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PAPER

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

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Abstract

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

1. Introduction

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

Researchers have used various methods to estimate economic losses from climate-related damages, with projections ranging from under 2% to over 40% of global GDP at 3 °C of warming (NGFS 2024). Key approaches include impact enumeration (Nordhaus 1994), surveys (Howard and Sylvan 2020), computable general-equilibrium (CGE) models (Kompas *et al* 2018), econometrics (Burke *et al* 2015, Kalkuhl and Wenz 2020, Kotz *et al* 2024), and meta-analyses of several studies (Nordhaus and Moffat 2017), each with unique strengths. Recent studies, such as Kalkuhl and Wenz (2020) and Kotz *et al* (2024), often use econometric methods like panel regressions to estimate the so-called damage functions. Damage functions vary widely in their coverage of impacts (e.g. temperature, precipitation, extreme weather events), assumptions about non-linear damage escalation, and whether climate shocks affect economic levels or growth rates, contributing to ongoing uncertainty in long-term projections.

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

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

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

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

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

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

The results support the need for early and rapid climate action to avoid significant risks associated with climate damages of increasing temperatures, which outweigh those risks from the transition process. Additionally, comparing two modeling approaches provides policymakers with guidance on navigating diverse economic impact assessments and understanding the overarching conclusions of the model-based study.

2. Climate damages

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

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

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

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

3. Methodology

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

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

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

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

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

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

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

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

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

- **Carbon taxes**: Exogenously (in E3ME) or endogenously (in GEM-E3) set to meet emission reduction targets.
- **Emission caps**: With the tax level endogenously determined to clear demand and supply for emission permits.
- **Market-based instruments**: Such as emissions trading systems (ETS) and subsidies for clean technologies.
- **Regulatory instruments**: Including energy efficiency standards, renewable energy targets, CO_2 standards for vehicles, and phase-out policies for high-emission technologies.
- **Trade-related policies**: Like the Carbon Border Adjustment Mechanism and industrial tariff adjustments to mitigate competitiveness impacts on trade-exposed sectors.

3.1. E3ME model

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

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

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

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

3.2. GEM-E3 model

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

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

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

4. Scenario design

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

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

In the '*Net-zero*' scenario, a global carbon price is introduced after 2025 progressively increasing to 2050, affecting all sectors aiming to ensure a cost-efficient global transition towards net-zero emissions by 2050. The scenario includes additional ambitious climate policies including energy taxes, biofuel mandates, investments in clean technologies, and CO_2 standards and regulations on vehicles and boilers. The scenario also integrates major climate policies like the European Green Deal 2021 (European Commission 2020) and the U.S. Inflation