially higher economic costs than not overshooting 1.5 °C.

Regional economic impacts of overshooting 1.5 °C

Limiting overshoot implies huge social, economic and technological challenges. It requires a pronounced acceleration of the transformation of the whole economy towards net zero emissions by 2050. Using a global economy-wide CGE model (ENGAGE), we assessed the economic impacts of overshooting 1.5 °C across a range of sectors and regions in the period to the year 2050. ENGAGE primarily considers mitigation costs but does represent some agricultural and heat stress damages. Economic impacts of climate change from ENGAGE are consistent with literature projections.

ENGAGE projects higher global economic growth over the period to 2050 through not overshooting 1.5 °C, as a result of earlier investment to increase energy and material efficiencies that have positive long-term economic benefits. In contrast, TIAM-UCL projected a higher cost of mitigation for the period 2020–2050 for the “No Overshoot” pathway. The discrepancy is likely due to TIAM-UCL assuming constant energy service demands in all pathways and only accounting for improved energy efficiencies in the energy system rather than across the whole economy.

All global regions benefit economically from earlier decarbonisation in the ENGAGE analysis. While the optimum rates of decarbonisation in each region vary over time, similar overall increases in GDP occur in each region by 2050 in the “No Overshoot” pathway compared to the “Very High Overshoot” pathway.

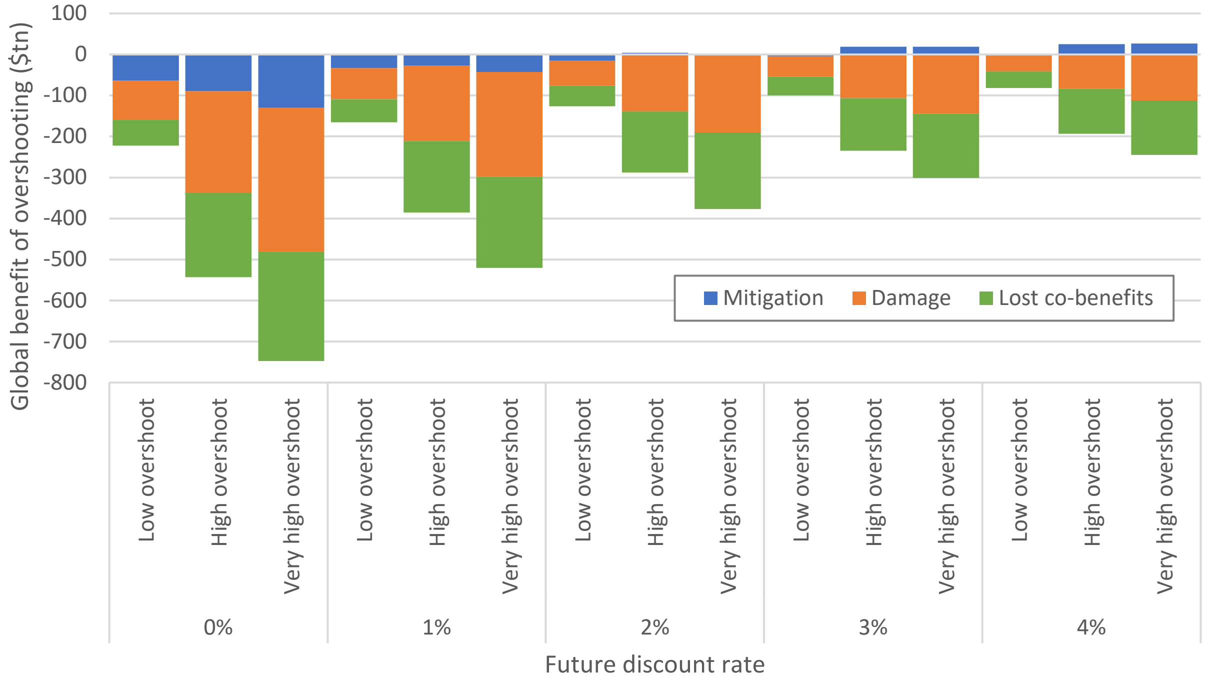

Figure ES1. Total global benefit of overshooting 1.5 °C in each overshoot pathway using Burke damage costs. Global benefits are plotted for the period 2023 to 2100 in $tn.

1. Introduction

A stable climate is an example of an economic phenomenon known as a global public good. Public goods are activities for which the cost of extending the service to an additional person is zero and for which it is impossible or expensive to exclude individuals from enjoying (Nordhaus, 2013a). Climate change has damaging impacts on the atmosphere and the wider environment of the planet (see Annex 5 of this report on natural system impacts). Cooperation between world governments is required to protect global public goods, such as by reducing climate change. Climate change that reduces climate stability represents a cost, so reducing climate change is a benefit. However, reducing climate change may also entail costs. Many governments use benefit-cost analyses to inform decisions in such situations.

Examining the benefits and costs of taking or not taking actions is an important part of understanding the impacts of scenarios that overshoot global warming temperature targets. Moreover, the economic implications of following overshoot scenarios could have substantial impacts on the human systems examined in Annex 6 of this report. This annex therefore examines the economic implications of overshoot scenarios, including a high-level benefit-cost analysis and a consideration of the regional implications of overshooting over the next 25 years. It builds on the pathway development in Annex 1 and the CO_2 removal feasibility in Annex 2, and contributes to the analysis of energy system impacts in Annex 6.

There is particular uncertainty about the magnitude of the potential costs of climate change damages. This annex therefore starts with a review of climate change damages, from statistical and modelling methods, while reflecting on the most important reasons for these differences.

1.1 Previous approaches to assessing economic implications

The IPCC has repeatedly estimated the economic implications of climate change, and of mitigating climate change, since its first assessment report of 1990.

Köberle *et al.* (2021) identify many studies that have focused on the cost of mitigating climate change amid a widespread debate about whether it is affordable. The cost of mitigating climate change is often estimated by energy system models and specified in terms of a long-term change in GDP, compared to a counterfactual baseline. Hence authors of Chapter 3 of

IPCC WG3 AR6 were asked to assess “Economics of mitigation and development pathways, including mitigation costs” (IPCC, 2017). Yet a full benefit-cost analysis should extend beyond mitigation costs. If mitigation actions are not taken then the cost of climate change damage will be higher and the cost to adapt to climate change will be higher. So a benefit-cost analysis should include damage and adaptation costs as well as mitigation costs. It would ideally also include co-benefits of mitigation and adaptation actions, although this is less common.

Integrated Assessment models (IAMs) have been used since Nordhaus (1991) to examine trade-offs between mitigation and climate damage costs. A key assumption in IAM studies is the future social discount rate. The choice of discount rate is important because a high rate assumes that costs and benefits in the future are much less important than costs and benefits today. This means that for a low discount rate, future damages are considered more important and investments today to avoid climate change (i.e. mitigation costs) are easier to justify than if a higher discount rate is used. This choice is particularly important for overshoot pathways as these assume delayed mitigation actions compared to a “No Overshoot” pathway but with higher carbon dioxide removal (CDR) costs later in the century, as described in Annex 1 (overshoot pathways development) and Annex 2 (CDR feasibility) of this report.

Stern (2007) examined the cost of climate change for the UK Government, using a discount rate[1] of 1.4% and found that early, deep mitigation actions were justified to avoid climate damages. Yet the future is normally discounted at higher rates in economic appraisals (Yohe and Tol, 2007). The UK Government’s Green Book recommends a social discount rate of 2.5–3.5% (HM Treasury, 2022).[2] Hence the costs and benefits of taking early climate action remain contested.

IAMs have been the principal source of damage and adaptation costs over the last few decades, for example using the DICE or PAGE models with costs taken from process-based

[1] The social discount rate is used to put a present value on costs and benefits of a social project, such as avoiding climate change, that will occur at a later date. Future costs and benefits are commonly discounted so this rate is almost always positive or zero.

[2] The Green Book asks UK government departments to use discount rates of 3.5% for the first 30 years, 3% for years 31–75 and 2.5% from year 86 (Table 5).

models. As the global temperature has increased, particularly in the last 20 years, econometric studies have attempted to estimate the actual cost of climate change to date. Resulting actual damages have been found to be much higher than previously projected by IAMs and call into question previous assumptions.

Co-benefits of climate change mitigation include better air quality and better health, for example through reduced particulate and other local emissions from fossil fuel combustion, better diets and active travel. These have not generally been included in benefit-cost analyses of taking mitigation actions because they are difficult to assess, as different future pathways would have varying levels of co-benefits, and because monetisation of the number of avoided deaths through co-benefits is controversial and there is no agreement on an approach.

1.2 Structure of this report

Given the considerable uncertainty in the cost of damages from climate change, Section 2 reviews damage cost appraisals from a range of methods. Section 3 presents a global benefit-cost analysis of overshoot scenarios. As many studies have concluded that mitigating climate change could have wide economic implications, Section 4 uses a general equilibrium model to explore these implications in world regions. That analysis also provides an alternative appraisal of global mitigation costs to complement the energy system model appraisal in Section 3.

2. Damage cost appraisals

Climate change damage costs are a key component of the benefit-cost analyses of taking mitigation and adaptation actions. Many studies have quantified damage costs using statistical methods (also called empirical or econometric), computable general equilibrium (CGE) models, integrated assessment models (IAMs), and hybrid approaches. As results of these studies vary considerably, depending on the methodological framework and the underlying data, this section reviews the literature to better understand the causes of these variations.

Section 2.1 reviews the development of and insights from statistical models. CGE models and IAMs are reviewed in Sections 2.2 and 2.3, respectively. The review concludes by considering why climate change damage estimates vary so much between these methods in Section 2.4.

2.1 Statistical models

Three statistical methods have primarily been used to estimate the impact of climate change: cross-sectional approaches, panel data regressions, and long differences regressions. Each has strengths and weaknesses (Dell *et al.*, 2014, Auffhammer, 2018).

Cross-sectional models use data from various units of analysis observed in the same period to relate an outcome of interest (e.g. GDP, crop yields, industrial output) to climate and weather variables (usually temperature and precipitation). This approach has, however, a key weakness, as any factor influencing the variable of interest that is not taken into account by the dataset used in the estimation will bias the estimates produced by the model, if any of those excluded factors correlate with the variables incorporated in the model. This is called the omitted variables bias. This problem can be addressed by either adding more variables to a cross-sectional model or, ideally, by using panel data regressions.

By using a dataset incorporating observations across different units (firms, consumers, countries, etc.) observed across time, panel data regressions can control for any unit-specific, time-invariant factor affecting the variable of interest through so-called individual (fixed or random) effects. For this reason, panel data methods have become popular to uncover the effects of climate change on the economy (Dell *et al.*, 2014, Mérel and Gammans, 2021). For example, Deschênes and Greenstone (2007) use panel data regressions to identify the effects of climate change on agriculture by exploiting annual weather data and agricultural outcome. Since then, many studies have used this framework to identify the climate change effects on the economy.

However, panel data methods have drawbacks too. Since these approaches exploit short-run weather shocks, often using year-to-year temperature variations, the estimates they produce are probably more representative of short-term impacts, not long-run effects (Dell *et al.*, 2014, Auffhammer, 2018). To capture long-term effects, Burke and Emerick (2016) developed the long-differences regression model, which uses average data over long periods, such as five years or a decade, rather than annual weather data. Since this approach exploits economic and weather changes over several years, it is more likely to identify long-term impacts of climate change and potential adaptations. For example, based on data across 1,500 regions in 77 countries over the period 1985–2014, Kalkuhl and Wenz (2020) use 10 years as a window to compare different periods to each other and find that the relationship between 10-year average temperature and growth has not changed across time.

The studies examined in this section are summarised in Table 1.

Table 1. Summary of variables, data, and findings used in econometric studies.

Study	Outcome Variable	Weather variable	Data
Aggregate Output			
Dell *et al.* (2012)	GDP growth rate; GDP; growth in agricultural value added; growth in industrial value added; growth in investment	Temperature	1950–2003, 125 countries
Burke *et al.* (2015)	GDP	Temperature	1960–2010, 166 countries
Burke and Tanutama (2019)	Log per-capita GDP growth rate	Temperature; precipitation	2000–2015, 11,000 districts across 37 countries
Kalkuhl and Wenz (2020)	Log per-capita growth rate of gross regional product	Temperature; precipitation	1900–2014; 1500 sub-national regions in 77 countries
Newell *et al.* (2021)	Log per-capita GDP and Log per-capita GDP growth rate	Temperature; precipitation	1960–2010, country-level
Kotz *et al.* (2021)	Growth rate of gross regional product	Temperature	1979–2018, 1,537 regions

Study	Outcome Variable	Weather variable	Data
Kotz *et al.* (2022)	Growth rate of gross regional product	Precipitation	1979–2019, 1,554 regions
Kotz *et al.* (2024)	Regional income per capita	Temperature, precipitation	1979–2019, 1,660 sub-national regions
Agriculture			
Mendelsohn *et al.* (1994)	Land prices	Temperature; Precipitation	1982, 2,933 counties
Schlenker *et al.* (2005)	Annual profits	Temperature; precipitation	1982, 2,197 dryland non-urban counties, 514 irrigated non-urban counties, and 227 urban counties
Deschênes and Greenstone (2007)	Agricultural profits	Temperature; precipitation	1978–2002, county-level
Fisher *et al.* (2012)	Agricultural profits	Temperature; precipitation	1978–2002, county-level
Schlenker and Roberts (2009)	Crop yields: corn and soybeans	Temperature	1950–2005, county-level
Tack *et al.* (2015)	Crop yields: wheat	Temperature; precipitation	1985–2013, field trials
Lobell *et al.* (2011)	Crop yields: wheat and maize	Temperature; precipitation	1980–2008, county-level
Moore and Lobell (2015)	Crop yields: wheat and barley	Temperature; precipitation	1989–2009, European countries
Gammans *et al.* (2017)	Crop yields: wheat and barley	Temperature; precipitation	1950–2015, county-level
Chen *et al.* (2016)	Crop yields: corn and soybean	Temperature; precipitation; radiation	2001–2009, county-level

Study	Outcome Variable	Weather variable	Data
Zhang *et al.* (2017)	Crop yields: rice, wheat, and corn	Temperature; precipitation; humidity; wind; sunshine; evaporation	1980–2010, county-level
Chen and Gong (2021)	Yields, labour, fertiliser, machinery, total factor productivity (TFP)	Temperature; precipitation; solar duration; humidity; wind force	1981–2015, 2,495 counties
Feng *et al.* (2010)	Crop yields: corn	Temperature	1995–2005, state-level
Colmer (2021)	Agricultural labour, agriculture wage	Temperature; rainfall	2003–2008, sector-level
Schlenker and Lobell (2010)	Crop yields: staple crops	Temperature; precipitation	1961–2006, country-level
Levine and Yang (2006)	Crop yields: rice	Rainfall	1993–1999, district-level
Agnolucci and De Lipsis (2020)	Crop yields: maize, wheat	Temperature; precipitation	1961–2014, Belgium, France, Germany, Italy, Spain, UK
Agnolucci *et al.* (2020)	Crop yields: 18 crops	Temperature; precipitation	1986–2012, 164 countries
Liang *et al.* (2017)	Agricultural TFP change	Temperature; precipitation	1980–2010, national-level
Ortiz-Bobea *et al.* (2021)	Agricultural TFP	Temperature; precipitation	1961–2015, 172 countries
Aragón *et al.* (2021)	Agricultural productivity; area planted; crop mix	Temperature; precipitation	2007–2015, household-level

Study	Outcome Variable	Weather variable	Data
Industrial and service outputs			
Hsiang (2010)	Total Production (per-capita value added); agricultural production; non-agricultural production	Temperature; tropical cyclone; rainfall	1970–2006, 28 Caribbean-basin countries
Somanathan *et al.* (2021)	Plant output; worker productivity;	Temperature; rainfall	1998–2012, 58,377 plants
Colmer (2021)	Total output; labour allocation to agriculture	Temperature; rainfall	2003–2008, plant-level
Zhang *et al.* (2018)	Output; TFP; labour allocation; capital	Temperature; precipitation; humidity; wind speed; visibility	1998–2007, firm-level
Adhvaryu *et al.* (2020)	Quantity of garments produced	Temperature	1,001 days' data at the production line level from 30 garment factories
Chen and Yang (2019)	Value added per worker	Temperature	1998–2007, firm-level
Jones and Olken (2010)	Export	Temperature; precipitation	1973–2001
Health and Mortality			
Carleton (2017)	Annual suicide rate	Temperature; precipitation	1967–2013, state-level
Deschênes and Greenstone (2011)	Annual mortality rate	Temperature; precipitation	1968–2002, county-level
Yu *et al.* (2019)	Annual mortality rate	Temperature; precipitation; humidity	2004–2012, county-level
Barreca (2012)	Monthly mortality rate	Temperature; humidity	1973–2002, county-level

Study	Outcome Variable	Weather variable	Data
Barreca *et al.* (2016)	Monthly mortality rate	Temperature; precipitation	1900–2004, state-level
Deschenes (2018)	Annual mortality rate	Temperature; precipitation	1960–2015, 16 countries
Burgess *et al.* (2017)	Annual mortality rate	Temperature; precipitation	1957–2000, district-level
Anttila-Hughes and Hsiang (2013)	Infant mortality rate	Typhoon	1993–2008
Carleton *et al.* (2022)	Annual mortality rate	Temperature	1957–2010, 40 countries

2.1.1 Aggregate output

Estimates of the aggregate economic impacts of climate change in the literature vary widely, although most studies agree that these effects are negative. Temperature could affect economic activity in two ways. First, it could influence the *level* of economic output, for example, by affecting agricultural yields. Second it could influence an economy's ability to *grow*, for example, by affecting investments or institutions that influence productivity growth (Dell *et al.*, 2012). Some econometric studies focus on relationships between temperature and the level of GDP while other focus on temperature and GDP growth. Some studies also consider the impacts of precipitation on economic output and growth.

Dell *et al.* (2012) constructed panel regressions to identify the impact of temperature shocks on economic growth by using country-level data from 1950 to 2003. They found a 1 °C temperature increase in any year causes GDP growth that year to reduce by 1%–1.3% in low-income countries but does not affect high-income countries.

After Dell *et al.* (2012), many studies used weather variations to identify the effects of climate change on the economy. The estimates from these studies show some variation (Hsiang and Narita, 2012, Hsiang and Burke, 2013, Dell *et al.*, 2014, Burke *et al.*, 2015). In contrast to Dell *et al.* (2012), Burke *et al.* (2015) find higher temperatures reduce per capita GDP for both low-income and high-income countries. Based on an analysis of 166 countries over the period 1960–2010, they project that the *marginal* damage (i.e. the damage caused by the temperature increasing by 1 °C) sharply increases to a 1.2% loss of regional GDP when the temperature exceeds 25 °C. As there is wide agreement in the literature that climate change impacts vary by region, estimates from global-level and country-level data may be imprecise or even biased, especially for large countries, such as Russia, China and Brazil, that span several climatological regions. Burke and Tanutama (2019) tackle this challenge by using data from 11,000 districts across 37 countries. Similar to Burke *et al.* (2015), they concluded that the relationship is non-linear for both affluent and less affluent regions, with the marginal damage to regional GDP of 1.7% at 25 °C. Higher losses have been estimated by Kalkuhl and Wenz (2020), with marginal damage to regional GDP of 3.5% at 25 °C, through using changes in temperature levels rather than absolute temperature levels in the statistical model. Hence there is no agreement in the literature about the potential impacts of climate change on high-income countries. While impacts in regions are expected to be larger as the temperature exceeds 25 °C, there is no agreement about the magnitude of the marginal increase in damages at this temperature.

Variations in the estimates for changes in economic *growth* from climate change are even larger. In terms of causal mechanisms, climate change could affect the growth rate of the economy through damaging the capital stock (Fankhauser and Tol, 2005), reducing labour supply and productivity (Shalizi and Lecocq, 2007), and changing investment behaviour (Moore and Lobell, 2015). The variation in estimates is exemplified by the findings of Newell *et al.* (2021), which are based on 800 economic models of the GDP–temperature relationship that use country-level data through 1960–2010. The models that compare the effects of temperature rise on GDP *growth* range from an 84% reduction to a 359% increase in any particular year.

An important disagreement in the literature is the extent to which growth impacts could persist and further reduce long-term GDP levels. The models in Newell *et al.* (2021) that compare the effects of temperature rise on GDP *levels* project GDP losses of only 1%–3% by 2100 for an RCP8.5 scenario (see IPCC (2014, 2018) for a discussion of RCP and SSP scenarios). This study uses models that assume GDP losses are not compounded over time. Similarly, while Kalkuhl and Wenz (2020) find higher marginal GDP losses than other studies, the reduction in the GDP level in 2100 is 7%–14% for RCP8.5 as losses are assumed to not compound. In contrast, while Burke *et al.* (2015) has lower marginal GDP losses, the assumptions that these compound leads to a higher projection of a 23% reduction in global incomes by 2100 under the RCP8.5[3] and SSP5[4] scenarios, compared to a no climate change counterfactual. If losses were to compound then containing global temperature rises to 1.5 °C is projected to reduce climate change damages considerably compared to a 2 °C rise (Burke *et al.*, 2018).

Over the last decade, methods to produce projections of economic losses due to climate change have become increasingly sophisticated. The initial studies examined annual temperature and precipitation variations on economic sectors in countries. Subsequent studies greatly increased the spatial resolution and also considered impacts over longer time periods. But by using annual meteorological data, impacts of changes in the frequency of extreme weather is not considered. Recent studies have attempted to address this shortcoming. Kotz *et al.* (2021) analyse the impacts of daily temperature variations for 1,537 worldwide sub-national regions over 1979–2018, using economic data from Kalkuhl and Wenz (2020). Based on this historic data, they find that an increase in the day-to-day temperature variability of 1 °C in a region causes a reduction in the regional growth rate of at least 5%, and up to 12% in low-latitude countries with low interseasonal temperature variability. A similar study examining the impacts of greater numbers of days with both high (>1 mm) and extreme precipitation, caused by climate change, concludes that the negative economic impacts on global manufacturing and service sectors are larger than any benefits of higher precipitation for agriculture (Kotz *et al.*, 2022). Examining the impacts of both temperature and precipitation changes caused by climate change, Kotz et al. (2024) conclude that income per capital in 2050 would be 18% lower for an RCP2.6 pathway and

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[3] A Representative Concentration Pathway (RCP) is a greenhouse gas concentration (not emissions) trajectory adopted by the IPCC. Four pathways were used for climate modelling and research for the IPCC Fifth Assessment Report (AR5) in 2014. The pathways describe different climate futures, all of which are considered possible depending on the volume of greenhouse gases (GHG) emitted in the years to come. The RCPs – originally RCP2.6, RCP4.5, RCP6, and RCP8.5 – are labelled after a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6, and 8.5 W/m2, respectively). RCP1.9 was introduced for the 1.5 °C Special Report.

[4] Shared Socioeconomic Pathways (SSPs) are scenarios of projected socioeconomic global changes up to 2100. They are used to derive greenhouse gas emissions scenarios with different climate policies. The scenarios are: SSP1: Sustainability (Taking the Green Road); SSP2: Middle of the Road; SSP3: Regional Rivalry (A Rocky Road); SSP4: Inequality (A Road divided); SSP5: Fossil-fuelled Development (Taking the Highway).

21% lower for an RCP8.5 pathway. After 2050, the impacts from these two pathways would diverge, with the RCP2.6 pathway loss not exceeding 20% throughout the century while the RCP8.5 pathway impact increases to a 60% reduction in income per capital by 2100, relative to a baseline without climate impacts. A similar study published at the same time from Waidelich *et al.* (2024), who conservatively assume that compounded GDP losses would not occur, projects a global reduction in GDP of 3% for 1.5 °C warming and 10% for an RCP8.5 pathway in 2100. In both studies, impacts on low-income countries are proportionally much greater than on high-income countries.

In summary, climate change is projected to reduce global GDP in all studies. Impacts on low-income countries are projected to be much higher than on high-income countries. Projections of the long-term impact of climate change on GDP vary widely, with the lower close to projections from integrated assessment models (1%–3%) but with several studies projecting impacts in 2100 in an RCP8.5 scenario of 7%–23%, and 60% in one study. Projected impacts are higher for studies than consider changes in extreme weather and that assume that GDP losses will compound over time. All of the studies make conservative assumptions in some ways, and none examine all climate change impacts (e.g. sea-level rise tends to not be considered), so losses could be higher than projected.

2.1.2 Agriculture

Econometric studies conclude that climate change has already reduced crop yields. Impacts are likely to continue to increase, in particular as the number of high-temperature periods increases. Many of these statistical studies have looked at a range of regions in each country, over long time periods, so should have accounted for adaptation to climatic changes. However, more rapid temperature changes and increasing weather variability in the future could reduce the effectiveness of adaptation. Yields to date have grown through technical improvement but gains have been reduced slightly by climate change.

Since agriculture is directly influenced by weather factors, the impact of climate change on this sector has been extensively studied (Carter *et al.*, 2018). There is a consensus of negative impacts from the various applied methods. By estimating a Ricardian model to evaluate the impact of climate change on US county-level land values, Mendelsohn *et al.* (1994) find that land price declines by 89–103 $/acre with a 1 °C temperature increase.

Using the same approach but focusing on irrigation, Schlenker *et al.* (2005) show that climate causes an annual loss of about 5–5.3 $bn for dryland non-urban counties, where dryland counties have less than 20% of the harvested cropland irrigated.

Most studies have used panel data approaches to uncover the causal effects of climate change on agriculture. Deschênes and Greenstone (2007) found no significant relationship between weather and agricultural profits, corn yields or soybean yields in the US, but their results were questioned by Fisher *et al.* (2012), who identified data and coding errors. After correcting these errors, Fisher *et al.* (2012) concluded that climate change would significantly reduce agricultural outputs and profits, which is more consistent with the following literature.

Using the same econometric framework and based on US county-level data from 1950–2005, Schlenker and Roberts (2009) concluded that the relationship between weather and crop yields, including corn, soybean, and cotton, are nonlinear, with yields declining quickly when a critical threshold is exceeded. Results show that for corn, the critical daily mean temperature threshold is 29 °C; for soybean 30 °C, and for cotton 32 °C. Based on these estimated relationships and climate projections, they further predict that crop yields will decline by 30%–46% in the B1 scenario with the least warming by 2100 from the Hadley III model and by 63–82% for the most rapid A1FI scenario.[5,6] These scenarios are from the IPCC SRES (IPCC, 2000). Using US wheat yield data from Kansas Performance Tests[7] during 1985–2013, Tack *et al.* (2015) find that wheat yields decline by 7.6% for one additional degree day when temperatures exceed 34 °C.

Lobell *et al.* (2011) find that past climate trends have decreased global wheat and maize yields by 5.5% and 3.8% over 1980–2008, respectively. European crop yields, such as wheat and barley, have experienced stagnation since 1989, and climate trends are key factors for this. Moore and Lobell (2015) concluded that climate change decreased

[5] The HadCM3 is a coupled climate model released by the UK Met Office that has been used extensively for climate prediction, detection and attribution, and other climate sensitivity studies. https://www.metoffice.gov.uk/research/approach/modelling-systems/unified-model/climate-models/hadcm3
[6] A1FI is a fossil fuel-intensive scenario from the IPCC Special Report on Emission Scenarios (SRES) with narrative similarities to SSP5.
[7] The Kansas Crop Performance Tests, conducted annually, provide producers, extension workers, and seed industry personnel with unbiased agronomic information for the major agricultural crops marketed in Kansas. Website: https://www.agronomy.k-state.edu/outreach-and-services/crop-performance-tests/

continent-wide barley and wheat yields by 3.8% and 2.5% during 1989 to 2009, respectively, which accounts for about 10% of the stagnation. Using county-level crop yields data from 1950–2015 in France, Gammans *et al.* (2017) project that under RCP8.5, winter wheat and barley yields in 2100 would decline by 21% and 17%, respectively.

Studies focusing on low-income countries have found a larger negative effect, which is concerning as agriculture generally has a larger role in the economies of these countries. For China, several studies have used county-level data and panel regressions to estimate an inverted U-shaped relationship between temperature and precipitation and crop yields. Under HadCM3 model A1FI scenario, rice, wheat, and corn yields decline by 36%, 18%, and 45% by 2100, respectively (Chen *et al.*, 2016, Zhang *et al.*, 2017). Using data from 2,495 counties for 1981–2015 in China, Chen and Gong (2021) find that an additional one-day cumulative exposure to temperatures above 33 °C during the whole year reduces crop yields by 4.4%. Other studies focusing on Mexico (Feng *et al.*, 2010), India (Guiteras, 2009, Colmer, 2021), Sub-Saharan African countries (Schlenker and Lobell, 2010), and Indonesia (Levine and Yang, 2006) find consistently negative impacts of climate change on agriculture.

As crop yields represent partial agricultural productivity, studies have turned to agricultural total factor productivity (TFP) to capture the impact of climate change on the overall productivity of the agricultural system. For example, Liang *et al.* (2017) estimate the correlation between regional climate anomalies, including temperature and precipitation, and agricultural TFP changes in the US. Results show that climate variation can account for 70% of TFP changes during 1980–2010. Based on the relationship, they project that climate change reduces TFP by an average of 4.3% per year under RCP 8.5. Ortiz-Bobea *et al.* (2021) use panel regression with quadratic terms to examine whether the impact of climate change on global agricultural TFP is non-linear, using data based on 172 countries over 1961–2015 and find that climate change has reduced global agricultural TFP by 21% since 1961. Other authors have estimated the impact of climate change on agricultural TFP in other countries. Using household-level data over 2007–2015 in Peru, Aragón *et al.* (2021) find that each additional average “harmful” degree day above a 33 °C threshold daily temperature results in a 7% decrease in agricultural productivity, an impact farmers respond to by increasing the area planted and changing crop mix. As the sample used in the study includes subsistence farmers, much of whose crops or livestock are used by the household, one should be careful about extending this result to farmers growing crops mainly for trading. In China, based on county-panel data over 35 years, results of Chen and Gong (2021) show that an additional one-day cumulative exposure to temperatures above 33 °C reduces agricultural TFP by 2.6%.

2.1.3 Industrial and services output

Several studies have identified a negative impact of climate change on industrial and service sector output, through impacts on labour productivity, factor input, and total factor productivity. Rising temperatures have been found to reduce labour productivity in non-agricultural sectors (Hsiang, 2010, Somanathan *et al.*, 2021). Productivity reduction and more absenteeism under heat stress in hot days can account for this decline (Zhang *et al.*, 2018, Colmer, 2021, Somanathan *et al.*, 2021). This is examined in the health section of Annex 6.

Hsiang (2010) evaluates the effects of temperatures on several sectors using data from 28 Caribbean-basin countries from 1970 to 2006. Results show that a 1 °C increase in the annual temperature in the region results in a 0.1% reduction in agricultural production and 2.4% decline in non-agricultural production. Dell *et al.* (2012) concluded using country-level data that no substantive negative impacts on economic growth have occurred in high-income countries due to temperature shocks (see Section 2.1.1 and note that other studies have concluded that high-income countries have had negative impacts). Several subsequent studies focused on the impacts of climate change on industrial output in middle- and low-income countries (Zhang *et al.*, 2018, Chen and Yang, 2019, Adhvaryu *et al.*, 2020, Somanathan *et al.*, 2021). For China, Zhang *et al.* (2018) found that the relationship between temperature and firms' outputs was an inverted U-shape based on firm-level data in during 1998–2007. When plants were exposed to one more day with temperatures exceeding 32 °C, plant outputs declined by 0.45%. TFP reduction might be a driver of this output decline (Chen and Yang, 2019). For Indian manufacturing, a 1 °C increase in local temperatures decreased plant outputs by about 2% (Somanathan *et al.*, 2021). Also in the case of exports, losses from climate change seem to depend on the level of economic development. Jones and Olken (2010) found that higher temperatures reduced exports from lower-income countries but did not have any significant effects on high-income countries. Although not explored in the literature, climate-related reductions in exports from lower-income countries might indirectly affect high-income countries by increasing food prices if only higher-priced alternatives were available.

2.1.4 Health and mortality

Climate change has negative impacts on individuals' health and mortality through temperature increases and extreme heat stress. Studies have found an inverted U-shaped relationship between temperatures and mortality rates, with both high and low extreme temperatures increasing mortality rates (Deschênes and Greenstone, 2011, Carleton, 2017, Yu et al., 2019). Deschênes and Greenstone (2011) found that each additional day with temperatures exceeding 32 °C increased the annual mortality rate by about 0.11% in the US. However, temperature-induced mortality rates decline steeply after 1960 in the US due to air conditioning becoming widespread (Barreca et al., 2016).

Humidity is also a key factor for mortality rates: one additional day with humidity of 18 g/kg, relative to the 8–10 g/kg average in the USA, raises the annual mortality rates by 0.01% (Barreca, 2012). Impacts are larger for tropical lower-income countries as they tend to experience higher temperatures and have less capacity to adapt. This is confirmed by Deschenes (2018) in a study of 16 Asian countries: the annual mortality rate increased by 1% when there was one more day with temperatures above 32 °C, compared to a day with temperatures between 21–26 °C. In India, an additional day with temperature exceeding 35 °C increases annual mortality rates by 0.74%, compared to temperatures of 21–23 °C (Burgess et al., 2017). In China, a day with temperatures above 32 °C was found to increase annual mortality rates increase by 0.6% relative to a day in the range 10–15 °C (Yu et al., 2019). It important to stress that increases in mortality are likely to vary depending on the age of those affected. As an example, in the case of extreme weather events in Philippines, infant mortality caused by typhoons constitutes 13% of the overall infant mortality rate (Anttila-Hughes and Hsiang, 2013). Using subnational data from 40 countries, Carleton et al. (2022) estimate the relationship between temperatures and mortality for people in specific age groups and find that a day at 35 °C increases the mortality of people over the age of 64 by 4.7 per 100,000.

2.2 Computable General Equilibrium models

Computable General Equilibrium models (CGE) describe the relationships between multiple economic sectors, economic entities, production factors (such as labour, capital, and resources), goods, and services across different regional scales. They can evaluate climate impacts on production, consumption, trade, and endowment markets (such as labour and capital markets), among others. CGE models can be extended to capture non-market impacts such as human health risks (including mortality effects). CGE models have the strength of being able to analyse direct economic effects of climate shocks and the way in which they propagate across sectors of the economy through price changes and substitution effects, while also considering adaptations (McDermott *et al.*, 2021, Piontek *et al.*, 2021). Weaknesses of CGE models include very detailed data requirements for which real world data are often not available. Computational challenges also arise when solving optimisation problems with high spatial and temporal dimensionality (Kompas and Ha, 2019, Cantele *et al.*, 2021, Piontek *et al.*, 2021, Zhao *et al.*, 2021). As a macroeconomic model, CGE models represent aggregated sectors, regions and institutions.

Subnational CGE models disaggregate a country into different regions and analyse economic interlinkages between regions within the country and the rest of the world. National CGE models represent a single country, where all other economies are aggregated in a rest of the world region (Pradhan and Ghosh, 2019, Zhang *et al.*, 2021, Vrontisi *et al.*, 2022). In global CGE models, economies are represented at the country or regional level and linked through international trade (Dellink *et al.*, 2019, Knittel *et al.*, 2020, Zhang *et al.*, 2021). Most CGE models are enriched by satellite accounts, including data on land use, crops, forestry, energy, CO_2 emissions and air pollution, to assess climate impacts (Joshi *et al.*, 2016, Bosello *et al.*, 2018, Costantini *et al.*, 2018, Takakura *et al.*, 2019, Wei *et al.*, 2020).

2.2.1 Modelling climate change impacts in a CGE framework

Many CGE models are paired to a climate module to evaluate climate change impacts, either through an one-way connection (Kompas *et al.*, 2018, Wang *et al.*, 2020) with fixed damage functions translating the biophysical impacts of climate change into economic impact (Ciscar *et al.*, 2012, Costantini *et al.*, 2018), or a two-way connection in which climate conditions and socio-economic systems interact with each other. There are three steps (Eboli *et al.*, 2010, Dellink *et al.*, 2019, Zhang *et al.*, 2021):

1. The CGE model projects GHG emissions based on a projected future socio-economic scenario.
2. The climate module translates these emissions into greenhouse gas concentrations and temperature changes.
3. Climate damage functions estimate the economic consequences of climate impacts, for example as changes to productivity, endowments, production, and consumption patterns, to be fed back into the CGE model and iterated.

Unlike for integrated assessment models (IAMs), where the relationship between the economy and climate change is normally summarised by an aggregated damage function, CGE models can use a series of damage functions describing different climate impacts in each economic sector and at regional scales (Diaz and Moore, 2017, Dellink *et al.*, 2019, Piontek *et al.*, 2021). Climate impacts that have been represented in CGE models include the effects of sea-level rise, losses in agricultural productivity, extreme events such as floods, hurricanes, and typhoons, biodiversity loss, water availability, temperature effects, and health (Roson and Sartori, 2016, Moore *et al.*, 2017, Yamaura *et al.*, 2017, Hoffmann and Stephan, 2018). Biophysical climate impacts will directly influence goods demand and production factors (e.g. land, capital, labour, energy as well as associated productivities and total factor productivity), and the aggregate output. For example, sea-level rise impacts are translated into a negative shock to the supply of land and capital (Ouraich and Tyner, 2018, Chatzivasileiadis *et al.*, 2019, Dellink *et al.*, 2019, Fan and Davlasheridze, 2019, Kompas and Ha, 2019, Takakura *et al.*, 2019, Knittel *et al.*, 2020, Solomon *et al.*, 2021).

2.2.2 Estimates of the economic costs of climate change using CGE model

A key issue when assessing economic damages is the breadth of the coverage of impacts (Piontek *et al.*, 2021). Damage costs are higher when a greater number of impacts are represented. Table 2 lists the impacts examined by a range of studies.

Table 2. Studies of climate impacts using CGE models.

Study	Scope	Year	Climate impacts	Valuation
Pradhan and Ghosh (2019)	India	Up to 2050	Agriculture	Agriculture productivity
Bosello *et al.* (2018)	Nigerian	2050	Agriculture	Agriculture productivity
Ouraich and Tyner (2018)	Moroccan	2050	Agriculture	Agriculture productivity
Dudu and Çakmak (2017)	Turkey	Up to 2060	Agriculture	Agriculture productivity
Bosello *et al.* (2012)	EU	2085	Sea-level rise (SLR)	Land losses
Pycroft *et al.* (2016)	World	2085	Sea-level rise (SLR)	Forced migration, consumption (other than from migration) and capital stock
Joshi *et al.* (2016)	World	Up to 2100	Sea-level rise (SLR)	Loss of cropland area, capital loss, number of people affected and investments
Zhao *et al.* (2021)	World	/	Heat stress	Labour productivity
Knittel *et al.* (2020)	German	Up to 2050	Heat-related labour productivity losses	Labour productivity
Fan and Davlasheridze (2019)	Orleans Parish, the USA	2012	Hurricane	Loss in population and skilled labour
Hasegawa *et al.* (2016)	World	Up to 2100	Undernourishment	Healthy lives lost
Hoffmann and Stephan (2018)	Switzerland	Up to 2090	Floods	Total factor productivity
Zhang *et al.* (2021)	China	Up to 2100	Extreme climate events	Total factor productivity
Vrontisi *et al.* (2022)	European islands	Up to 2100	(1) Energy demand; (2) transport infrastructure; (3) tourism flows	(1) Changes in the demand for electricity; (2) capital stock of the maritime sector; (3) touristic expenditures
Takakura *et al.* (2019)	World	Up to 2100	(1) Agricultural yields; (2) undernourishment; (3) heat; (4) cooling/heating demand; (5) health; (6) energy capacity; (7) fluvial flooding and coastal inundation	(1) Agricultural productivity; (2) demand for healthcare; (3) population/labour; (4) installation and use costs for heating/cooling device; (5) labour productivity; (6) energy productivity
Wang *et al.* (2020)	World	2050	(1) Crop yields; (2) human health and labour productivity; (3) sea-level rise; (4) residential energy demand	(1) Land productivity; (2) labour productivity (3) land resources; (4) household consumption

Study	Scope	Year	Climate impacts	Valuation
Dellink *et al.* (2019)	World	2060	(1) Sea-level rise; (2) fisheries catch; (3) hurricanes; (4) diseases and heat stress; (5) cooling/heating demand (6) agriculture (7) tourism	(1) Land and capital; (2) natural resource stock; (3) capital; (4) health care expenditures, labour productivity; (5) consumer demand for energy; (6) agricultural tfp and land productivity; (7) tfp of tourism services;
Kompas *et al.* (2018)	World	2100	(1) Agriculture; (2) sea-level rise; (3) health effects	(1) Production-augmenting technical change in agriculture; (2) supply of land; (3) labour productivity

Among those studies that only consider a single impact, several estimate the loss of climate-induced agricultural productivity. Pradhan and Ghosh (2019) estimate a reduction in GDP of 2%–6% by 2050 in India (0% discount rate). Bosello *et al.* (2018) project Nigerian GDP losses of 3%–4.4% compared to the baseline in 2050, while Ouraich and Tyner (2018) project GDP impacts of -3.1% to +0.4% for Morocco. For Turkey, Dudu and Çakmak (2017) concluded that GDP loss would be relatively low in the period 2010–2035, with a mean and median around zero, but in 2035–2060 the probability of a loss would increase substantially.

Several studies have examined the impacts of sea-level rise. Bosello *et al.* (2012) concluded that the overall effects on GDP would be quite small among EU countries (max −0.05% of GDP in Poland) in 2085. Pycroft *et al.* (2016) analysed three scenarios that correspond to a rise of 0.47 m, 1.12 m, and 1.75 m by the 2080s and projected a loss of global GDP of 0.5% for the 1.75 m scenario, with some large regional disparities (the costs for northern Central Europe region and parts of Southeast Asia and South Asia are especially high). Joshi *et al.* (2016) similarly concluded the impacts would be heterogeneous, as the highly urbanised and densely populated coastal areas of Southeast Asia, Australia, and New Zealand would likely have substantial losses.

A few studies assess the economic consequences of other climate impacts, such as those related to labour productivity, extreme events, and health. One example of a historic event is Hurricane Katrina, for which Fan and Davlasheridze (2019) find damages caused GDP loss in Orleans Parish, USA, of 34% relative to a 2012 business as usual scenario (BAU) with no hurricane. Zhao *et al.* (2021) project that global GDP loss in 2100 due to heat-related loss of labour productivity would range from 0.3% (0.1%–0.5%) for RCP2.6 to 2.6% (1%–4%) for RCP8.5. Hasegawa *et al.* (2016) find that the economic valuation of healthy lives lost due to undernourishment caused by climate change is equivalent to -0.4% to 0% of global GDP but with regional variation, being as great as -4% of GDP in South Asia in 2100. Hoffmann and Stephan (2018) indicate that floods in highly exposed regions in Switzerland lead to regional output decreases, depending on reference floods, by between -0.07% and -0.2%. Knittel *et al.* (2020) estimate a loss of German GDP up to 0.4% (RCP4.5) and 0.5% (RCP8.5) associated with labour productivity losses by 2050. Zhang *et al.* (2021) examined economic impacts of extreme climate events in China and concluded that climate-induced economic losses of GDP, at 0.2% in 2013, would increase to a 10%–16% reduction in GDP by 2100 for RCP2.6 to RCP8.5, respectively, assuming the Chinese economy would otherwise continue to grow at a rate of 5%.

Studies simultaneously considering several types of impacts can obtain more comprehensive estimates of the aggregate equilibrium effects of climate change. For example, Vrontisi *et al.* (2022) estimate that climate change impacts on energy demand, transport infrastructure and tourism in southern European islands[8] would cause GDP losses of 0.2%–2.6% in 2050 and 0.3%–6.0% in 2100 for RCP2.6, and 0.6%–5.7% in 2050 and 1.4%–13.8% in 2100 for RCP8.5. But most of these studies have estimated global impacts. Takakura *et al.* (2019) set out to estimate the global economic impacts of climate change, including agricultural productivity, undernourishment, heat-related excess mortality, cooling/heating energy demand, occupational-health cost, hydroelectric power generation capacity, thermal power generation capacity, and fluvial flooding and coastal inundation. They conclude that the global economy is most adversely affected under SSP3, while adverse effects are concentrated in developing regions under SSP4. The net economic loss is equivalent to 7% (4%–9%) of global GDP by 2100 under the SSP3-RCP8.5 scenario and around 1% for RCP2.6. Wang *et al.* (2020) examine impacts on crop yields, human health, labour productivity, sea-level rise, and residential energy demand. Their results indicate global GDP total losses by 2050 of 0.7% for a Nationally Determined Contributions (NDC)

[8] The southern European islands include the Azores, Balearic Islands, Canary Islands, Crete, Cyprus, Madeira, Malta, Sardinia and Sicily.

scenario,[9] which reduces to 0.4% for a 2 °C warming scenario. Dellink *et al.* (2019) project global annual GDP losses of 1%–3% by 2060 when accounting for sea-level rise, agriculture, tourism, fisheries catch, hurricanes, disease and heat stress, and energy usage change due to cooling and heating. The effects in OECD countries are much smaller, with losses in 2060 amounting to -0.2%, -0.3% and -0.6% for OECD Europe, OECD Pacific and OECD America,[10] respectively. Kompas *et al.* (2018) account for agricultural productivity, sea-level rise and health effects on GDP, and estimate a global loss of 3% of world GDP in 2100 for a 3 °C warming scenario and 7% for a 4 °C scenario.

2.3 Integrated Assessment Models

Two types of Integrated Assessment Model (IAM) have been developed to investigate the impacts of climate change and policies to mitigate GHG emissions. IAMs originated from Nordhaus (1991) for climate damage assessment, calculation of emission abatement costs, and optimal climate policies (Wang and Watson, 2010, Nordhaus, 2015, Wei *et al.*, 2015). A more recent generation of models such as IMAGE (Stehfest *et al.*, 2014) and MESSAGE-GLOBIOM (van Ruijven and Min, 2020) combine energy system and land use models. Damage cost assessments have tended to be performed using the older type.

IAMs normally include several steps: (i) economic activities produce GHG emissions; (ii) higher concentrations cause global average temperatures to increase; (iii) higher temperatures result in economic losses in most world regions; and, (iv) climate policies are required to mitigate these losses (Nordhaus, 2019). A typical IAM includes three modules: a carbon cycle module, a climate module and an economic growth module (Nordhaus, 2018).

IAMs link climate variables (e.g. temperature; CO_2 emissions; sea-level rise) to economic outputs in the economic module to assess the impacts of climate change on socioeconomic systems. IAMs can be divided into two categories: Detailed Process (DP-IAMs) and Benefit-Cost (BC-IAMs), according to the content, the complexity and the level of detail in describing the climate-economic relationship (Weyant, 2017).

[9] An NDC, or Nationally Determined Contribution, is a climate action plan to cut emissions and adapt to climate impacts. Each Party to the Paris Agreement is required to establish an NDC and update it every five years.
[10] OECD Europe: EU large 4 (France, Germany, Italy, United Kingdom), Other OECD EU, and Other OECD (Iceland, Norway, Switzerland, Turkey, Israel). OECD Pacific: Oceania (Australia, New Zealand), Japan, and Korea. OECD America: Canada, Chile, Mexico, and United States.

Table 3 lists the studies examined in this section and summarises the damages they consider and their scope.

Table 3. IAM studies of GDP losses using a range of impacts.

Study	Damages considered	Effect scope	Year	Physical climate change	Valuation
Nordhaus and Moffat (2017) (DICE)	Aggregation of different impacts	Global	Up to 2100	Global Temperature	GDP
Hope (2011b) (PAGE)	Sea-level rise, economic and non-economic impacts	Regional	Up to 2300	Regional Temperature	GDP
Anthoff and Tol (2013) (FUND)	agriculture, forestry, water resources, energy consumption, sea-level rise, ecosystems, human health, extreme weather, mortality, and morbidity	Regional		Regional Temperature, rate of temperature change	GDP
Stehfest *et al.* (2014) (IMAGE)	climate impacts, agricultural impacts, water stress, terrestrial biodiversity, aquatic biodiversity, flood risk, land degradation, ecosystem services, and human development	Regional	Up to 2100	Many	Economic impacts and climate impacts
Edmonds *et al.* (1997)	macroeconomics, energy, land, water supply	Regional		Many	Economic impacts and climate impacts
Bressler (2021) (DICE-EMR)	Aggregation of different impacts and mortality	Global	Up to 2100	Global Temperature	GDP and population

Bastien-Olvera and Moore (2021) (greenDICE)	Market damages and non-market damage	Global	Up to 2300	Global Temperature	Output and Natural capital
Moore and Diaz (2015) (groDICE+DJO)	Aggregation of different impacts	Regional	Up to 2105	Global Temperature	TFP growth, capital depreciation
Glanemann *et al.* (2020) (DICE+BHM)	Aggregation of different impacts	Global	Up to 2300	Global Temperature	GDP
Ricke *et al.* (2018) (growth model+BHM)	Aggregation of different impacts	Global	Up to 2100	Global Temperature	GDP growth
(Gazzotti *et al.*, 2021) (DICE+BHM)	Aggregation of different impacts	Regional	Up to 2100	Regional Temperature	GDP
Brown and Saunders (2020) (DICE+BHM)	Aggregation of different impacts	Global	Up to 2300	Global Temperature	GDP
Hänsel *et al.* (2020)	Aggregation of different impacts	Global	Up to 2100	Global Temperature	GDP

2.3.1 Detailed Process Integrated Assessment Models

DP-IAMs seek to estimate climate change impacts at a detailed regional and sectoral level, with a focus on intra- and inter-sectoral interactions. They obtain not only estimates of the impacts of climate change on the economy, but also projections of the physical impacts of climate change (e.g. on reduced crop growth and land inundated by rising seas) to provide detailed policy options. In contrast, BC-IAMs have a more aggregated representation of climate change mitigation costs and aggregate impacts by sector and region into a single economic metric.

Two representative DP-IAMs are the Integrated Model to Assess the Greenhouse Effect (IMAGE) and the Global Change Assessment Model (GCAM). The IMAGE3.0 climate change impacts module contains a wide range of indicators on agricultural impacts, water stress, flood risk, land degradation and human development (Stehfest *et al.*, 2014).

Therefore, the model integrates economic and non-economic sectors to account for the impact of climate change in various sectors through temperatures and CO_2 concentration. The Pacific Northwest National Labouratory in the United States developed the GCAM, a model including multiple subsystems, such as macroeconomics, energy, land, water supply and climate (Calvin *et al.*, 2019). The core operational principle of the model is market equilibrium. The GCAM model takes population, technology, and policies as exogenous variables, thereby driving the energy consumption behaviour in the model, and then analysing the development of the future energy system under a given scenario.

2.3.2 Benefit-Cost Integrated Assessment Models

BC-IAMs combine the mitigation costs and the sectoral impacts of climate change into a single economic indicator, such as GDP losses. With the aim of informing benefit-cost analyses, BC-IAMs include one or a few equations to monetise climate change impacts and the feedback processes between the climate system and the economic system. As BC-IAMs can be used to determine the optimal climate policy and to calculate the abatement costs and the potential benefits of avoided climate change, they are widely used to determine the optimal emissions abatement path and to calculate the Social Cost of Carbon (SCC) (Weyant, 2014) and the climate-induced economic losses per unit of CO_2 emissions (IPCC, 2022a). Compared to DP-IAMs, BC-IAMs must monetise the impacts of climate change with a simplified form of damage functions because there is limited or no physical representation of natural and human systems in the model except for simple climate modules. However, they highlight key issues such as discount rates and damages, and rapidly incorporate new scientific findings into cost and benefit projections (Nordhaus, 2013c).

In BC-IAMs, the damage functions directly model the economic losses from climate change (Lemoine and Kapnick, 2016). The results from damage functions, reflecting the damage caused by climate change in BC-IAMs, can be used to compare the impacts of climate change in different models and is used in the benefit-cost analysis in the model to compare adaption and mitigation policies to damages.

2.3.3 Estimates of the economic costs of climate change from IAMs

This section focuses on damage cost insights from the principal BC-IAMs, including the Dynamic Integrated Climate Economy (DICE) (Nordhaus, 2008), the Policy Analysis of the Greenhouse Effect (PAGE) (Hope, 2011b), and the Climate Framework for Uncertainty, Negotiation, and Distribution (FUND) (Anthoff and Tol, 2013). Estimates of the SCC, however, vary considerably: from \$10 in FUND (Anthoff and Tol, 2013) to \$18 in DICE (Nordhaus, 2014) and \$71 in PAGE (Hope, 2011b).

FUND is a welfare maximisation model for sixteen regions. Its climate impact assessment module on the economy is detailed, covering multiple sectors and regions (Ackerman and Munitz, 2012). In FUND, the damage function describes the relationship between percentage changes in GDP and temperature rise, initially:

$$\frac{dGDP(\%)}{d\Delta T} = 2.46\Delta\mathrm{T} - 1.1\Delta\mathrm{T}^2$$

from a review of 14 studies in Tol (2009) and later updated to:

$$\frac{dGDP(\%)}{d\Delta T} = -0.25\Delta\mathrm{T} - 0.16\Delta\mathrm{T}^2$$

from Tol (2014).

Nordhaus and Moffat (2017) tried to replicate the analyses of Tol (2009, 2014) but reported a large number of errors. In their review of 36 estimates of climate damages from 27 studies, they chose to use a quadratic damage function:

$$\frac{dGDP(\%)}{d\Delta T} = -0.236\Delta T^2$$

This function was integrated into DICE2016, which is a global-scale model with a damage function that seeks to capture the impact of temperature rise on economic output (Nordhaus, 2018). The DICE 2013 version (Nordhaus, 2013b, Nordhaus, 2014) uses the same equation with a quadratic coefficient of –0.267, based on Tol (2009).

PAGE is a simulation model of eight regions. It can evaluate the SCC under different scenarios and assess emissions abatement strategies in terms of abatement costs and climate losses (Hope, 2011a). The climate conditions and future emissions are exogenous.

The damage, calculated based on a second-order polynomial equation, is divided into economic impacts, non-economic impacts, impacts of sea-level rise, and discontinuous impacts, expressed as a function of the relationship between GDP change and temperature rise or sea-level rise. The first three have an aggregate impact before adaptation of just under 2% of GDP for a temperature rise of 3°C (Warren *et al.*, 2021).

Comparing the three models shows that despite major differences in damage components, the global annual losses in the three models do not vary widely. For a temperature increase of 1.5 °C, the damage in DICE2016 and PAGE is about 0.5% of GDP, while in FUND it is about 0.7%. For an increase of 2 °C, the damage in DICE and PAGE is about 1% of GDP, and in FUND about 1.1% (Tol, 2014). Damages arising from a 6 °C temperature increase are about 10% in PAGE, 8.5% in DICE2016 and 7.2% in FUND (Tol, 2014).

2.4 Reasons for estimates difference

Statistical models tend to produce much higher estimates of economic losses from climate change than models. There are several underlying reasons.

First, statistical studies primarily identify ex-post impacts of climate variability on the economy, using spatially-explicit and firm-level data. These studies examine long time periods (typically 40 or more years) at high spatial resolution, and more recently have examined the impacts of changes in extreme weather. Some statistical studies have then extrapolated these trends forwards for future scenarios.

Modelling studies project climate change costs on the basis of future emission and socioeconomic scenarios using damage functions. Pindyck (2013) has criticised damage functions for embedding many opaque assumptions and poor linkages to the underlying processes. In addition, damage functions are frequently based on evidence from a few countries with sufficient data and extrapolated to the rest of the world, so lack a solid empirical foundation (Yang, 2016, Hsiang *et al.*, 2017). While empirical studies have provided evidence on the historic impacts of climate change on economic growth rates, the damage functions of IAMs reflect only static loss of economic output or GDP and lack a dynamic impact mechanism on economic growth, so may underestimate damages caused by climate change (Moyer *et al.*, 2014, Dietz and Stern, 2015).

Second, the assumptions on the relationship between climate and the economy differ across methodologies. Statistical methods tend to focus on the impact of specific weather indicators on economic factors, such as GDP, crop yields, and industrial output, while CGE models and IAMs usually have multiple impacts and estimate both direct and indirect impacts of climate change (Piontek *et al.*, 2021). For example, including the effects of climate change on agricultural productivity, sea-level rise, and health in a CGE model, Kompas *et al.* (2018) find that the global loss is estimated to be 3% of GDP in the case of a 3 °C warming scenario by 2100 and 7% for a 4 °C warming scenario, while empirical studies tend to examine only one of the effects in isolation, such as agricultural impacts (Deschênes and Greenstone, 2007) or mortality (Carleton *et al.*, 2022). Therefore, variations might stem from considering different breadths of impact. It is therefore even more surprising that statistical studies tend to project higher impacts than model studies.

Third, adaptation is an important factor affecting these estimates. Empirical studies do not directly incorporate adaptations into impact estimates, although those examining long time-series are likely to account for any adaptations that occurred. Where studies have identified adaptation strategies, the results are mixed. For example, results of Burke and Emerick (2016) from using US county-level corn and soybean yields data from 1980 to 2000 show that there is no significant difference between long- and short-run effects, indicating that farmers have implemented only limited adaptation to mitigate climate change impacts. On the other hand, other papers have concluded that farmers' adaptation offsets some of the climate damages (Auffhammer and Schlenker, 2014, Hertel and Lobell, 2014, Moore and Lobell, 2014, Cui, 2020b, a, Chen and Gong, 2021, Cui and Xie, 2021). As studies normally include direct proxy variables for adaptation, such as crop acreage, growing season or labour reallocation, there is a risk that statistical methods include only part of the adaptation effort to climate change. In a modelling study, it is more difficult to disentangle the impact of specific adaptation actions. On the other hand, the inclusion of structural, theoretical equations, especially in CGE models, may offer a more comprehensive framework able to include a wider set of adaptation strategies, including input changes (Diaz and Moore, 2017, Schinko *et al.*, 2020). Therefore, different consideration of adaptations may also lead to variations in the estimates of climate change damages.

3. Benefit-cost analysis of following overshoot scenarios

Many technoeconomic studies have examined the cost of GHG emissions mitigation actions that are needed to avoid climate change. Technoeconomic models that focus on energy system decarbonisation tend to find a higher cost of decarbonisation than for a counterfactual “business-as-usual” scenario, and these are interpreted by some as showing that mitigating climate change has negative economic consequences for society. However, such studies have several shortcomings.

First, they consider only the energy system and not the wider economy, and do not consider potential economic gains from innovation and investment, for example in energy efficiency, which could lead to economic gains from emissions mitigation. Our analysis of mitigation costs in Section 3.3 uses a general equilibrium model and identifies economic benefits from mitigation.

Second, they do not consider damage costs or co-benefits of mitigation actions. A better approach is to consider both mitigation and damage costs together. A range of studies using IAMs have carried out full benefit-cost analyses that include damage and adaptation costs due to climate change in scenarios with low emissions mitigation, and we also take this approach. Most of these studies do not consider co-benefits of mitigation measures but these are included in the appraisal presented in this section.

3.1 Methods

The benefit-cost analysis used here sums damage and adaptation costs (Section 3.2), mitigation costs (Section 3.3) and the cost of not realising co-benefits (Section 3.4) to calculate and compare the overall costs of each pathway. The methods used are described in each of these sub-sections. The choice of future global discount rate is a key parameter affecting the benefit-cost analysis. It is particularly important for this study as overshoot pathways delay mitigation but have higher long-term CDR costs than pathways that do not overshoot. We examine a range of discount rates in this study.

The four pathways developed in Annex 1 (overshoot pathways development) are examined in this section:

- “No Overshoot” (NO), in which the global temperature does not exceed 1.5 °C.
- “Low Overshoot” (LO), in which the global temperature peaks at 1.6 °C in about 2060 before returning to 1.5 °C by the year 2100, with the lowest CDR requirement.
- “High Overshoot” (HO), in which the global temperature peaks at 1.8 °C in about 2065 before returning to 1.5 °C by the year 2100, with a higher CDR requirement.
- “Very High Overshoot” (VHO), in which the global temperature peaks at 1.9 °C in about 2065 before returning to 1.5 °C by the year 2100, with the highest CDR requirement.

3.2 Damage and adaptation costs

Section 2.4 concludes that there are substantial uncertainties over future damage costs, and that means adaptation costs must be similarly uncertain. For this reason, two estimates of damage and adaptation costs were examined in this study. One, based on the standard version of the PAGE model, is consistent with the magnitudes of costs from IAMs. The other, based on Burke *et al.* (2015), is consistent with much higher econometric projections of damage costs. Both estimates were implemented in the PAGE model

3.2.1 Overview of the PAGE model

PAGE (Policy Analysis of Greenhouse Effect) is an IAM that values the impacts of climate change and the costs of policies to abate and adapt to it (Hope, 2011a). It was the primary tool used in the Stern report to estimate the impacts of climate change (Stern, 2007). It has been employed by environmental agencies such as the United States’ EPA, in combination with the DICE model (Moore and Diaz, 2015) and the FUND model (Anthoff and Tol, 2013). PAGE is regularly updated to incorporate the latest improvements in climate and economic developments. The version used in this study contained updates by Moore *et al.* (2018) and Yumashev *et al.* (2019).

PAGE splits the world into 8 large geopolitical blocs.[11] Radiative forcing is represented by six anthropogenic agents, including CO_2, CH_4, and N_2O. A climate sensitivity-based model is used to calculate the global mean temperature change, which is scaled for the 8 regions, and also sea-level rise and discontinuity impacts. The default version of PAGE extends until the year 2200 to incorporate slower processes such as ice sheet melt. It estimates climate-driven impacts in each region across four broad categories:

- sea-level rise (coastal flood damage; relocation);
- economic (both direct and indirect damages to the aggregate economy);
- non-economic (ecosystem services; public health); and,
- discontinuity (large-scale damages associated with possible tipping points in the climate and economy).

Regional economic and non-economic impacts are calculated as percentage loss/gain of the relevant regional GDP in a given future year using regional temperature change. Non-economic sector monetarisation relies on existing standardised measurements (e.g. loss of life or health) or commonly valued effects (e.g. ecosystem services). It is difficult to compare PAGE assumptions with other models as the underlying assumptions from other models for metrics such as the Value of a Statistical Life (VSL) are not transparent. These affect consumption only, as endogenous impacts on economic growth are currently being developed. Regional adaptation spending is designed to allow tolerable levels of warming and sea-level rise, beyond which climate-induced damages occur. PAGE is unique in its representation of all three sets of costs in a risk-based framework. The assumptions for adaptation levels and damage reductions are harmonised to the results from de Bruin *et al.* (2009). The regional impacts are equity-weighted depending on relative wealth and are discounted to a base year. Future GDP and population projections follow exogenous SSP scenarios – SSP2 in our analysis. Uncertainty quantification is achieved by Monte Carlo analysis over the probability distribution functions (PDF) of roughly one hundred parameters, most of which are poorly constrained (Hope, 2011a). The probability distributions are

[11] Europe (EU), the United States (US), other countries in the Organisation for Economic Cooperation and Development (OT), the former Soviet Union (EE), China, Southeast Asia (SE), Africa (AF), and Latin America (LA).

calibrated from more sophisticated earth system, energy system, climate impact, infrastructure exposure and economic models.

3.2.2 PAGE damage functions

The method used in PAGE is described in detail in Hope (2011a), Moore *et al.* (2018) and Yumashev *et al.* (2019). Refer to these papers for details beyond the summary here.

Economic and non-economic impacts before adaptation are represented using a polynomial function of the difference between the regional temperature and the tolerable temperature level, with regional weights representing the difference between more and less vulnerable regions. For example, in developed regions, if no economic impacts occur until 2 °C is exceeded then the tolerable temperature is 2 °C. If there is no tolerable temperature for non-economic impacts anywhere then the model would compare the difference between the regional temperature and the preindustrial temperature to estimate damages. The tolerable temperature level can be increased by adaptation investments in PAGE. For our scenarios, we assumed investments for a global tolerable temperature of 1.5 °C in 2100.

These impacts are then equity weighted, discounted at the UK Government Green Book discount rate of 3% per year (HM Treasury, 2022) and summed over the studied period. Initial benefits from small increases in regional temperature are represented by linking impacts explicitly to GDP per capita. Finally, to reflect saturation in GDP loss, the impacts drop below their polynomial values on a logistic path once they exceed a certain proportion of remaining GDP due to the vulnerability of economic and non-economic activities to climate change.

Sea level impacts are represented using a polynomial function of sea-level rise calculated from the global temperature change. The estimation of damages from sea-level rise then follows the mathematical representation of economic and noneconomic impacts explained above.

The risk of large-scale discontinuities, such as the Greenland ice sheet melting, is represented if the temperature rise is substantial. Losses associated with a discontinuity do not all occur immediately but instead develop with a characteristic lifetime after the discontinuity is triggered. As the baseline scenario of this study follows the Paris Agreement target of 1.5 °C, discontinuity impacts were not expected to strongly influence the results.

To represent the high damage costs scenario, the damage function from PAGE09 was recalibrated to have impacts consistent with Burke *et al.* (2015). This study projects higher damages than most econometric studies (23% reduction in income per capita in 2100 for an RCP8.5 scenario) but makes some conservative assumptions (see Section 2.1.1 for a discussion of this and other econometric studies). Burke *et al.* (2015) propose estimating the impact of climate change on the log of the output growth rate in a given country as a function of how much the temperature in the country changes relative to its base year value. We therefore changed the damage function in PAGE to be a function of the absolute temperatures in the 8 regions corresponding to the present-day climatology obtained from ERA-Interim re-analysis (ECMWF, 2022), adjusted to the PAGE base year climatology using EEA (EEA, 2022) and NOAA temperature records (NOAA, 2022). The function uses linear and quadratic coefficients for the Burke log GDP per capita change impact function of the regional temperatures. This new function is plotted in Figure 1 for the simulated mean and ±1 standard deviation range. The standard deviation represents the uncertainty representation in PAGE.

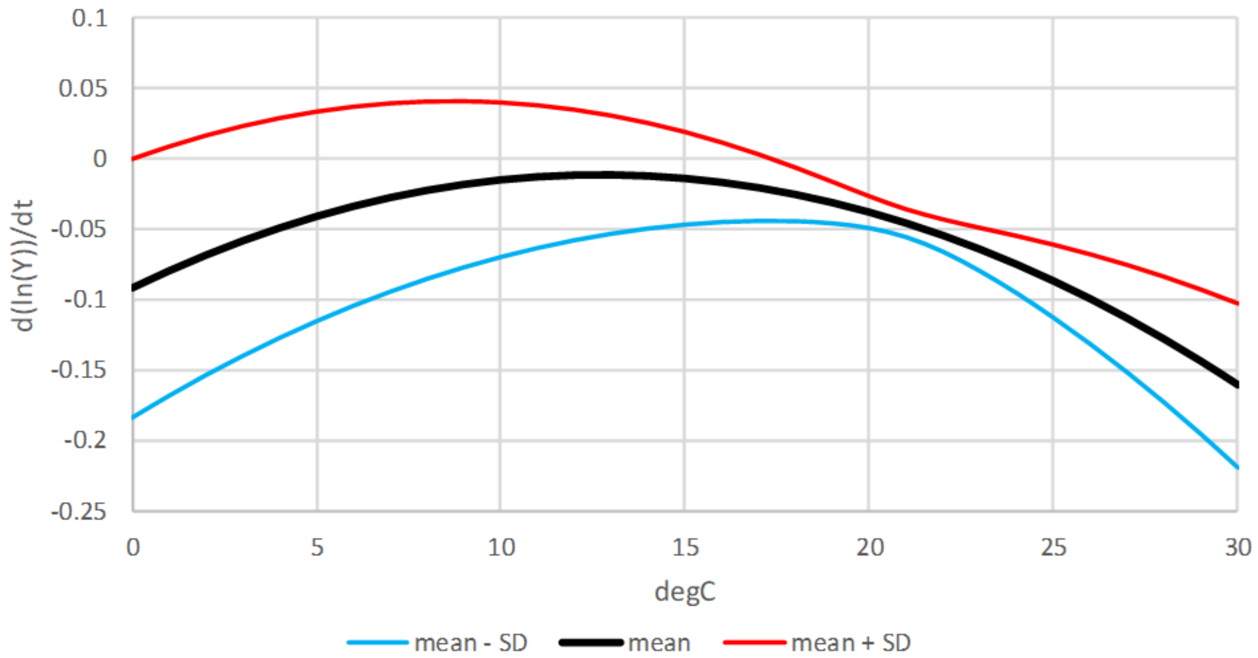

Figure 1. Economic impact function $h(T)$ in PAGE representing the Burke damage function expressed in terms of the absolute temperature T in °C. Only a few Sahel countries have mean temperatures exceeding 30 °C and these are aggregated across Sub-Saharan Africa. Reproduced from: Yumashev (2020).

A large proportion of climate damages are likely to be impacts on human wellbeing, particularly the quality of life. Some health economists measure benefits using "Quality Adjusted Life Years" gained, which is closely related to per capita GDP. As a consequence, impacts are equity-weighted so that for each region they are a function of the GDP per capita and the elasticity of the marginal utility of consumption. This last parameter increases the (relative) valuation of impacts in regions that are poorer and decreases the valuation of impacts in regions that are richer. PAGE uses the equity-weighting scheme proposed by Anthoff *et al.* (2009) that converts changes in consumption to utility. The equity-weighted damage is then discounted at the consumption rate of interest. All these inputs are represented as probability distributions.

3.2.3 PAGE representation of adaptation

In PAGE, adaptation increases the tolerable level of temperature change or sea-level rise. It also reduces any climate change impacts that occur above the tolerable levels.

Adaptation policy is specified by seven uncertain inputs that are each applied to three damage categories: sea level, economic and non-economic impacts (discontinuity impacts – i.e. tipping points – have no adaptation policy available, but most are unlikely to be triggered in overshoot scenarios in which the global temperature increase does not exceed 2 °C). We assumed full adaptation to 1.5 C warming by 2100 through investments over the next 75 years, starting in 2025. Adaptation is assumed to increase linearly over this period. Future studies could examine the impacts of higher levels of adaptation (e.g. adapting to 1.5 °C by 2075, or even adapting to overshoot temperatures during the overshoot). However, the representation of adaptation in PAGE is quite simplistic and the assumed costs and deployment levels are quite old, so we have low confidence in the treatment of adaptation in the model. For example, investing to achieve Sustainable Development Goals (SDGs) might reduce the vulnerability of poorer populations to climate change, but such strategies are not considered in page as damage functions are fraction of GDP at each temperature.

The adaptation costs in PAGE are consistent with the findings of de Bruin *et al.* (2009). They are scale-dependent as they are expressed as a percentage of GDP per unit of deployed adaptation measures. The total cost of adaptation depends on the change in the slope and plateau of the function representing tolerable temperature or sea level increase over time, and on the percentage reduction in weighted impacts that occur as a result of the climate variable increasing above its tolerable level. Beyond the tolerable maximum sea level or temperature rise, adaptation against impacts becomes ineffective. Adaptation costs are assumed to benefit from autonomous technical advances.

3.2.4 PAGE method for this study

To analyse the full range of damages from climate change that are represented in PAGE, including the sea-level rise impacts and discontinuity effects, it is often run over the period up to 2200 to include ice cap melting and ocean thermal expansion. Since the global temperature change target of each of the pathways in this study is 1.5 °C, and we focus on the potential effects of overshooting the target before 2100, the simulations for this report have been limited to up to 2100. Moreover, the pathways created in this study were only defined for the period 2010 to 2100.

The climate module of TIAM-UCL was calibrated to the latest IPCC AR6 climate sensitivity to analyse the overshoot pathways, as reported in Annex 1. PAGE is calibrated to the IPCC AR5 climate sensitivity (IPCC, 2014), which has a wider range and higher central value (Table 4). So instead of using the PAGE climate module, global temperature changes from the TIAM-UCL scenarios were used directly in the PAGE framework and the analysis was focused only on the benefit-cost analysis of damages and adaptation.

Table 4. Equilibrium Climate Sensitivity (ECS) estimates from IPCC AR5 and AR6.

Assessment/Study	Central ECS (°C)	ECS Range (°C)	Confidence Interval
IPCC AR5 (Collins *et al.*, 2013, Flato *et al.*, 2013)	3.2	1.5–4.5	Likely (>66% probability)

IPCC AR6 (Forster *et al.*, 2021)	3.0	2.5–4.0	Likely

Climate change damages were estimated for each of the three overshoot pathways and for the NO pathway. For each pathway, damage costs were estimated for scenarios that used either the PAGE09 (P) or Burke (B) calibrations of PAGE. Table 5 summarises the analysed scenarios and the names used in this report to denote the scenarios. One set of scenarios did not consider adaptation. A second set of scenarios estimated the costs and impacts of adaptation to temperature change and sea-level rise corresponding to their global extent in 2100 in the NO pathway. In the results, the damage cost scenarios are denoted using <pathway>_<P/B>(-Ad) as shown in Table 5.

Table 5. Damage cost pathways examined in this study.

Pathway	Damage costs	Damage cost scenarios
No Overshoot (NO)	PAGE09 (P) and Burke (B) calibrations, each without and with adaptation (-Ad)	NO_P, NO_B, NO_P-Ad, NO_B-Ad
Low Overshoot (LO)		LO_P, LO_B, LO_P-Ad, LO_B-Ad
High Overshoot (HO)		HO_P, HO_B, HO_P-Ad, HO_B-Ad
Very High Overshoot (VHO)		VHO_P, VHO_B, VHO_P-Ad, VHO_B-Ad

3.2.5 Comparison of the PAGE09 and Burke damage estimates from PAGE

Annual damage costs without adaptation and without discounting from a probabilistic assessment in PAGE are presented in Figure 2. The high uncertainty shown in each graph is the result of around 150 different parameters in the model encompassing uncertainties in climate, emission, socio-economic and costs representations. Burke damage costs are an order of magnitude larger than PAGE costs (note the differing y-axis scales). The damages in the NO pathway are relatively flat for the PAGE09 damage function, reaching a maximum of \$3tn/year in 2050. In contrast, the Burke damage function for the same scenario has damages up to \$39tn in 2025–2030, which then decrease to around \$13tn/year in 2100.

The variation arises from the different way the damage functions have been produced. The PAGE09 damage function is derived from the physical impact of climate changes reported by impact models in IPCC AR4, while the Burke function has been estimated from econometric analyses of existing climate impacts. The shape of the function is also important. As the global temperature increases, the level of damages increases exponentially in the PAGE09 function in Figure 2, due to the typical PAGE09 damage functions that are illustrated in Figure 3.

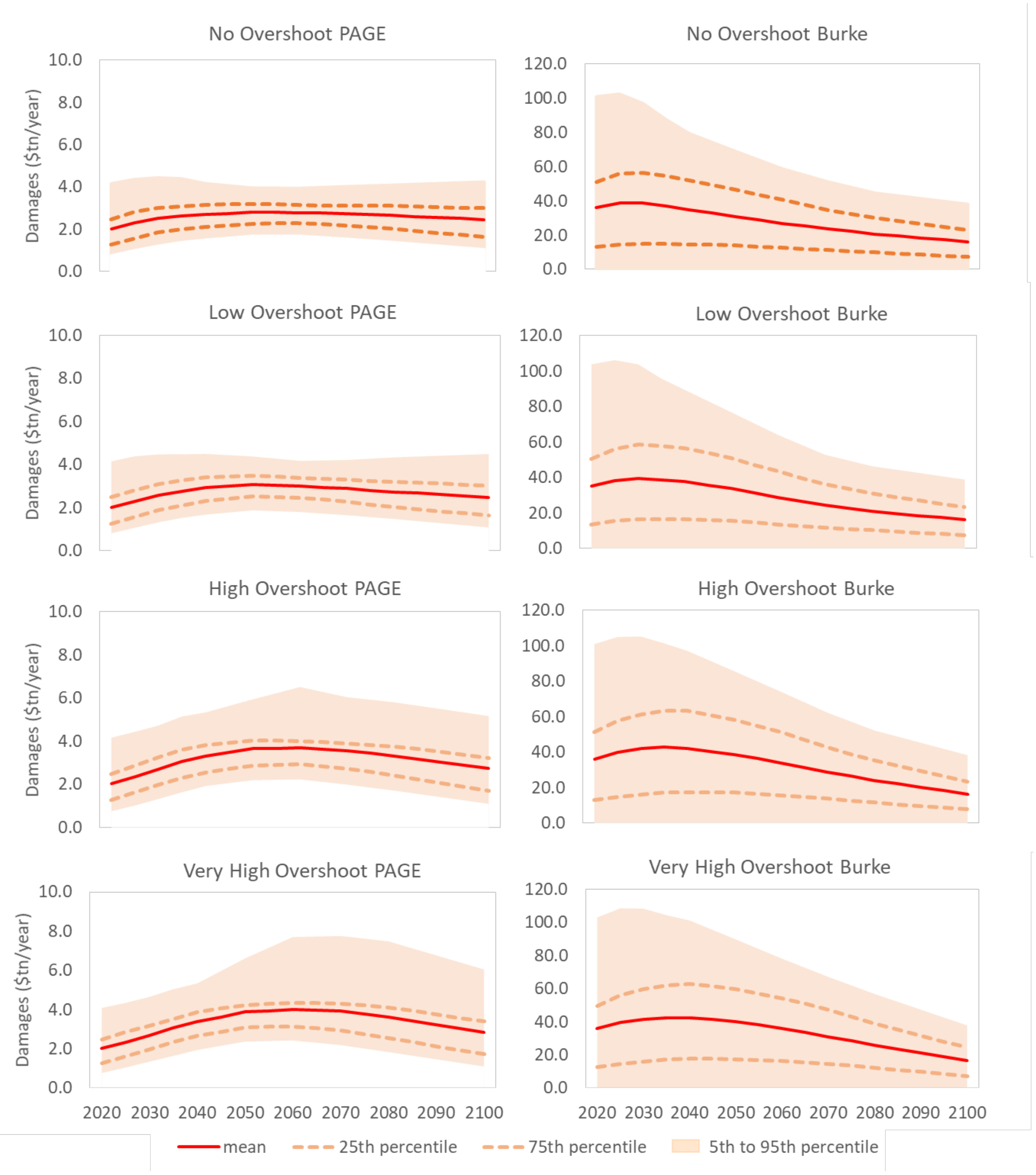

Figure 2. Annual global damage costs without adaptation for the four pathways. The left and right columns present results using the PAGE and Burke damage functions, respectively, with costs undiscounted. The solid red line represents the mean damage cost, the orange dashed lines represent the 25th and 75th percentiles and the shaded area represents the 5th to 95th percentiles.

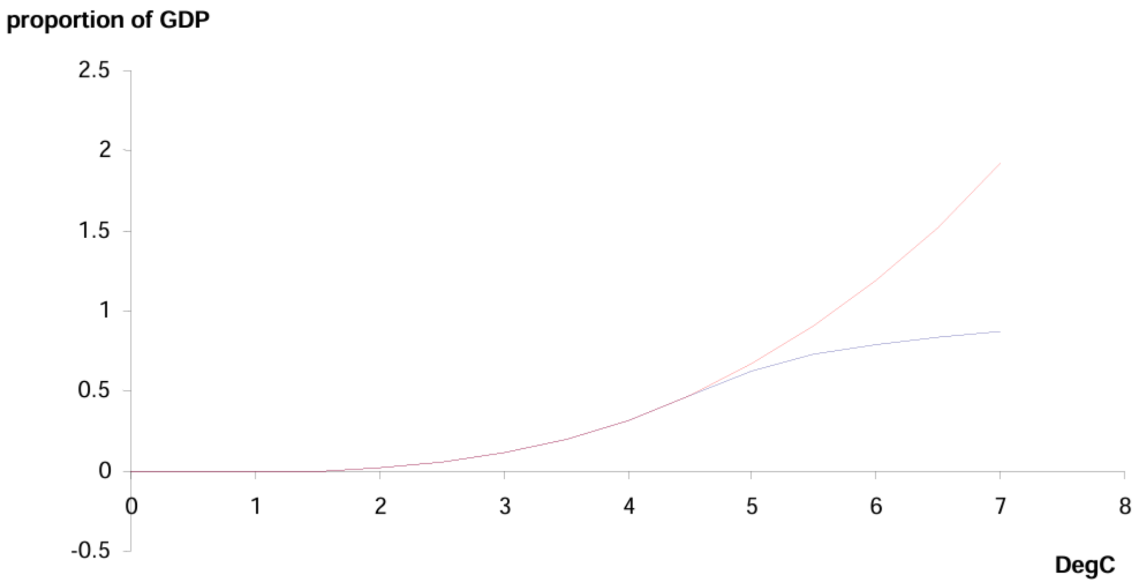

Figure 3. Examples of exponential GDP loss functions in PAGE09 as a function of temperature. The blue line is not exponential because there is saturation of 100% GDP loss in some regions. From: Hope (2011a).

In contrast, damages reach a plateau and decrease in the Burke function in Figure 2. The Burke damage function has a convex shape and is function of the annual mean land surface temperature over the region, as shown in Figure 4 (Burke *et al.*, 2015). Regions such as the EU are to the left of the apex of the curve, so increasing temperature causes the growth rate to increase rather than decrease. At the apex of the curve, the effects on GDP are slightly positive. As the differences in temperature between the NO and overshoot pathways are quite small (1.5 °C to 1.9 °C global mean), the overall impact is a reduction in damages over time, which is driven by higher GDP rises in richer, high-latitude countries and lower GDP in the Global South. If warming were to rise further, beyond 2 °C globally, then the damages would increase sharply as more countries moved to the right of the apex, particularly high-latitude countries.

In the VHO pathway in Figure 2, Burke damage costs continue reducing even as the temperature falls from 1.9 °C to 1.5 °C, which does not appear to be consistent with Figure 4. The reason for this non-intuitive behaviour is that damages for small changes in the global temperature (i.e. around 1.5 °C) are greatly affected by the choice of applying equity weighting to damage values. Damages are higher in lower-income countries and equity weighting is applied in PAGE to account for the relative cost of damages reducing in the future as those countries develop. The weighting in PAGE is calculated from European Union values for GDP/capita (the focus region in PAGE) using future GDP/capita projections of each region. In SSP2, there is an increase in GDP in all regions, and this drives the reduction in damage costs. Damage costs from PAGE with and without equity weighting are compared in Figure 5. With no equity weighting, damage costs increase approximately linearly with GDP even as temperature stabilises at 1.5 °C as they are proportional to GDP. With equity weighting, the damages reduce over time despite the temperature not changing after 2050 due to higher GDP development in the Global South. Using equity weighting will dampen the differences between the NO and overshoot scenarios in the long term. Anthoff *et al.* (2009) consider the implications of using equity weighting for climate damages on the social cost of carbon.

One important uncertainty is the temperature at which the convex shape peaks. A higher temperature would cause lower damages as the global temperature rises. Burke *et al.* (2018) estimate a median of 13 °C with a 5%–95% range of 10–17 °C. In contrast to the Burke scenario in Figure 2, that study concludes that limiting the global temperature rise to 1.5 °C would have around a 70% chance of net economic benefits in 2100 compared to a 2 °C rise, with the benefits mostly realised in the Global South.

The uncertainty in the Burke function, in Figure 1, reduces as the temperature increases up to 20 °C. This causes the uncertainty envelope in the PAGE outputs in Figure 2 to reduce over time. It is not clear that the consequent damage estimates from the Burke function – reducing over time as global warming increases towards 1.5 °C – is realistic in practice, not least because these estimates do not consider increases in weather instability and extremes as warming increases.

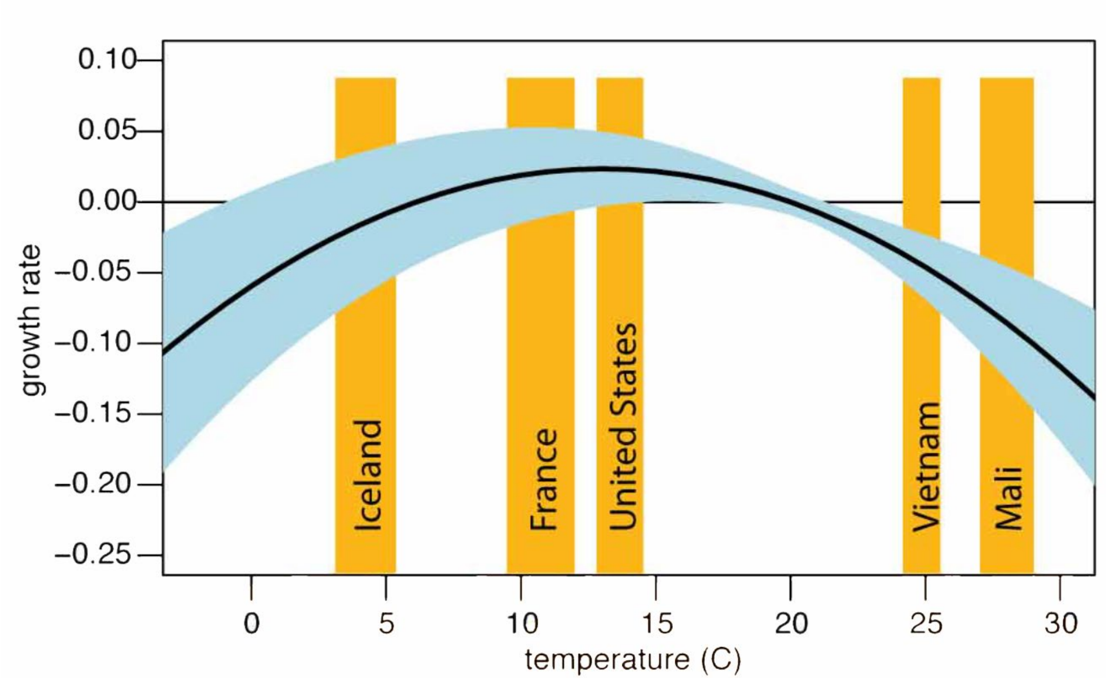

Figure 4. Burke damage function with the temperatures of some countries illustrated. From: Burke *et al.* (2015). [Reproduced with permission from Springer Nature](#).

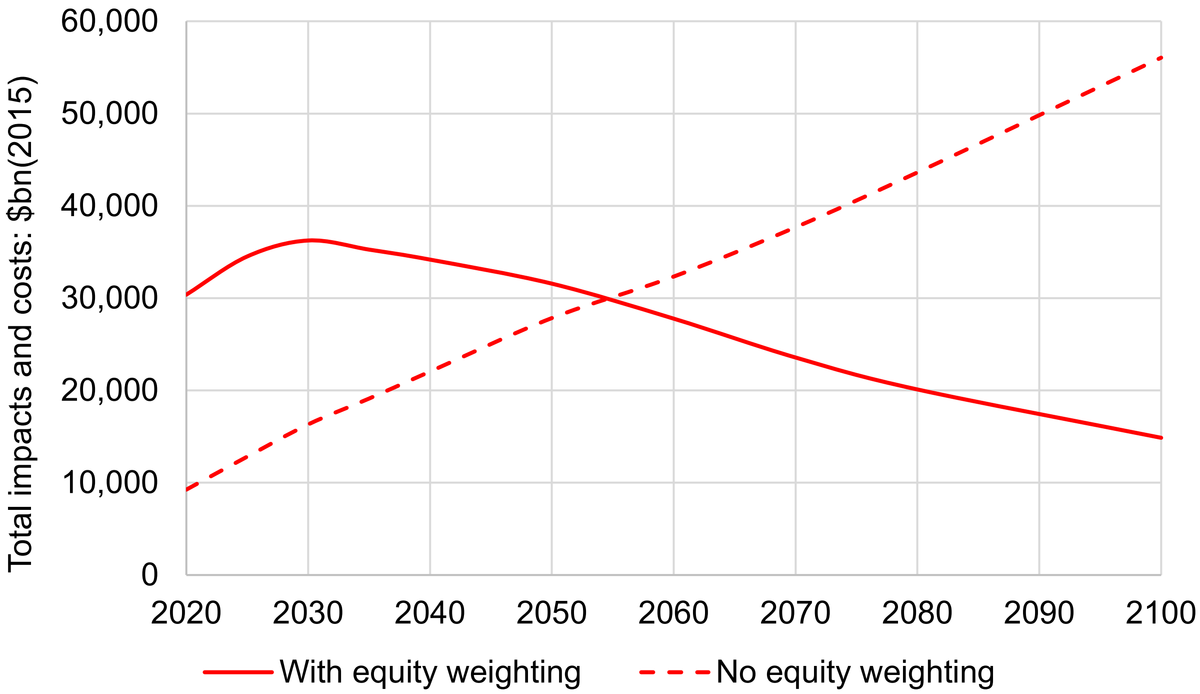

Figure 5. Global damage costs using the Burke function with and without equity weighting. Costs are shown for the NO pathway using the Burke Damage costs function. Units: $bn(2015).

3.2.6 Results of scenarios without adaptation

In comparison with the NO pathway, Figure 2 shows that the maximum damages in the LO, HO and VHO pathways using the PAGE09 function increase by 0.3, 0.9 and 1.2 $tn/year in 2050. Although Burke damage costs reduce over time, this reduction is lower for the overshoot pathways than for the NO pathway, so overshooting causes higher damages. The increase in 2050 using the Burke function is 3.5, 7.8 and 9.5 $tn/year, respectively. So the impacts of overshooting are amplified when using the Burke damage function.

Overall damages 2025 to 2100 are presented in Table 6. These were discounted in PAGE at 3%/year, following the Green Book recommendation in HM Treasury (2022), and aggregated over the period 2020–2100. The discount was removed for the integrated cost analysis in Section 3.5.

For both damage functions, the LO pathways increase the aggregated discounted damage costs over the period 2023–2100 by 5% and the High overshoot pathway by 16% (Table 6). The VHO pathway increase is 25% for PAGE09 and 22% Burke. Even the difference in the peak global temperature of less than 0.1 °C between the VHO and High overshoot pathways increases the aggregated discounted damage costs by 8% for PAGE09 and 6% for Burke.

Table 6. Aggregated damage costs for each pathway over the period 2023 to 2100. Differences between the overshoot and NO pathways are also shown. Results are presented for both the PAGE09 and Burke damage functions. All figures assume a future discount rate of 3%/year.

Pathway	Undiscounted damage costs	Difference (overshoot – NO)		Damage function
		($tn)	(%)	
NO_P	207			PAGE09
NO_B	2161			Burke
LO_P	217	10	5%	PAGE09
LO_B	2258	97	5%	Burke
HO_P	243	35	17%	PAGE09
HO_B	2509	348	16%	Burke
VHO_P	260	53	25%	PAGE09
VHO_B	2639	478	22%	Burke et al.

3.2.7 Results with adaptation

The adaptation level and rate of deployment of adaptation measures are parameters in PAGE that are chosen by the modeller. As the pathways in this study all limit the global temperature rise in 2100 to 1.5 °C, the adaptation level is assumed as the response to temperature and sea-level rise in each region. As the overshoot is temporary, adaptation for 1.5 °C was assumed for economic and non-economic damages and up to 0.86 m for sea-level rise. These assumptions correspond to the global values in 2100 in the pathways. While the final sea-level rise would be different in each pathway as it is a function of the total additional heat (see Annex 5 of this report on natural system impacts), the impact of overshoot on sea-level rise by 2100 is limited as the time lag between atmosphere and ocean is quite long.

Figure 6 compares damage and total costs (defined here as the sum of damages and any adaptation) with and without adaptation for the cases with the Burke damage function. PAGE outputs are presented for the NO and VHO pathways and the difference between the two. Including adaptation in the pathway leads to the total cost increase due overshooting peaking at up to $7.5tn/year in 2050, which is $2tn/year lower than for the same pathways without adaptation.

Adaptation is assumed to start in 2025 and be implemented gradually over the period 2025–2100, as shown in the panels inside the “With adaptation” panels of Figure 6. Adaptation costs reach a maximum of $0.5tn/year in 2070 so are much smaller than damages. By this year, more developed economies have reached the level of adaptation required. However, investment in adaptation in 2100 is still around $0.3tn/year, which suggests that all required adaptation has not yet been put in place in lower-income countries.

Adaptation reduces the impacts of damages produced by climate change. The resulting values of undiscounted damages reduce towards zero in 2100 as the global temperature rise returns to 1.5 °C. Moreover, the total costs, including damage costs, reduce from 2025 due to investments in adaptation, in contrast to the reasonably flat costs that occur if adaptation is not implemented (particularly in the VHO pathway when costs peak in about 2040).

The overall aggregated costs of damages and adaptation investments for each pathway are presented in Figure 7 and in Table 7 for the two damage functions. Both show undiscounted costs and Table 7 also shows costs discounted at 3%/year from 2023. Adaptation level and speed of deployment are identical in all the overshoot scenarios with adaptation. Adaptation decreases the damage costs for each pathway (Figure 7). The level of adaptation has been adjusted to the climate change levels expected to be achieved in 2100 (1.5 °C above pre-industrial) and the overall cost of adaptation is much smaller than the damage costs they avoid.

The total undiscounted cost of adaptation is $24tn over the period from 2025 to 2100. Discounting at 3%/year reduces the aggregated adaptation cost to $7tn over the same period as the maximum yearly adaptation investments occur relatively late in the period (between 2060 and 2080).

With adaptation, the aggregated undiscounted damages for the VHO pathway are reduced from $260tn to $109tn for the PAGE09 damage function, and from $2639tn to $1347tn for the Burke function. Hence $24tn of adaptation investment reduces the damage costs by

$151tn for the PAGE function and $1292tn for Burke function. So adaptation costs are only 1% of Burke damage costs but about 10% of PAGE09 damage costs.

Figure 6. Annual undiscounted global damage costs for the Burke damage function. The right-most panels present the differences between the VHO and NO pathways. Uncertainty ranges are presented in the same way as Figure 2.

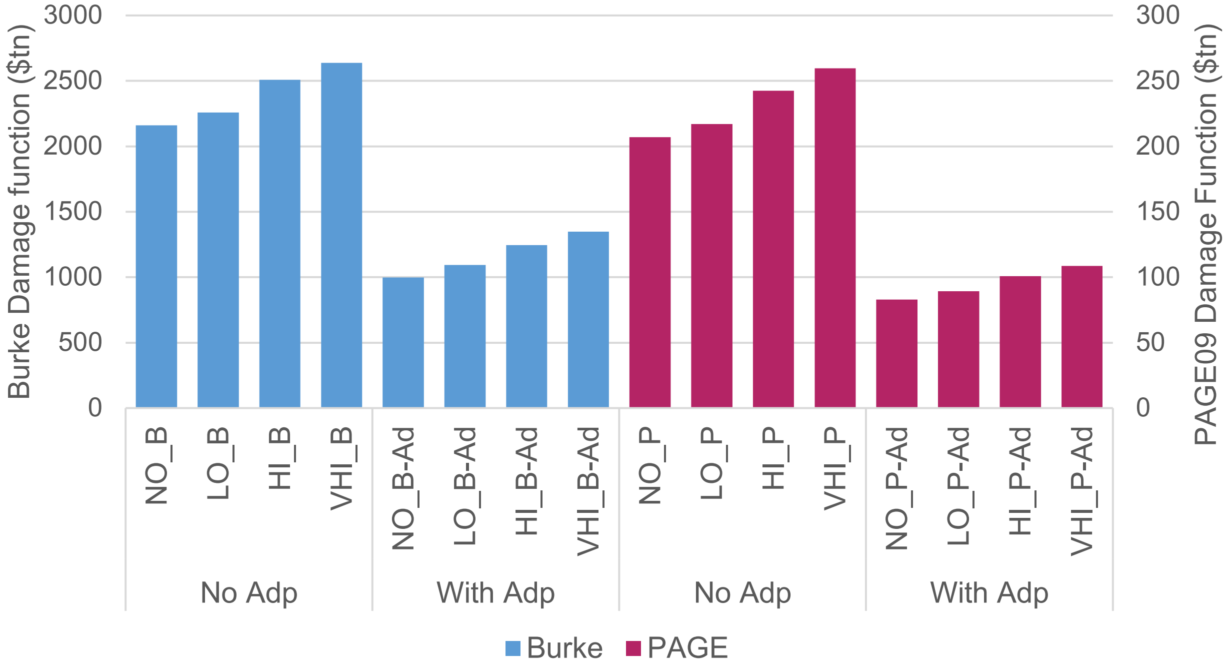

Figure 7. Total undiscounted aggregated damage costs for each overshoot pathway. Total costs include damage only in the cases without adaptation and sum of damage and adaptation costs in the cases with adaptation. Separate costs are shown for the PAGE09 and Burke damage functions. The y-axes for each damage function have different scales.

Table 8 shows that adaptation reduces the overall undiscounted damage costs of the pathways by around 60% for PAGE09 and 50% for the Burke damage function, with the difference caused by variations in the shape of the damage cost curve between the two functions. The reduction in total discounted costs is around 44% and 35% for the PAGE09 and Burke damage functions, respectively. The difference between the undiscounted and discounted damage costs reflects the predominance of adaptation later in the century, as the adaptation level builds-up from 2025 to 2100.

3.3 Mitigation costs

The IPCC AR6 concluded that mitigation measures to reduce emissions sufficiently to limit probable warming to 2°C would cause losses to global GDP of between 1.3% and 2.7% in 2050 (Riahi *et al.*, 2022). In this study, we compare the costs of overshooting 1.5 °C, for all three overshoot pathways, against a counterfactual pathway of not overshooting.

Table 7. Aggregated damage costs of each overshoot pathway for the two damage functions. Total costs include damage and adaptation investment costs and are presented undiscounted and discounted at 3%/year for the period to 2100.

Damage function	Adaptation	Aggregated total costs ($tn)				Pathway: X=
		NO_X	LO_X	HO_X	VHO_X	
Undiscounted costs						
PAGE09	No	207	217	243	260	P
Burke	No	2161	2258	2509	2639	B
PAGE09	Yes	83	89	101	109	P-Ad
Burke	Yes	997	1094	1246	1347	B-Ad
Discounted 3%/year						
PAGE09	No	79	83	91	97	P
Burke	No	968	1002	1096	1151	B
PAGE09	Yes	44	47	51	54	P-Ad
Burke	Yes	607	657	714	752	B-Ad

Table 8. Percentage change in aggregated damage costs due to adaptation for the two damage functions. Costs are presented undiscounted and discounted at 3 %/year.

Damage function	Adaptation impact on aggregated costs (%)			
	NO_X	LO_X	HO_X	VHO_X
Undiscounted costs				
PAGE09	-60%	-59%	-58%	-58%
Burke	-54%	-52%	-50%	-49%
Discounted 3%/year				
PAGE09	-44%	-43%	-44%	-44%
Burke	-37%	-34%	-35%	-35%

3.3.1 Method

We assessed the mitigation costs for each pathway using the TIAM-UCL integrated assessment model. TIAM-UCL is a cost-optimising technoeconomic energy system model linked to a climate module that has a detailed representation of the entire global energy system. Supply chains for primary energy sources (oil, gas, coal, nuclear, biomass, and renewables) are represented from production through to conversion (e.g. electricity production), transport and distribution, and eventual use to meet energy service demands across a range of economic sectors. The model is described in detail in the documentation from Pye *et al.* (2020). Using a scenario-based approach, it identifies the lowest-cost evolution of the system to meet future energy service demands across the economy (mobility; residential and service sector heating, cooling and cooking, lighting and other electrical demands; industrial process and other industrial and agricultural demands). The least-cost objective is to minimise the discounted total system cost over the whole time horizon of the model. Annex 1 of this report contains further details on TIAM-UCL and how it was used to develop the pathways for this study.

TIAM-UCL normally assumes a future social discount rate of 3.5%. This figure was also used for the cost optimisation in this study. Undiscounted costs were outputs from the model and several other discount rates were applied to the cost outputs to understand the sensitivity of the results to the future discount rate.

Another key determinant of total costs and differences between pathways is the assumed cost of future CDR. Annex 2 reviews the costs assumed in TIAM-UCL and finds they are substantially higher than assumed in recent literature. For this reason, a second set of cost-optimised pathways were developed with lower future CDR costs in line with the literature. As overshoot pathways have higher CDR than the NO pathway, assuming lower CDR costs should reduce the relative costs of overshooting.

The LO pathway assumes lower CDR availability than the other three pathways. This causes LO costs to be higher than for the other pathways. In order to compare the pathways fairly, the LO pathway was rerun with full CDR availability for this cost analysis. The two LO pathways are compared below.

3.3.2 Results

Although TIAM-UCL produces a wide range of information on energy system technology deployment and costs for each of the 16 regions, the results presented here are aggregated globally across all sectors of the economy and only the influence of discount rate and CDR costs on the overshoot pathways is considered.

The total global undiscounted energy system costs are compared for each pathway in Figure 8 as a function of the assumed cost of CDR. The NO pathway has higher costs than the two high overshoot pathways until around 2060 as a result of much greater emissions mitigation, but then has lower costs to 2100 through lower investments in CDR. The LO pathway tends to have high costs over the whole period to 2100 because biomass availability and CDR availability are assumed lower in this pathway than the other pathways, so deeper mitigation using expensive abatement measures is required to offset the reduction in CDR. A variant of the LO pathway with the same biomass and CDR availability as the NO pathway has a higher overall undiscounted cost, due to higher CDR costs from 2050, but has a similar discounted cost at the model discount rate of 3.5%. The high deployment of CDR in the two high overshoot pathways causes the undiscounted costs to diverge from 2080, in Figure 8b, when higher CDR costs are assumed.

Several factors cause the steady increase in the total undiscounted cost of all pathways in Figure 8. First, the energy system in 2020 uses plants that existed prior to 2005, the start of the model time horizon, and the investment value of these plants is assumed written off. In contrast, investment costs for new plants are fully counted when the old obsolete plants are replaced. Second, population and economic growth both increase demands for energy services worldwide over the time horizon. Third, decarbonisation increases the cost of energy provision; the total cost in 2100 in Figure 8a would be £43tn even if the global economy were not decarbonised. While renewables become the cheapest option to generate electricity and are wider deployed in all scenarios, decarbonising the wider economy, particularly heat and mobility, and deploying CDR causes an overall cost increase. As GDP is assumed to rise steady throughout the century, the increasing energy system cost in real terms does not necessarily mean that energy takes an increasing share of GDP over time. As none of the four pathways exceed warming of 1.5 °C in 2100, they all have substantial mitigation costs compared to pathways with substantial climate change; for example, Luderer *et al.* (2013) conclude that mitigation action costs would greatly reduce if the global mean temperature were allowed to exceed 2 °C.

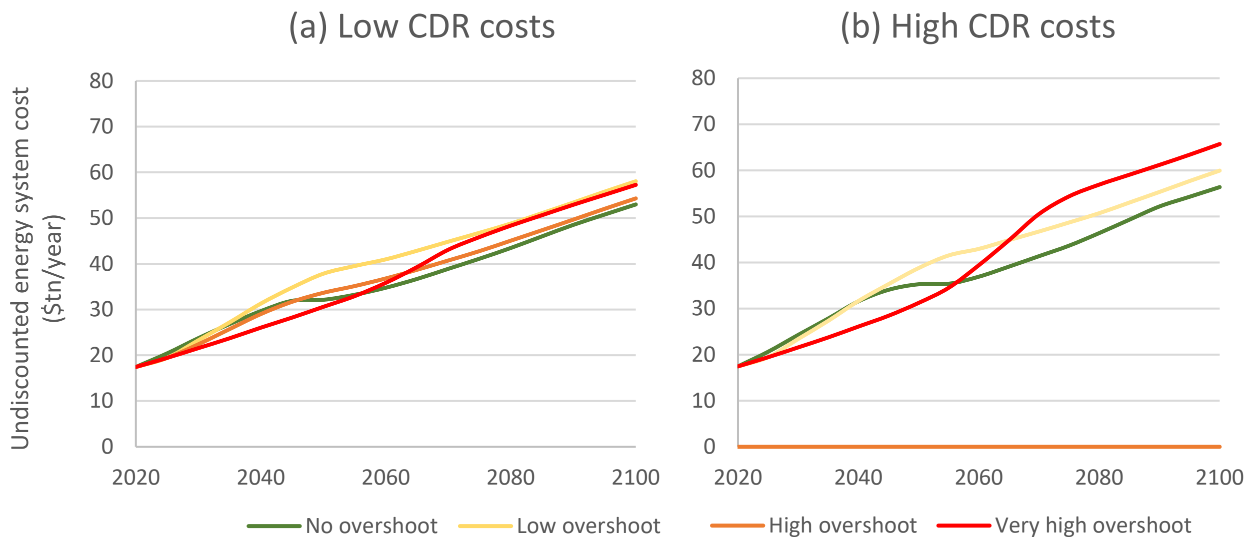

Figure 8. Undiscounted total global energy system costs assuming (a) low CDR costs in line with recent literature, and (b) higher costs previously assumed by TIAM-UCL.

Discounting future costs reduces their relative importance compared to present-day costs. Figure 9 demonstrates the importance of discounting by presenting Figure 8a with a global social discount rate of 3% applied using a base year of 2023. Differences between the pathways are very small after 2060, despite the higher undiscounted costs in the high overshoot pathways.

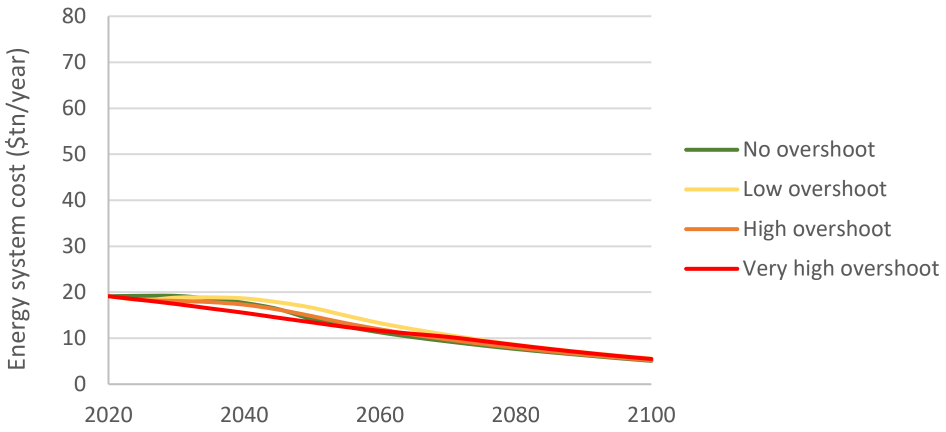

Figure 9. Total global energy system costs with low CDR costs and a social future discount rate of 3%.

The changes in total mitigation costs over the period 2023–2100 due to overshoot are shown in Table 9 for both low and high CDR costs. The LO pathway is always higher cost than not overshooting due to the limited availability of CDR. At 0% and 1% discount rates, all overshoot pathways are higher cost than the NO pathways as a result of higher CDR costs after 2060. At higher discount rates, the overshoot pathways become cheaper as these higher CDR costs are heavily discounted. Higher CDR costs generally cause overshoot pathways to be more expensive relative to the NO pathway, so it would be conservative to use low CDR costs in the overall benefit-cost analysis.

Table 9. Change in mitigation costs due to overshoot as a function of the global social discount rate. All overshoot pathways are compared with the NO pathway. All costs have units $tn in the year 2018 and are cumulative for the period 2023–2100.

Discount rate	0%	1%	2%	3%	4%
Low CDR costs					
Low Overshoot	314	195	123	79	51
High Overshoot	90	27	-4	-19	-25
Very High Overshoot	131	43	0	-19	-27
High CDR costs					
Low Overshoot	237	143	87	53	31
High Overshoot	240	101	28	-8	-25
Very High Overshoot	314	127	34	-11	-30

3.4 Co-benefits of mitigation

Co-benefits of taking mitigation actions are not generally considered in benefit-cost analyses due to their complexity and the challenge of monetising their benefits. In this study, health co-benefits from decarbonising the global economy are included. These health benefits result from better air quality, better diet and greater physical activity due to increased active travel. Air quality improves as fossil fuel use reduces. Diet and physical activity gains are assumed from behavioural change to reduce GHG emissions.

3.4.1 Method

The loss of health improvements through mitigation co-benefits not being realised was estimated in terms of the increase in mortality in the year 2050 compared to a deep mitigation case (Table 10). This analysis was carried out for the International Energy Agency (IEA) “Stated Policies” and “Sustainable Policy” scenarios (Wunderling *et al.*, 2021), which until 2050 have similar but slightly lower temperature trends to the VHO and NO pathways, respectively, as shown in Figure 10. The methods used to identify the impacts in 2050 and the insights are documented in detail in the CS-N0W “Co-impacts of climate change mitigation” report.

Table 10. Increased mortality in 2050 due to not realising mitigation co-benefits, by health domain and region in 2050. Units are deaths/100k population.

Region	Air Pollution	Diet	Physical activity
East & Southeast Asia	55	94	12
European Union	15	183	13
Latin America	15	142	5
North Africa & Middle East	18	141	14
Other Europe	28	268	7
South & Central Asia	55	103	9
Sub-Saharan Africa	10	53	2
USA and Canada	9	154	7
World	34	92	7

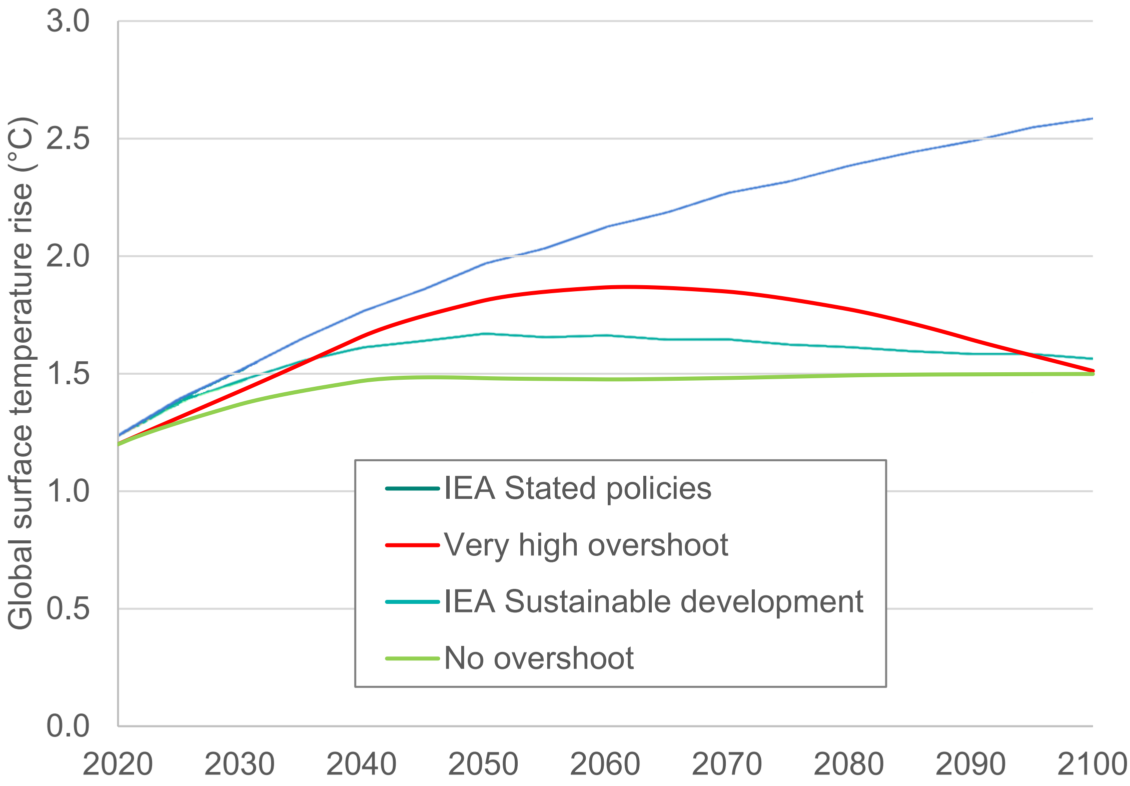

Figure 10. Global temperature pathways for IEA scenarios and the VHO and NO pathways. The IEA pathway data is from IEA (2021) and has since been updated.

The next step was to estimate the number of additional deaths and their economic impacts for each of the overshoot pathways. The low, high and very high pathways delay meaningful decarbonisation by around 5, 15 and 20 years, respectively. The difference in CO_2 emissions between the NO and overshoot pathways shown in Figure 11 was used as a proxy for the level of co-benefits in each 5-year period, in terms of the fraction of mortality from Table 10. This reflects the level of fossil decarbonisation and hence the change in air quality, and might also indirectly represent changes in diet and travel due to earlier decarbonisation measures. This assumption is discussed in detail in Section 3.6.3. Population projections for each world region from SSP2 were used to estimate the additional deaths in each region, for each 5-year period to 2100.

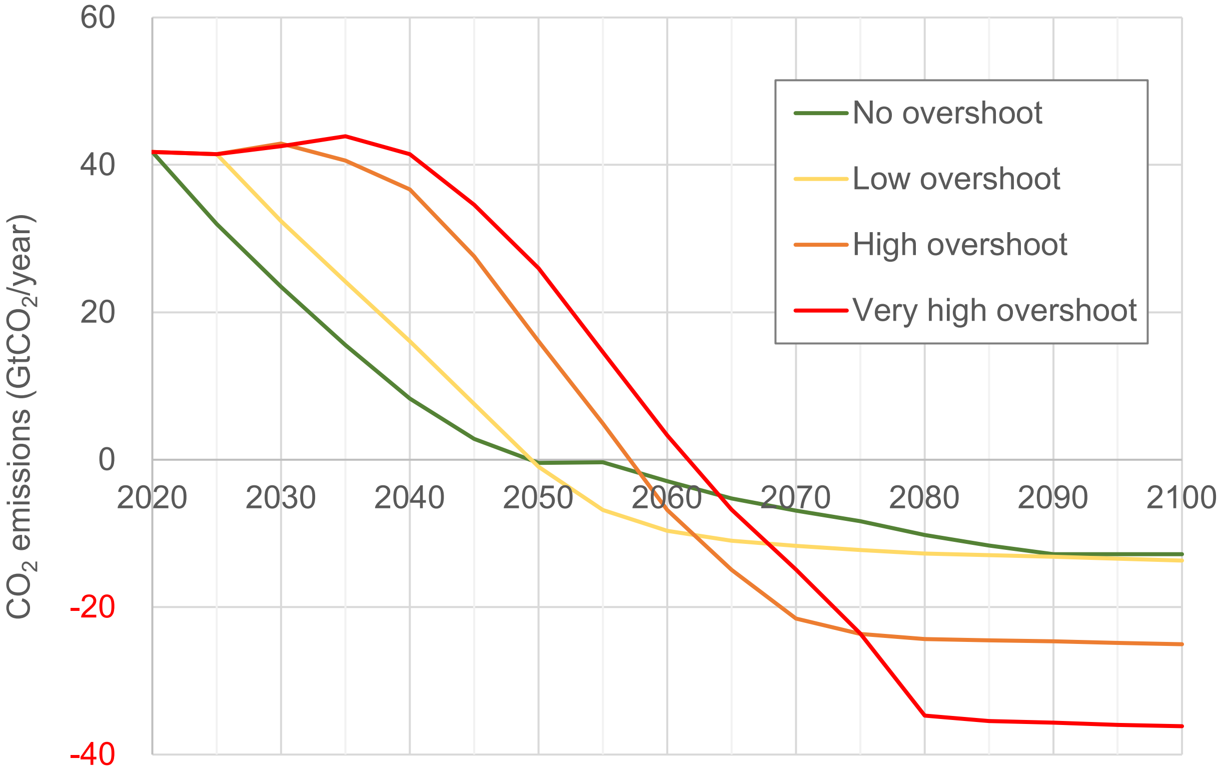

Figure 11. CO_2 emissions in each pathway, from Annex 1 of this report. Units: $GtCO_2$/year.

Finally, mortality was monetised by multiplying the number of deaths by the "value of a statistical life (VSL)". The VSL is an economic value used to quantify the benefit of avoiding a fatality. Estimates vary according to methods and between countries; for examples, \$0.6m in India (Majumder and Madheswaran, 2018) and \$12m in the USA (Putnam, 2021), with one study estimating a global average VSL of £1.3m (Sweis, 2022). VSL could be expressed as a proportion of GDP or average income, but this suggests that a life in high-income country is more valuable than a life in a low-income country. We chose to not differentiate between the value of a life according to the local economy and so we used a single global value between those that tend to be used for high-income and low-income countries. We used nominal value of \$1m/death to estimate the value of co-benefits, which is similar to Sweis (2022).

3.4.2 Results

The loss of co-benefits was represented in the benefit-cost analysis as an additional cost to the overshoot pathways rather than a reduction in the costs of each pathway. Figure 12 shows these undiscounted costs. These costs occur early in the century so are particularly important if a high global social discount rate is assumed. While they are substantially smaller than the total energy system costs in Figure 8, they have a similar magnitude to the difference in energy system costs between pathways in some years.

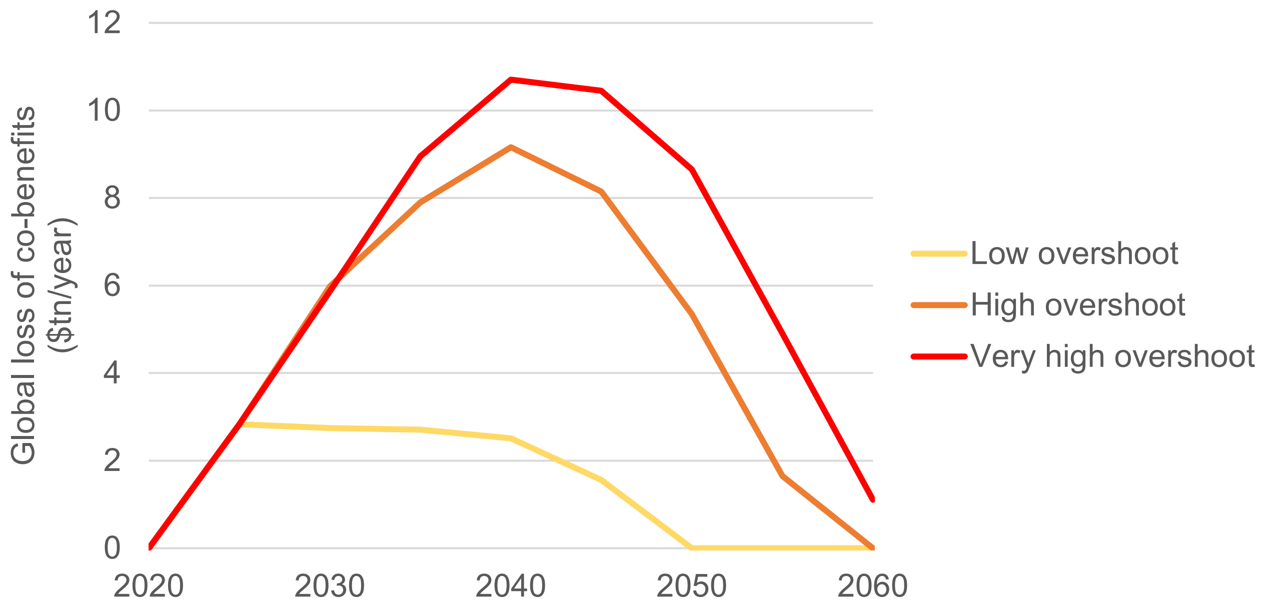

Figure 12. Estimated costs of not realising mitigation co-benefits in the three overshoot pathways, relative to the NO pathway. Global undiscounted costs with units $tn/year are shown.

3.5 Integrating mitigation costs, co-benefits and damage costs

This benefit-cost analysis sums damage and adaptation costs (Section 3.2), mitigation costs (Section 3.3) and the cost of not realising co-benefits (Section 3.4) to calculate and compare the overall costs of each pathway.

Figure 13 and Figure 14 show the total global undiscounted costs of the NO and VHO scenarios for PAGE and Burke damage costs, respectively. Energy system costs increase steadily over time, primarily as a result of a higher population that consumes more energy services in the SSP2 scenario rather than the cost of decarbonisation. With low PAGE damage costs, energy system costs dominate the overall cost throughout the century (Figure 13). With high Burke damage costs, the global cost is relatively unchanged over time but damage costs are gradually replaced with energy system costs (Figure 14).

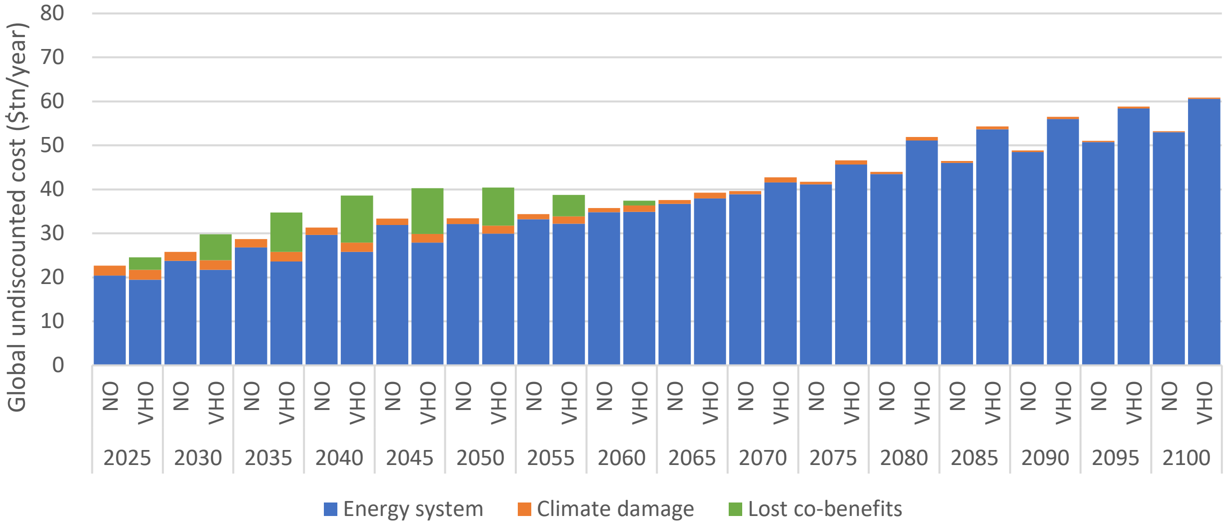

Figure 13. Global undiscounted cost trend assuming PAGE damage costs with adaptation. The NO and VHO pathway costs are shown.

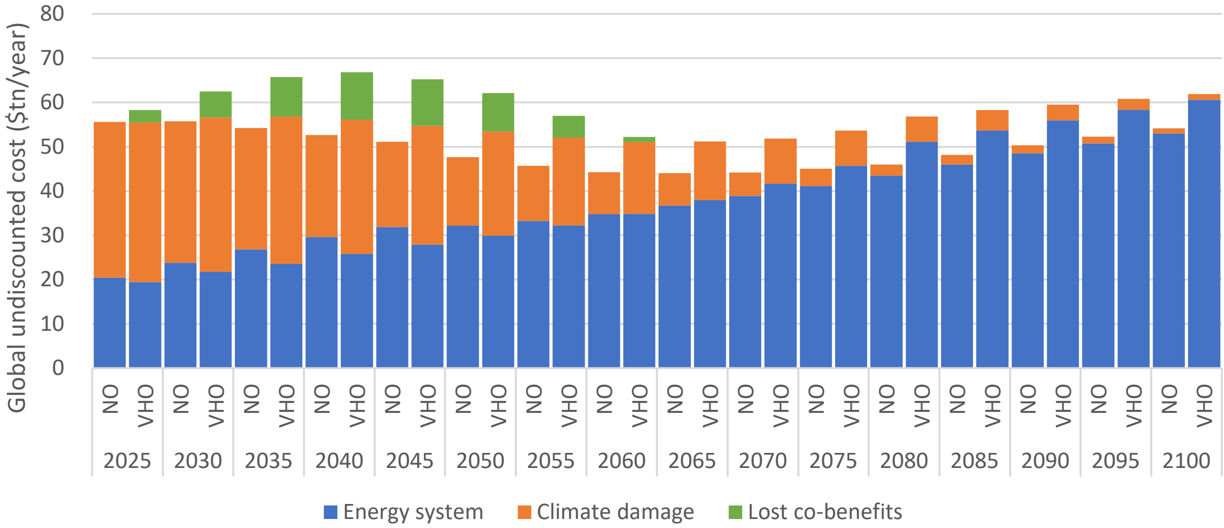

Figure 14. Global undiscounted cost trend assuming Burke damage costs with adaptation. The NO and VHO pathway costs are shown.

The choice of the future global discount rate is an ethical judgement that has been a key parameter affecting previous benefit-cost analyses. It is important for this study because overshoot pathways delay mitigation but have higher long-term CDR costs compared to the NO pathway. Figure 15 shows the global cumulative benefit of overshooting for each of the three overshoot pathways relative to the No overshoot pathway, as a function of the discount rate, using PAGE damage costs. Figure 16 shows the same graph for Burke damage costs. In all scenarios at all discount rates, there is a negative benefit (i.e. a cost) of overshooting 1.5 °C. This cost is smaller for lower overshoots and when using higher discount rates. Mitigation costs are similar for the four pathways so lost co-benefits dominate when the PAGE damage costs are used (Figure 15), while damages and lost co-benefits are similar in each scenario for higher BURKE damage costs (Figure 16).

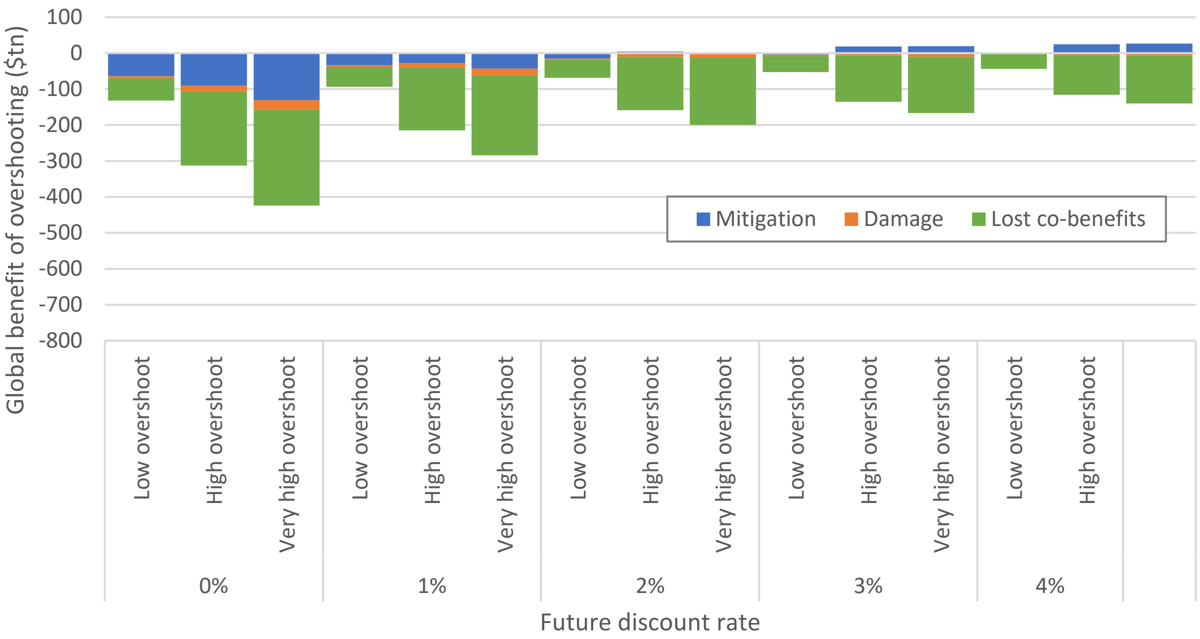

Figure 15. Total global benefit of overshooting 1.5 °C in each overshoot pathway using PAGE damage costs. Global benefits are plotted for the period 2023 to 2100 in $tn.

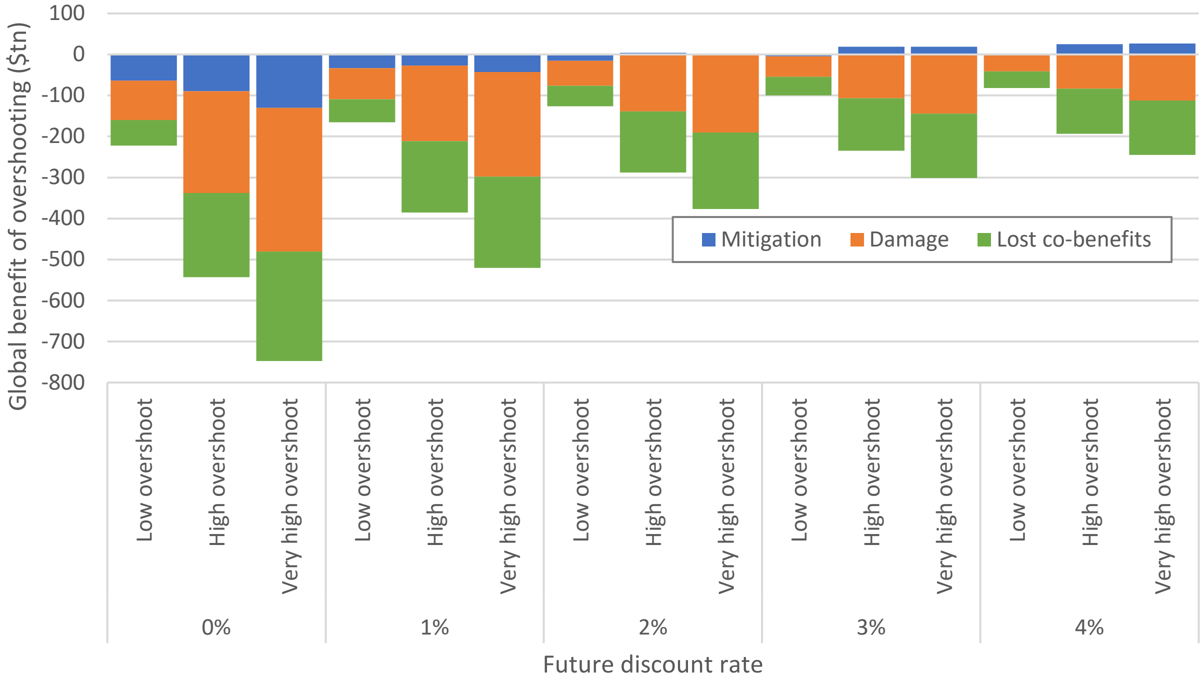

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Figure 16. Total global benefit of overshooting 1.5 °C in each overshoot pathway using BURKE damage costs. Global benefits are plotted for the period 2023 to 2100 in $tn.

As overshooting has negative economic implications in all pathways in Figure 15 and Figure 16, another approach is to ask, “under what conditions the total benefit of overshooting could be positive?”. A VHO pathway is only positive compared to a NO pathway if damage costs are low, co-benefits are excluded and a future discount rate of 3% or higher is chosen (Figure 17a). Figure 17 also shows that adaptation has a relatively small impact on the overall balance of benefits and costs. If the higher rate of mitigation in the NO pathway was substantially more expensive than that assessed in TIAM-UCL then theoretically the benefit of overshooting would increase, but there is no evidence to support such an outcome. On the contrary, damage costs are more likely to be underestimated by PAGE09 and climatic tipping points with huge economic impacts are more likely in an overshoot pathway, but are assumed to not occur.

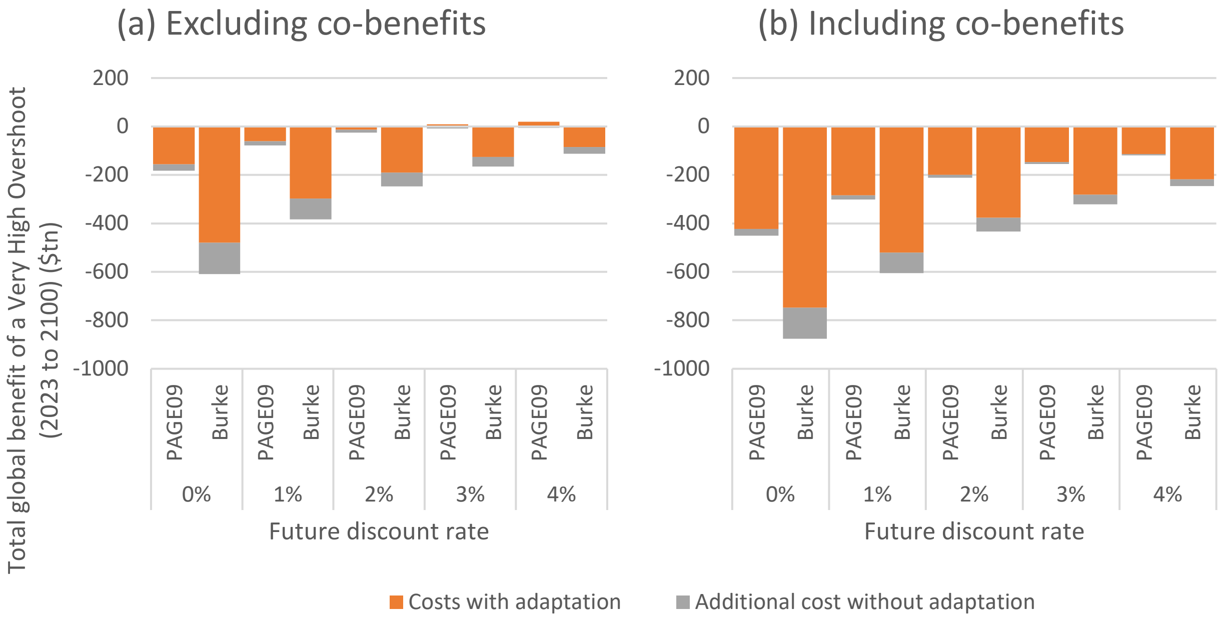


Figure 17. Total global benefits of a VHO scenario as a function of the assumed damage costs, co-benefits and the future discount rate.

3.6 Discussion

Estimating the economic implications of overshooting is challenging, given the very high uncertainty in damage costs and co-benefits and even uncertainties in the cost and performance of key mitigation technologies such as direct air capture.

3.6.1 Uncertainties in damage costs

The Burke damage costs, based on the econometrically-estimated costs of historic weather events, are an order of magnitude higher than the PAGE09 damage costs. As many previous economic assessments have been performed using process models that produced damage functions similar to PAGE09, this suggests that damages have been underestimated, possibly by a substantial amount, in many previous studies.

One criticism of economic assessments of climate change is that they have not assessed the implications of extreme events. The higher econometric damages from Burke *et al.* (2015) in this analysis were chosen to represent real-world damages that might represent changes to extremes (on the basis of past extreme weather events), in contrast to PAGE09 costs. But these are still difficult to project forward, particularly as damages from extremes might increase exponentially with temperature change (Royal Society, 2023). Although PAGE includes discontinuity impacts from large-scale damages associated with tipping points, damage costs have more generally been criticised for not including the economic impacts of earth system tipping points being passed (Royal Society, 2023). Annexes 4 and 5 of this report model and review evidence on tipping points and conclude that the risk of passing a number of tipping points increases if we follow an overshoot pathway. If, for example, the Atlantic Meridional Overturning Circulation (AMOC) were to weaken substantially, there would be global climatic changes that would change Asian and Amazonian rainfall seasons, increase the North Atlantic sea level by up to 100 cm and greatly reduce agricultural productivity in Europe (van Westen *et al.*, 2024), which would have huge economic and social impacts.

The temperature at which most climatic tipping points would occur is uncertain. Annex 5 of this report finds that the best-estimate temperature threshold for Greenland and the West Antarctic ice sheets to collapse is 1.5 °C, which would be exceeded by following an overshoot pathway. Although the AMOC has a best-estimate threshold of 4 °C, the lowest temperature at which it could occur is 1.4 °C. Hence overshooting will increase the chance of important earth system tipping points occurring. The economic damages resulting from tipping points could cause even the Burke estimates to underestimate total damage costs.

3.6.2 Uncertainties in mitigation costs

The future energy demand levels that drive decarbonisation costs are highly uncertain. There are a wide range of long-term global population projections. Average levels of consumption per capita in the future are also very uncertain. For example, the extent to which the gap in energy consumption per capita between OECD countries and non-OECD countries will reduce in the future varies between SSP scenarios. Moreover, any behavioural change and the adoption rate of energy efficiency measures will have a key impact on energy demand (Barrett *et al.*, 2022). Our analysis assumes the same demand in each pathway, but early decarbonisation in a NO pathway that includes substantial demand reduction could reduce the cost of this pathway compared to the overshoot pathways even in the period to 2050.

The future cost and performance of key low-carbon technologies is also uncertain. While larger plants such as nuclear power stations have historically not achieved reduced costs through innovation (Grubler, 2010), there are opportunities to reduce costs and improve the performance of smaller modular technologies such as solar PV, batteries, electrolysers and direct air capture. Renewable generation costs have reduced far faster and further than assumed in most models (Jaxa-Rozen and Trutnevyte, 2021). Grubb *et al.* (2021) argue that energy system models do not properly account for the potential impacts of innovation on technology cost so cannot accurately estimate the cost of decarbonising economies, and hence benefit-cost analyses based on such models are of limited value. However, such criticisms have not yet been translated into a new generation of improved quantitative tools.

3.6.3 Uncertainties in co-benefits

Estimating mortality is challenging. The mortality rate in Table 10 is a function of not only the particulate concentration in the ambient environment but also the age structure (Li *et al.*, 2023), with mortality ramping up towards 2050 in the IEA “Stated Policies” scenario compared to the “Sustainable Policy” scenario. To simplify our analysis, we assumed the age structure would not change over time and we did not account for ramp up. That means that relative mortality might be overestimated prior to 2050.

On the other hand, after 2050, it is likely the global population will be relatively older than today, which means a higher mortality burden due to air pollution at the same concentration and an underestimation of mortality in our analysis. However, as we have seen with the recent development of Ozempic medicine for obesity, it is plausible that the negative impacts of air pollution might be offset by improvements in healthcare more generally, which would lead to damages being overestimated.

An overshoot pathway post-2050 could encompass a wide range of exposures, depending on the exact ways in which GHG reductions are implemented. For example, relying on reducing CO_2 concentrations using CDR while continuing to use substantial amounts of fossil fuels might limit the global temperature rise to 1.5 °C by 2100 without necessarily delivering the health benefits associated with reducing $PM_{2.5}$ emissions at point of source and improving air quality. Given the many uncertainties on longer timescales, including the extent to which dietary changes contribute to reducing emissions, it is challenging to estimate reductions in mortality due to mitigation actions.

As global temperatures increase, it is likely that average population exposures to drivers of ill health will grow in other domains not represented here (e.g. exposure to extreme heat, lack of access to clean water, and increased rates of communicable disease). Some of these are discussed in Annex 6, which focuses on human impacts.

Converting mortality into an economic cost is also controversial, both as a concept and for the choice of the monetary value of a life. For example, estimating the monetary value using the economic value that someone would have generated during the years that were lost due to earlier mortality would produce a much higher VSL for an OECD country than for a non-OECD country. Others might consider the approach of assigning different VSLs to different countries to be unethical. There is no agreed approach to monetising mortality, but choosing to not do so means that co-benefits cannot be easily included in a benefit-cost analysis, yet mortality due to climate damages is commonly included.

3.6.4 Future improvements to this analysis

The economics of climate change has been a contested discipline for decades and numerous criticisms of current approaches continue. We have tried to represent some of the large uncertainties in damage costs and co-benefits in our analysis while taking an approach of identifying overall trends that affect the economics of overshoot. One method to improve our analysis would be to address some of the uncertainties and assumptions described above. Our best-estimate approach would ideally also be augmented with an analysis of uncertainties and confidence levels.

We have adopted a benefit-cost approach to be consistent with the wider literature. Yet the static nature of this approach might not identify the most appropriate mitigation actions that are required to underpin the dynamic energy system transformation that is required. Mercure *et al.* (2021) propose a risk-opportunity framework as a better approach to inform climate change policy design.

4. Wider economic implications of overshoot

The quantification of macroeconomic effects of mitigation are mainly based on cost-effectiveness, which is measured by comparing the costs of different mitigation strategies designed to meet a given mitigation goal (IPCC, 2022b). However, this type of analysis is limited as it considers only selected sectors (e.g. energy system costs) and overlooks cascading effects that extend throughout the economy. An economy-wide analysis captures the general equilibrium effects of mitigation pathways and provides a comprehensive assessment of their impact across sectors and regions.

4.1 Macro-economic modelling methods

To quantify the economy-wide impacts of overshoot, we use the UCL ENGAGE model, which considers direct and indirect impacts of policy interventions spanning across sectors and regions. In this section only the VHO pathway is compared with the NO pathway.

4.1.1 Overview of the ENGAGE model

The UCL Environmental Global Applied General Equilibrium (ENGAGE) model is a multi-sector, multi-region, recursive dynamic CGE model developed at the UCL Institute for Sustainable Resources for the analysis of energy, environmental, resource and economic policies (Winning *et al.*, 2017, Calzadilla and Carr, 2020, Nechifor *et al.*, 2020). ENGAGE is able to estimate the macro-economic impacts across sectors and across countries, accounting for the economic characteristics of each country and adjustment processes[12] in domestic and international markets.

ENGAGE is based upon standard general equilibrium assumptions such as market clearance, zero excess profits, and utility maximisation/cost minimisation of representative agents. All industries are modelled through a representative firm, which maximizes its profits in perfectly competitive markets. The production functions of each economic sector to create a level of sectoral output are specified using a series of nested constant elasticity of substitution (CES) functions. Domestic and foreign inputs are not perfect substitutes and

[12] Adjustments processes refer to adjustments in the equilibrium conditions of internal and external markets (for goods/services and factors of production) to satisfy utility and profit maximisation.

therefore are modelled using the “Armington assumption”, which accounts for product heterogeneity between different world regions (Armington, 1969). A representative consumer in each region receives household income, defined as the service value of national primary factors. The national income is allocated between aggregate household consumption, public consumption and savings.

The version of the ENGAGE model used here is based on the GTAP9-Power database (Peters, 2016) and represents the global economy in 2011. In addition to a detailed representation of different power technologies and energy-related industries, ENGAGE also represents other sectors of the economy (i.e. agriculture, industry and service sectors), allowing in this way the assessment of the economy-wide impacts of energy related policies and shocks. ENGAGE models 27 economic activities, 16 regions and 4 factors of production (Table 11). It is important to note that ENGAGE does not represent negative emission technologies or carbon capture, utilisation and storage (CCUS).

4.1.2 Modelling approach

ENGAGE uses the SSP2 regional population and GDP growth assumptions to calibrate a reference NDC baseline. This calibration process assumes that GDP is exogenised by treating total factor productivity as an endogenous variable. GDP is also endogenous in all other scenarios that represent different mitigation pathways. The reference NDC baseline assumes that 2015 nationally determined contributions to reduce emissions are achieved, but that no further emission reductions are made. This approach is consistent with NDC pathway developed in TIAM-UCL in Annex 1 of this report, which also uses SSP2 projections and IPCC AR6 climate sensitivity. For those countries with NDC pledges stretching only to 2030, emissions beyond 2030 are assumed to have the same regional GHG per GDP/capita from 2030 as an upper bound on emissions until the year 2100 (Winning *et al.*, 2019).

For the NO and VHO pathways, ENGAGE mimics the regional and global decarbonisation pathways produced by TIAM-UCL that are described in Annex 1 of this report. Moreover, the regional energy mix and cost reductions in renewable technologies used in ENGAGE are based on the TIAM-UCL model (Pye *et al.*, 2020). While global CO_2 emissions reach net zero by 2050 under the NO pathway, they only decline by 38% compared to 2020 under the

VHO pathway (Figure 11). The VHO pathway provides a benchmark against which the NO pathway is measured.

Table 11. Regions, sectors and factors of production in ENGAGE.

16 Regions		**27 Sectors**	
AFR	Africa	**PDR**	Paddy rice
AUS	Australia	**WHT**	Wheat
CAN	Canada	**GRO**	Cereal grains
CSA	Central and South America	**OCR**	Other crops
CHI	China	**A_F**	Agriculture and food
EEU	Eastern Europe	**MIN**	Minerals
FSU	Former Soviet Union	**PPP**	Paper
IND	India	**CRP**	Chemical
JAP	Japan	**NMM**	Non-metallic minerals
MEA	Middle East	**I_S**	Iron and steel
MEX	Mexico	**MPR**	Metal products
ODA	Other Developing Asia	**IND**	Other industry
SKO	South Korea	**COA**	Coal
UK	United Kingdom	**OIL**	Crude oil
USA	USA	**GAS**	Gas
WEU	Western Europe	**P_C**	Petroleum & Coke
		NUP	Nuclear power
		CFP	Coal-fired power
		GFP	Gas-fired power
		WIP	Wind power
		HYP	Hydroelectric power
		OFP	Oil-fired power
4 Factors of production		**OTP**	Other power
LND	Land	**SOP**	Solar power
LAB	Labour	**TnD**	Transmission and distribution
CAP	Capital	**SER**	Services

RES	Natural resources	**TRN**	Transport

A global carbon price in a future of global climate cooperation is the mechanism used in ENGAGE to align regional emissions per capita with the targeted emissions trajectories from TIAM-UCL. The decarbonisation of the regional economies also includes the development of renewable energy and the electrification of the economy. Cost reductions in renewables technologies and a gradual increase in the elasticity of substitution between electricity and other energy inputs help to achieve these outcomes. Changes in energy-demand are modelled via improvements in energy efficiency and lifestyle changes, which are achieved by gradually increasing the elasticity of substitution between energy goods in consumer demand. Moreover, capital is a scarce resource in the economy; therefore, the development of renewable technologies crowds-out investment in other parts of the economy.

All these changes are implemented alongside autonomous improvements in resource efficiency. The more stringent the climate target, the greater the assumed speed of improvement and transformation of the economic system. Cost reductions, energy efficiency improvements, resource efficiency improvements, and elasticities of substitution are region- and sector-specific.

4.1.3 Limitations of the economic modelling

There is a large uncertainty in the regional and global costs of mitigation, which depend on the type of model and the model's specification and assumptions. Results from a model intercomparison analysis using 7 CGE models show that regional GDP changes in 2030 under a submitted NDC scenario that is scaled up to be in line with a global carbon budget for a 1.5 °C scenario range between -15% and +2% (Akin-Olçum *et al.*, 2023).

Regional mitigation costs are not only dependent on the current energy mix and dependency level of fossil fuels. Other important factors include assumptions about future development, costs and financing of advanced technologies, such as direct air capture and CCUS, and about regional and sectoral resource efficiency improvements and elasticities of substitution. Since dynamic assumptions of these parameters are drawn from external sources, considerations, such as the dynamic effects of learning, are implicit on the assumptions provided by the sources.

The deployment of CDR technologies is expected to be small in 2050, but they play a fundamental role in the long run. Results from nine integrated assessment models that explore the role of CO_2 removal technologies in scenarios with limited overshoot show that only around 13% of the cumulative CDR required to keep the global temperature below 1.5 °C has occurred by 2050 (Riahi *et al.*, 2021). Our NO pathway developed in TIAM-UCL required 21% of the cumulative CDR to 2100 by 2050, while our VHO pathway has only 4% of the cumulative CDR by 2050. As ENGAGE evaluates the economic impacts up to 2050, the limited representation of these technologies in ENGAGE has only a small influence on the overall results. However, the economic cost of mitigation in 2050 might be overestimated, especially considering that some of these technologies (such as afforestation) are highly competitive. By omitting these technologies, we avoid the risk and uncertainties of negative technologies and CCS not being economically-viable as part of a portfolio of mitigation options in the future.

As a result, the economic analysis extends only to 2050, the year in which the NO pathway reaches zero emissions. Without negative emission technologies, ENGAGE is unable to find an optimal solution for the emission trajectory beyond 2050 in either pathway, as both heavily rely on these technologies during the period 2050–2100 to keep the global temperature rise to 1.5 °C in 2100.

Damages from climate change are not included in this annex. An integrated assessment of the economic impacts of climate change and policies to address it would compare the cost of mitigation and adaptation measures with the total cost of climate change damages. For instance, the IPCC Sixth Assessment Report highlights that the global economic benefit of limiting warming to 2 °C is expected to exceed the cost of mitigation (IPCC, 2022b).

4.1.4 Results within the literature context

Based on eight[13] state-of-the-art, climate-energy-economy models (three of them CGEs), Vrontisi *et al.* (2018) conclude that climate change mitigation actions affect economic growth to only a limited degree. The global annual GDP growth rates in the period 2020–2030 in the 1.5º C scenario are around 0.21–0.48 percentage points lower compared to the reference scenario. Moreover, Vrontisi *et al.* (2018) highlight that this decline is much lower than the uncertainty of the pace of economic growth reported in the different models. Akin-Olçum *et al.* (2023) compare seven[14] global CGE models to assess the costs of mitigation in 2030 in the 1.5º C scenario. They find similar changes in regional GDP compared to a reference scenario. The uncertainty among models is highlighted in both publications.

Vrontisi *et al.* (2018) do not use the same targeted emissions across models. Therefore, global emissions decline around 36% to 64% with respect to the reference scenario. Akin-Olçum *et al.* (2023) use the same targeted emission across models, with global emissions for the 1.5 °C scenario 33% below 2011 emissions.

The GDP costs presented in this report consider emission reductions in 2050 of around 59% in the VHO pathway and around 92% in the NO pathway, compared to the global emissions level in 2020 (Figure 18). The anticipated GDP growth rates in the VHO and NO pathways in this report are slightly lower than the above publications, but the emission reduction targets in 2050 are much more stringent.

4.2 Insights

Overshoot pathways assume slower and more flexible decarbonisation in the period to 2050, with the intention of later compensating with negative emission technologies, while the NO pathway requires immediate and large emission reductions to keep the global temperature below 1.5 °C. This section explores key temporal economic trade-offs of following the NO pathway rather than the VHO pathway, focusing on the global and regional impacts.

[13] The list of models in this study are: IAM/CGE, GEM-E3-ICCS, IMACLIM, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND and WITCH. The first three are CGE models.
[14] The list of models in this study are: EC-MSMR, EDF-GEPA, ICES, DART, C-GEM, TU-Berlin and PACE. All of them are CGE models.

4.2.1 CO_2 emission pathways

Staying below 1.5 °C without overshooting requires a strong acceleration of short-term emission reduction actions. While global CO_2 emissions slightly increase in the VHO pathway for the 2020–2030 period, they decline by 45% in the NO pathway (Figure 18). During the 2030–2040 period, the reduction in CO_2 emissions is still stronger in the NO pathway (35% compared to 26%). As CO_2 emissions have already been reduced to 20% of 2020 emissions by 2040 in the NO pathway, further reductions of only 13% of 2020 emissions are made during the 2040–2050 period, which is much lower than the 34% reductions of 2020 emissions in the VHO pathway.

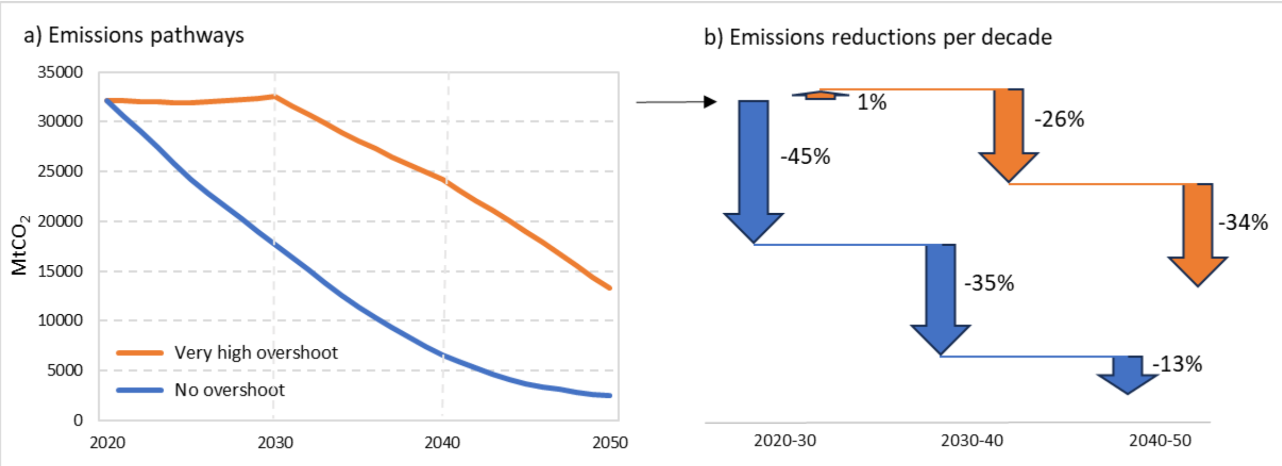


Figure 18. Global CO_2 emissions reduction for the ENGAGE versions of the two pathways. Panel (a) shows the decarbonisation pathways and (b) the emission reduction per decade. Only CO_2 emissions from energy are shown as ENGAGE does not account for industrial, land use, or land use change emissions.

Regional CO_2 emissions have similar trends (Figure 19). In the VHO pathway, only a few regions have emission reductions during the 2020–2030 period and emissions increase slightly in the majority of regions. In the next two decades, emissions decline in all regions, and the decline accelerates during the 2040–2050 period. However, the regional emission reductions achieved by 2050 in this pathway are far from those achieved under the NO pathway, which requires strong reductions in CO_2 emissions in all regions during the period 2020–2040.

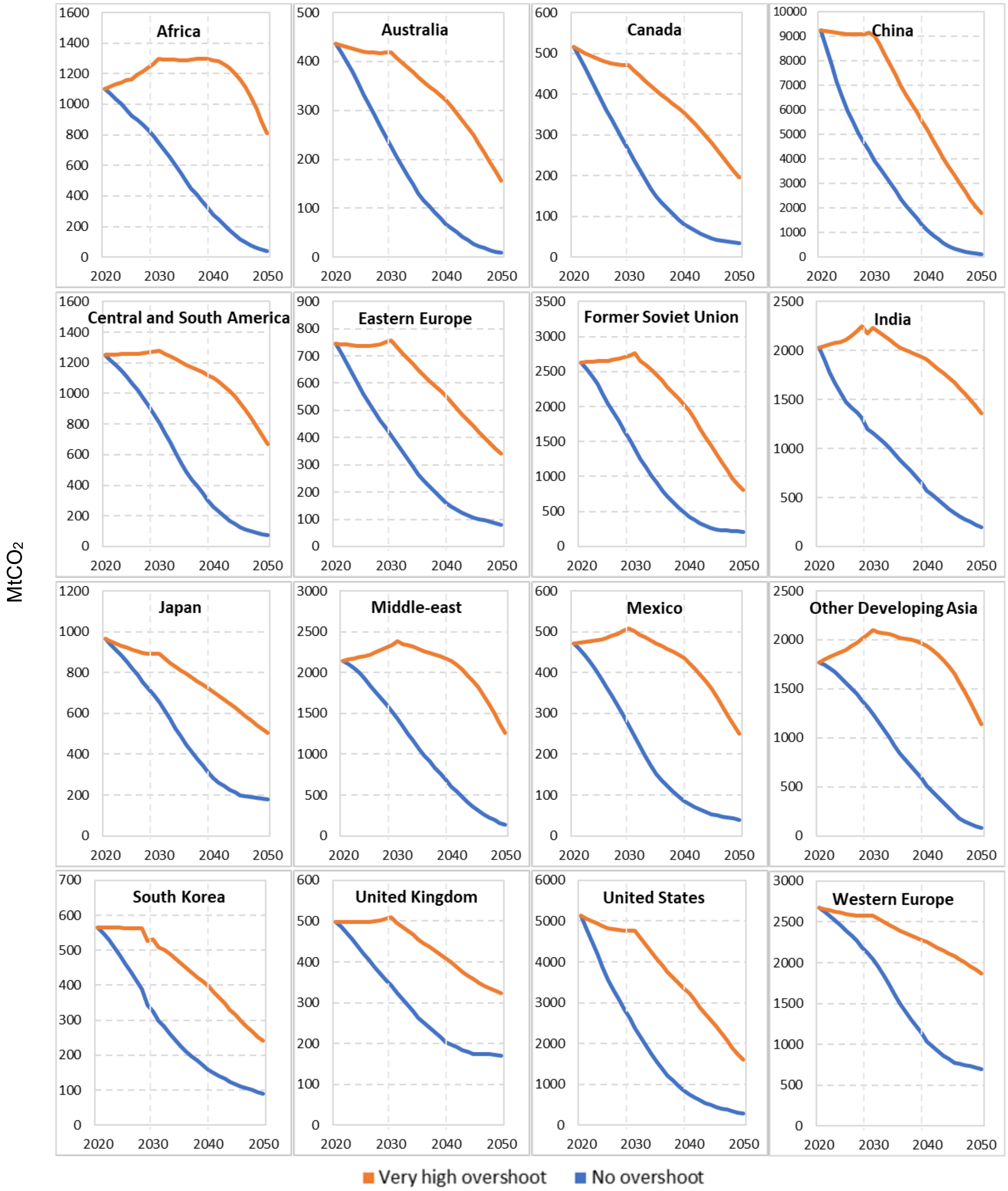


Figure 19. Regional CO_2 emissions by decarbonisation pathway. Only CO_2 emissions from energy are shown as ENGAGE does not account for industrial emissions.

4.2.2 Temporal economic implications

More ambitious policy actions to achieve more stringent decarbonisation targets result in a higher global GDP growth rate in the 2020–2030 period for the NO pathway (Figure 20). However, during 2030–2040, the global GDP growth rate is higher in the VHO pathway as the global economy is less affected by decarbonisation efforts. The global GDP growth rate in 2040–2050 is higher again in the NO pathway, as most of the global emissions were already reduced in the first two decades. Overall, the NO pathway has a higher GDP growth rate over the period 2020–2050.

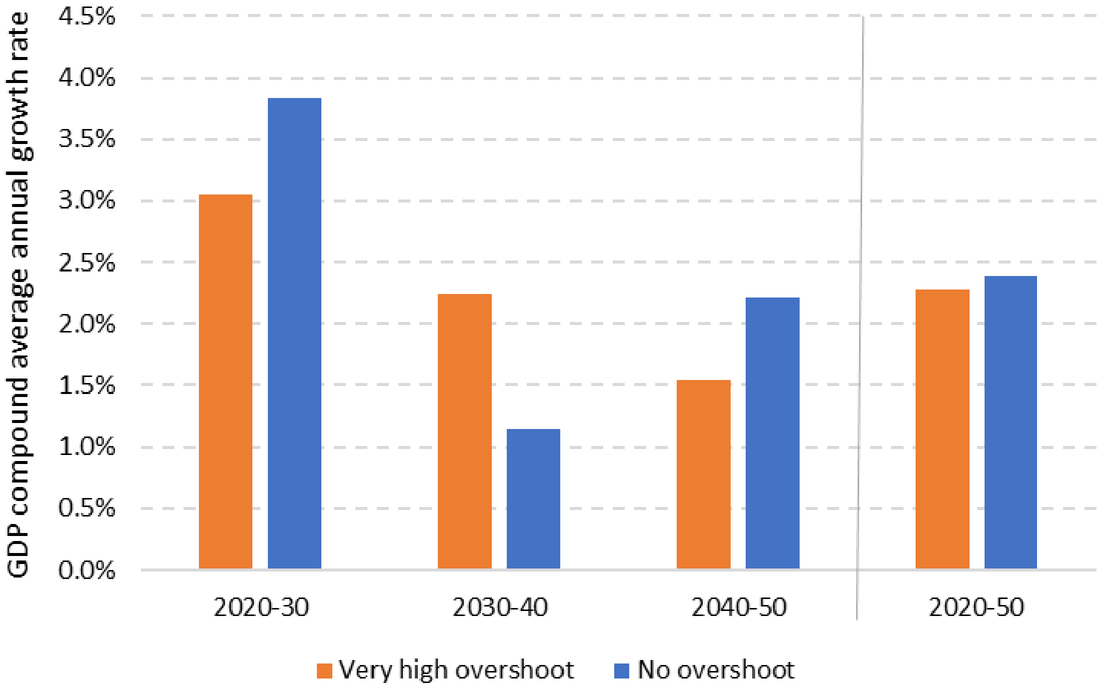


Figure 20. Global GDP growth rates by decade and decarbonisation pathway.

Regional GDP growth rates vary depending on the size and pace of emissions reductions, the level of the carbon tax, the current energy mix and dependency on fossil fuels, the future development of renewable energy and its cost, the speed of the industrial decarbonisation and electrification, and changes in competitiveness induced by climate and energy policies in other regions. While there are significant regional variations in GDP growth rates in individual decades (Figure 21), the variation is smaller when aggregated over the period 2020–2050.

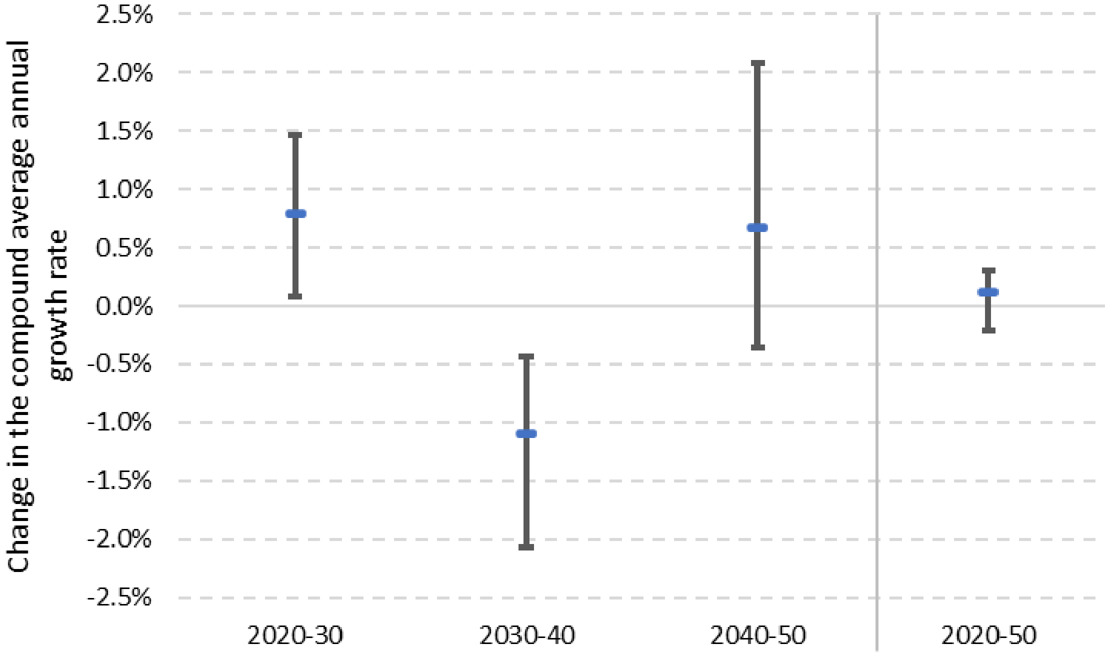


Figure 21. Change in global and regional GDP growth rates by decade (NO minus VHO). Errors bars show the range of regional changes in GDP growth rates.

Compared to 2020 levels, avoiding overshoot brings small economic gains in terms of higher GDP growth rates (an additional 0.7%) during the 2020–2030 period (Figure 22), as more ambitious policy actions are required in the short term. These policy actions are represented in the model as more rapid technological improvements and a faster transformation of the economic system. Accelerated improvements in material and energy efficiency, for instance, avoid crowding out investments in other sectors of the economy and provide an economic stimulus. Such mitigation measures are most efficient from an economic perspective.

These economic gains decrease during the next decade (2030–2040) as emission reductions are much larger in the NO pathway compared to the VHO pathway as more stringent mitigation measures need to be adopted. However, as this situation reverses again in 2040–2050, economic growth rates start to increase again.

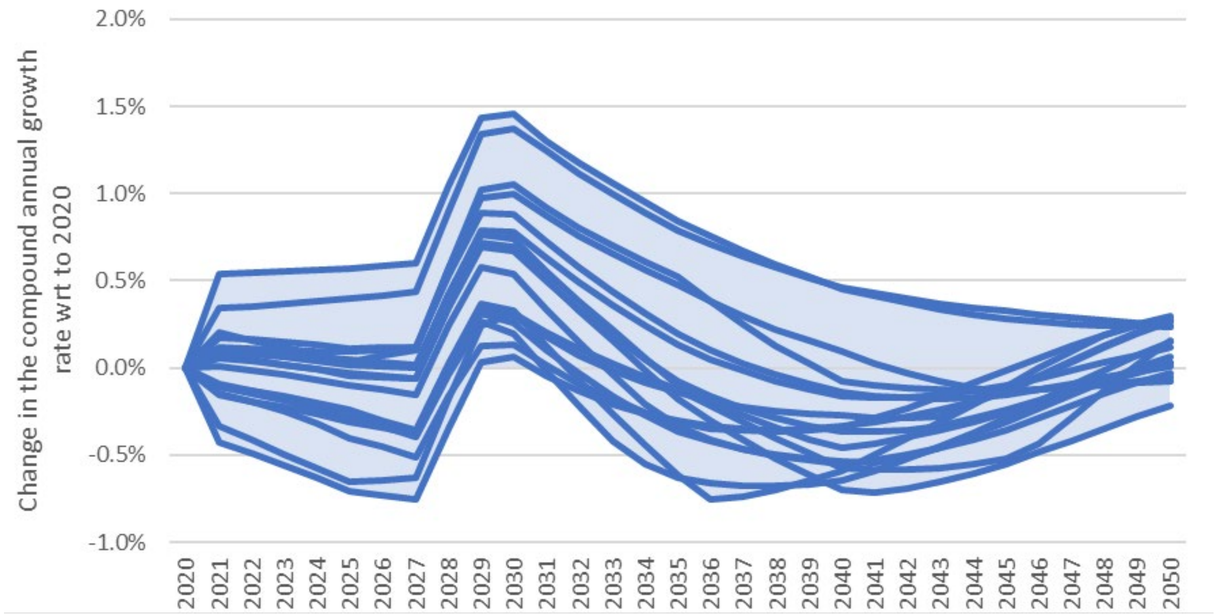
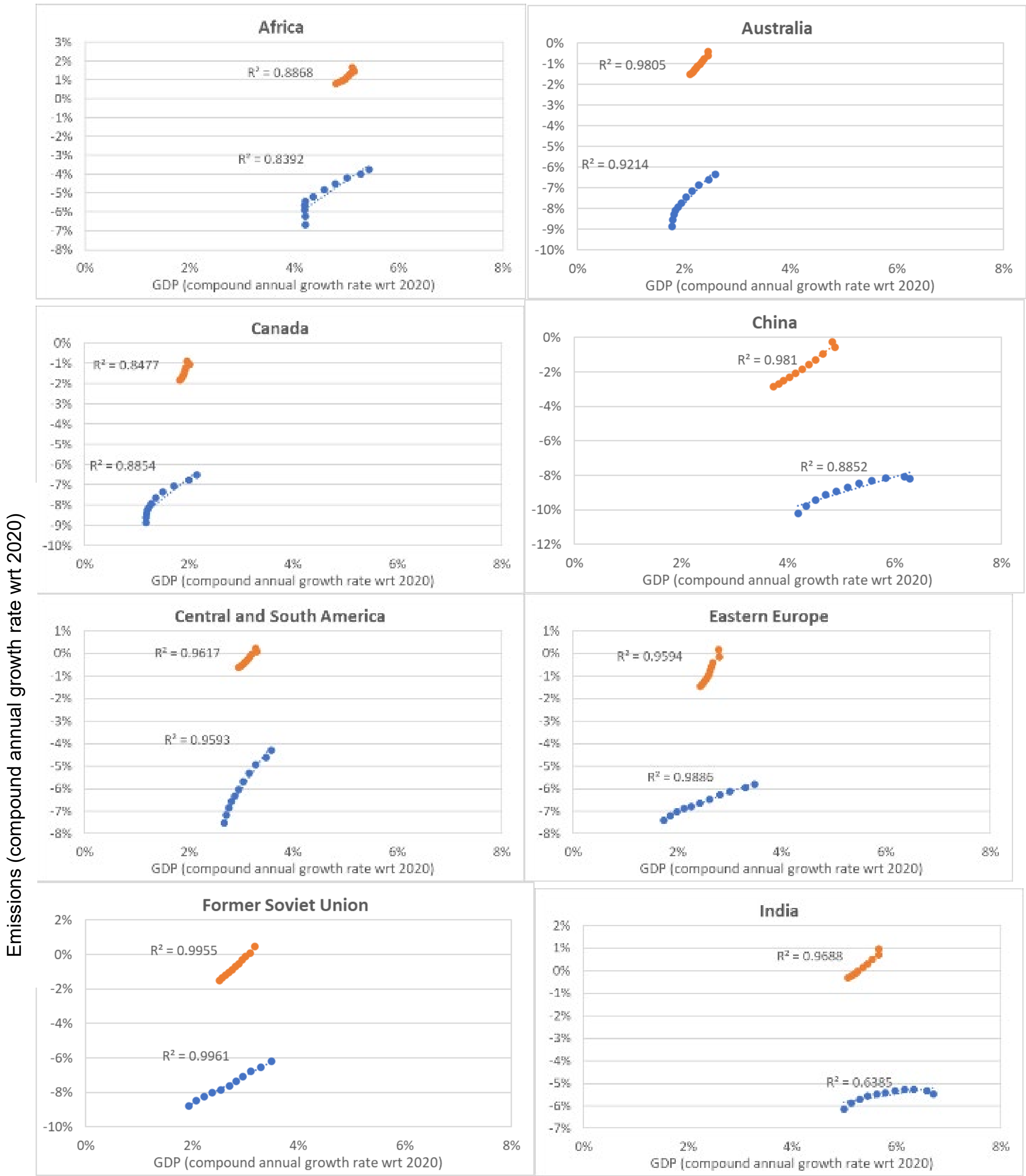


Figure 22. Change in regional GDP growth rates between scenarios (NO minus VHO). Compound annual growth rates relative to 2020 GDP in each region are shown.

Figure 23 shows the rate at which emissions are projected to decline in each pathway and how this is affects modelled GDP growth rates during 2030–2040. In all regions, the rate of emission reductions is slower in the VHO pathway compared to the NO pathway. Moreover, in some regions such as Africa, the Middle East and Other Developing Asia (primarily Southeast Asia), emissions in the VHO pathway in 2040 are still higher than in 2020. As the annual rate of emission reductions is slow (maximum 3%), the impact on the GDP growth rate is also modest (a maximum decline of around 1% percentage points during the whole decade).

The NO pathway has much more pronounced annual regional emission reductions of 3%–10% during 2030-2040 period. Despite a slightly higher initial growth rate in 2030, the NO pathway has larger reductions in GDP growth of around 2%. As shown in Figure 23, it is important to note that all economies are still experiencing positive economic growth (i.e. there is no ‘degrowth’ in any region). It is also important to consider that these figures do not include the economic benefits of mitigation from avoided climate change impacts, nor co-benefits.


Emissions (compound annual growth rate wrt 2020)
Africa
R² = 0.8868
R² = 0.8392
GDP (compound annual growth rate wrt 2020)
Australia
R² = 0.9805
R² = 0.9214
GDP (compound annual growth rate wrt 2020)
Canada
R² = 0.8477
R² = 0.8854
GDP (compound annual growth rate wrt 2020)
China
R² = 0.981
R² = 0.8852
GDP (compound annual growth rate wrt 2020)
Central and South America
R² = 0.9617
R² = 0.9593
GDP (compound annual growth rate wrt 2020)
Eastern Europe
R² = 0.9594
R² = 0.9886
GDP (compound annual growth rate wrt 2020)
Former Soviet Union
R² = 0.9955
R² = 0.9961
GDP (compound annual growth rate wrt 2020)
India
R² = 0.9688
R² = 0.6385
GDP (compound annual growth rate wrt 2020)

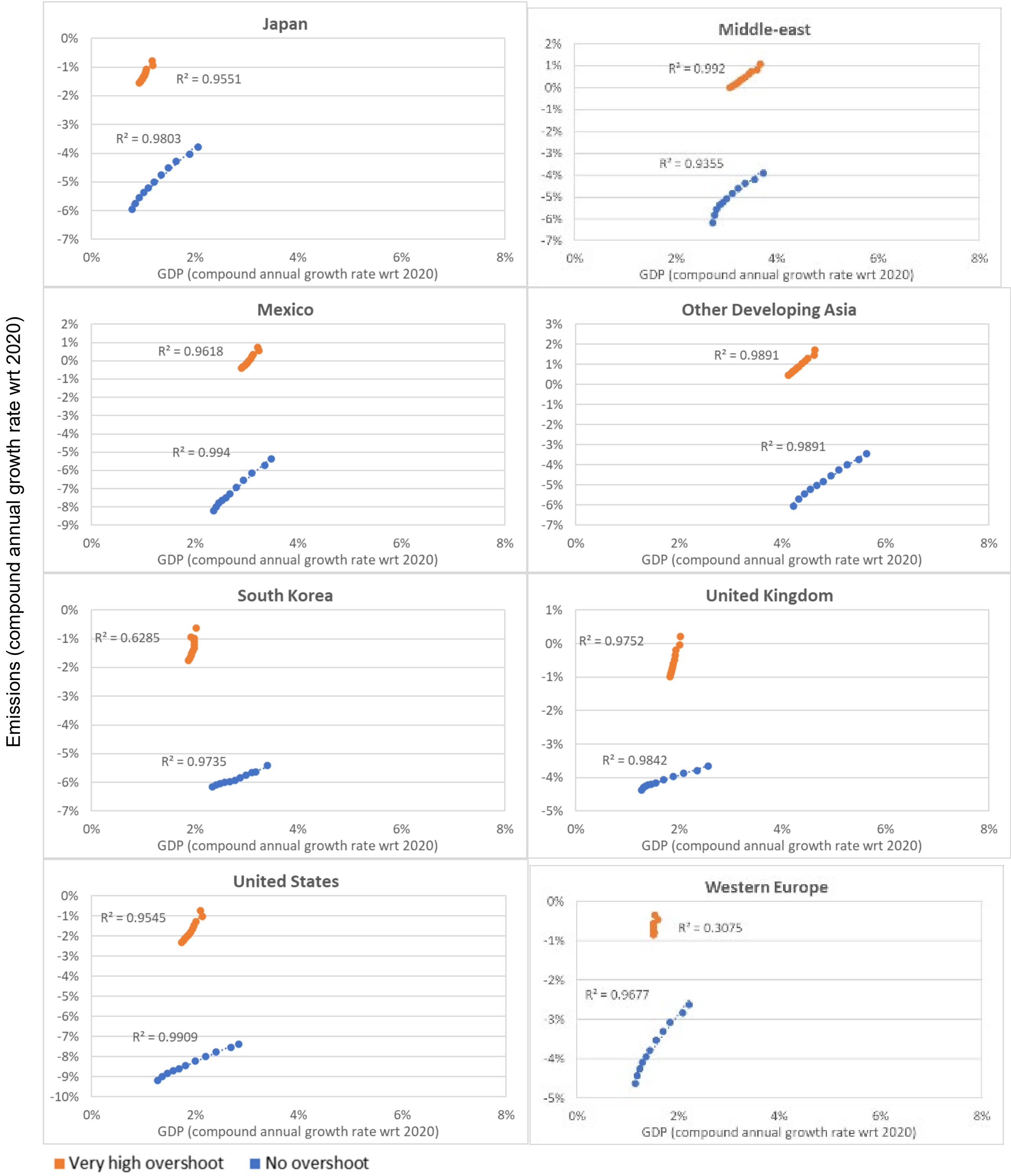


Figure 23. Regional emissions and annual GDP growth rates by decarbonisation scenario for the eleven years 2030–2040. Compound annual growth rates are shown relative to the year 2020.

In order to avoid an overshoot pathway, regional emissions during the 2030–2040 period have to decline sharply by up to 45%. This implies lower GDP growth rates in all regions (Figure 24, upper graph). China is an exception, as its emissions decline more in the VHO pathway than in the NO pathway during this period. However, the absolute level of emissions in China, and in all of the other regions, is always higher under the VHO pathway as shown in Figure 19.

Figure 24. Change of emission reductions and GDP growth rates by decade and decarbonisation scenario. Compound annual growth rates with respect to 2030 and 2040 GDP levels are shown.

As a result of the sharp decline in emissions during the 2030s to avoid overshoot, the effort to reduce emissions during 2040–2050 is smaller (Figure 24, lower graph). This might bring economic benefits for some regions. For example, Africa might experience an increase in the GDP growth rate of 2% in this period, as emissions only decline by 22% in the NO pathway compared to 43% in the VHO pathway. Figure 25 illustrates this general trend across all regions: the larger the avoided emission reductions in the 2040–2050 period due to following a NO pathway, the larger the increase in the GDP growth rate.

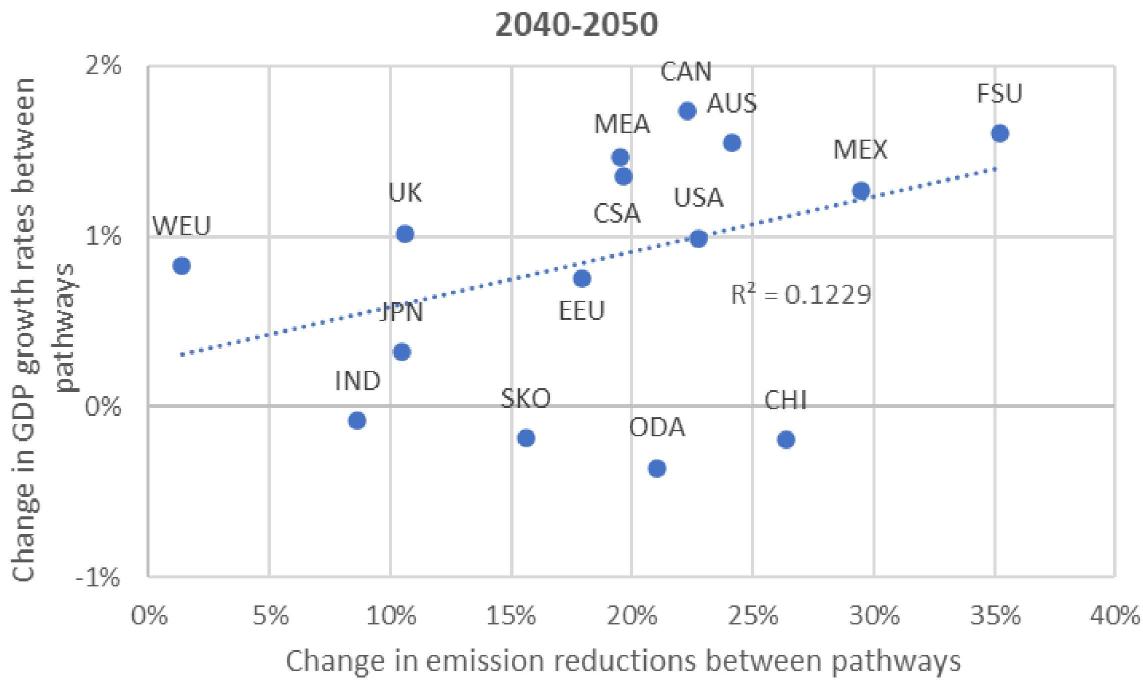


Figure 25. Change in GDP growth rates and emission reductions in the 2040–2050 period. The change is defined as NO minus VHO.

The carbon intensity in 2020 varies widely across regions. However, Figure 26 shows that while the decline is steadily in both pathways, it is much more pronounced in the NO pathway, especially during 2020–2040. By 2050, the NO pathway has a regional decline in carbon intensity ranging from 79%–99%, while the VHO pathway has a range of 54%–92%.

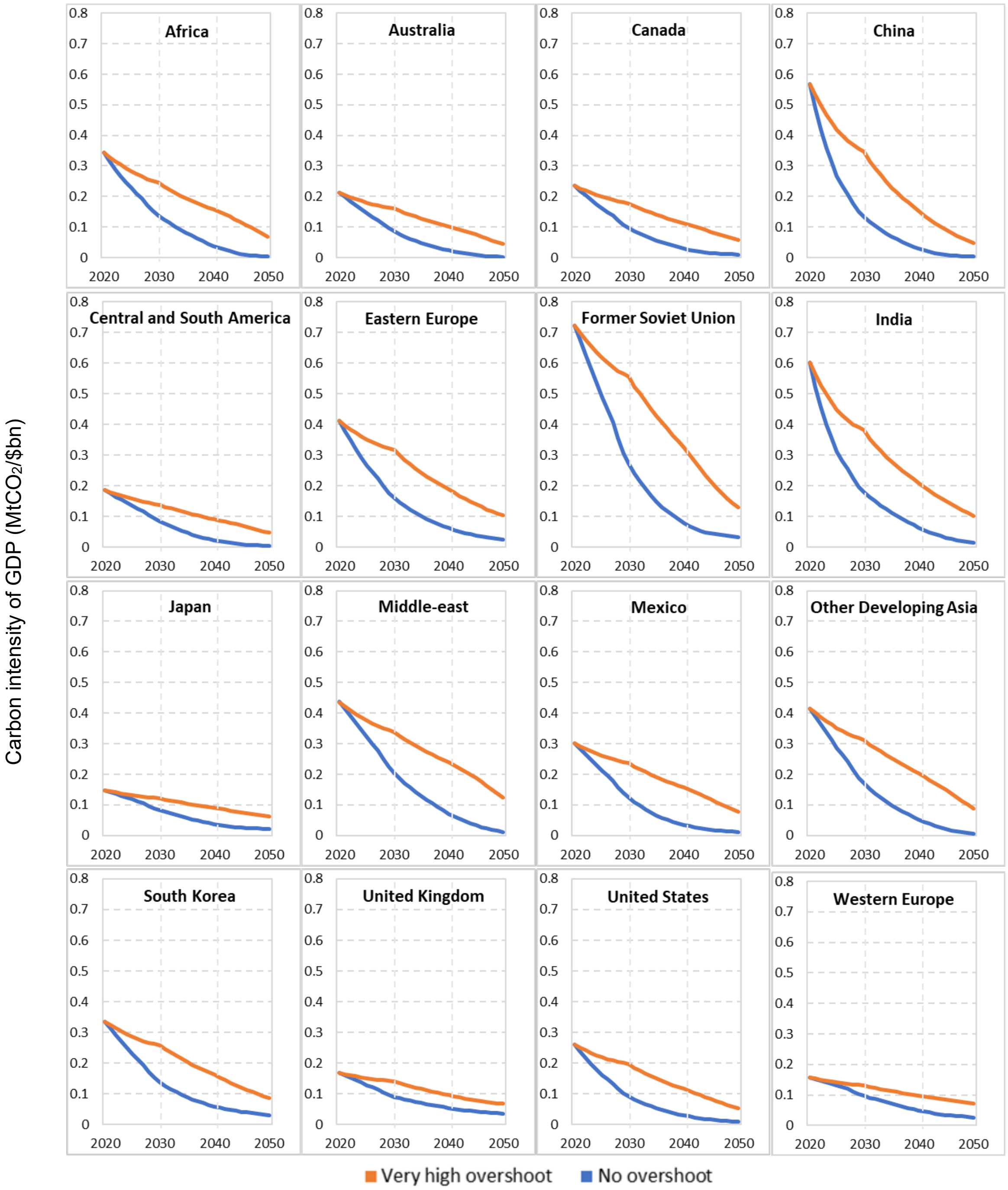


Figure 26. Regional carbon intensity of GDP by decarbonisation scenario.

4.3 Discussion

The economic analysis of mitigation costs in this section reaches a different conclusion to the mitigation costs analysis in Section 3.3. Although the analysis of mitigation costs in TIAM-UCL finds the undiscounted NO pathway costs would be smaller than for any of the overshoot pathways, this is primarily because it is substantially cheaper after 2050 due to requiring a lower deployment of negative emission technologies. In the period 2020–2050, the cost of the VHO pathway is 8% lower than the cost of the NO pathway in TIAM-UCL. The ENGAGE analysis, in contrast, finds that following a NO pathway would have positive economic benefits by 2050.

One reason for this discrepancy is that ENGAGE is a general equilibrium model so accounts for an early boost to GDP through increased energy and material efficiencies in the NO pathway. TIAM-UCL, in contrast, is a partial equilibrium model so only considers energy system costs, and such models invariably find decarbonising will be more expensive than the status quo if wider factors are not considered.

5. Conclusions

This annex has examined the potential economic implications of overshooting 1.5 °C. A key uncertainty from the literature is the potential level of climate change damage costs. We reviewed damage cost methods and found that econometric estimates based on historic climate change can be an order of magnitude higher than estimates from process models that have traditionally been used. More sophisticated econometric studies, for example through increased spatial resolution or considering extreme weather, tend to project higher future damage costs.

5.1 Benefit-cost analysis of following overshoot pathways

Our review confirmed our suspicion that the damage functions used in many integrated assessment models such as PAGE substantially underestimate climate change impacts. For this reason, we assumed two damage cost scenarios in our global benefit-cost analysis: one based on process models (PAGE09) and one based on an econometric synthesis study (Burke). The differences in damage costs between overshooting and not overshooting are very small using PAGE09 but substantial using Burke estimates. Yet Burke estimates reduce over time as many countries are assumed to benefit slightly from a small increase in the global mean temperature. Nevertheless, our Burke estimates project that overshoot pathways will have higher economic damages than the NO pathway. It is not clear whether the convex Burke function would change shape if changes in extreme weather were accounted for. Given the high uncertainty in damage functions and that the differences between the pathways are small compared to the total damages for each pathway, we have low confidence in these insights.

Energy system costs from the TIAM-UCL integrated assessment model for each pathway were much larger than damage costs or co-benefits, at least from 2050, but the differences between pathways (i.e. the mitigation costs) was small. The choice of global discount factor was a key factor affecting which pathway was cheapest, as the NO pathway has decarbonisation costs up-front while the overshoot pathways delay decarbonisation but have much higher negative emission technology costs after 2050.

Co-benefits of mitigation are difficult to assess and applying an economic valuation is controversial. Nevertheless, we attempted to estimate the value of co-benefits from better air quality, improved diet and more active travel in the NO pathway compared to delayed improvements in the overshoot pathways. Dietary improvements have the largest impact on reducing mortality but whether they could be achieved is questionable. The value of a life and hence the economic value of co-benefits is contested, but with the assumptions we used could be considerable.

Combining the damage costs, mitigation costs and co-benefits suggests that overshooting would have much higher overall costs than the NO pathway. For overshooting to be lower cost, it would be necessary to assume very low damage costs, no co-benefits and to use a high future discount rate. In reality, recent climatic experience suggests that damage costs will be higher than suggested by PAGE09, and there are likely to be at least some co-benefits, so claims that overshooting 1.5 °C might be cheaper are not supported by this study.

5.2 Wider economic implications of overshoot

In contrast to TIAM-UCL, our global macroeconomic analysis using the ENGAGE CGE model concludes that the NO pathway could lead to higher economic growth than overshooting even just during the period 2020 to 2050. The drivers of this trend are earlier investments in increased energy and material efficiencies that have positive benefits across the economy.

The differences in mitigation costs between the pathways are small in both the TIAM-UCL and ENGAGE analyses. The uncertainties in future costs and demands, and other assumptions, means it is difficult to make a credible case for overshooting having better or worse economic impacts if only mitigation costs are considered. It is clear, however, that including co-benefits of mitigation and climate damages in the calculation is very likely to make a strong economic case for not overshooting.

5.3 Future research needs

Estimates of the economic impacts of climate change are important to justify mitigation and adaptation investments but are inherently uncertain.

5.3.1 Narrowing damage cost uncertainties and adaptation potential and cost

Projected damage costs due to climate change have tended to increase across the literature as damage cost estimates have become more sophisticated, but the magnitude varies greatly between studies. For statistical models based on historic weather impacts, Section 2.1.1 identifies uncertainties about the shape of temperature-damage functions, the magnitude of GDP growth damages as temperature changes, impacts of weather extremes and natural system tipping points, and the extent to which growth impacts are likely to persist and further reduce long-term GDP levels. Many studies effectively make unsubstantiated assumptions about these uncertainties. There is a need to examine each of them, using new analyses where appropriate, to better understand their likelihood and potential impacts. The worst damages would occur in the Global South, where our understanding of damages is poorest, so it would be valuable to better explore their potential impacts in these regions to make a case for global mitigation action.

As our understanding of the potential impacts of climate damages is poor, we similarly do not have a good understanding of the potential benefits and costs of taking adaptation actions. This is reflected in the low confidence we have in the treatment of adaptation in the PAGE model.

5.3.2 Quantifying uncertainty in benefit-cost analyses

In our study, the mitigation and damage costs were similar across pathways so the differences between pathways were small compared to the total costs. This suggests considerable uncertainty, particularly as our mitigation cost analysis considered only the energy system rather than the wider economy, and as damage costs are so uncertain. Section 3.6 identifies many sources of uncertainty in our analysis. It would be valuable to examine a range of further scenarios for different overshoots that explore uncertainty in future global socioeconomic development (only SSP2 was considered in this study) and in climate sensitivity.

Lower-income countries are likely to benefit most from early mitigation as they will suffer most from climate change. Our analysis did not resolve the benefits at a country scale as our models used only either 16 regions (TIAM-UCL and ENGAGE) or 8 regions (PAGE and co-benefits analysis). A more detailed regional benefit-cost analysis would be useful so the benefits of climate mitigation actions could be estimated for each global region and for large countries individually. Financing costs vary greatly between countries (Ameli *et al.*, 2021) and it would also be useful to consider the implications of these disparities and of reducing financing costs in the future.

5.3.3 Alternative methodologies for benefit-cost analyses

Co-benefits of mitigation have received little attention in benefit-cost analyses but greatly strengthened the economic case for early mitigation to avoid overshoot. However, the potential benefits in terms of reduced mortality are uncertain and depend on which mitigation actions are taken (i.e. the extent to which fossil fuel combustion is reduced and emission reduction is achieved through positive behavioural change). Putting an economic value on mortality is also controversial, particularly where it varies between countries. Both uncertainties would ideally be examined using a range of socioeconomic and mitigation scenarios.

We have adopted a benefit-cost approach to be consistent with the wider literature. Other methods have been developed to explore the economic challenges of climate change, as exemplified by the three approaches to estimating damage costs in Section 2 and the CGE approach to estimating mitigation costs and damages in Section 4. The static nature of benefit-cost approaches might not identify the most appropriate mitigation actions that are required to underpin the dynamic energy system transformation that is required. For example, Mercure *et al.* (2021) propose a risk-opportunity framework as a better approach to inform climate change policy design and the UK Government-funded EEIST project[15] has examined complexity-based modelling solutions to value investments in innovation. It would be useful to consider the wider economic implications of mitigating climate change in such a framework that would ideally include co-benefits, adaptation and damage costs.

5.3.4 Positive economic benefits of mitigation actions

Our CGE model analysis in Section 4 concludes that mitigation actions could increase GDP growth rather than reducing growth. There is a question whether the higher energy and material efficiencies that underpin economic growth in the scenarios could be achieved in practice (Kotchen *et al.*, 2023). If they are feasible, then why have people not already invested in them? It would be valuable to review the assumptions underlying these trends and to consider the extent to which the projection of increased GDP growth depends upon these functions.

We carried out the economy-wide analysis only to 2050 as the model became unstable when we tried to extend the time horizon to 2100. We would ideally explore the period to 2100 to quantify the full impacts of an overshoot. Addressing the causes of the instability might improve the quality of the insights for the period to 2050 as well.

Negative emission technologies (NETs) are an important part of all our pathways but are not commonly represented in CGE models as they provide a service, atmospheric CO_2 removal, that does not exist in the economy today. We did not represent them in our model in Section 4 as our pathways from TIAM-UCL have only a small deployment of NETs prior to 2050 (see Annexes 1 and 2 of this report). They would ideally be included for an analysis to 2100 as our TIAM-UCL analysis shows that they account for a substantial part of the cost of the energy system after 2050, particularly for higher overshoot scenarios.

[15] EEIST project: https://eeist.co.uk/

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Quality assurance

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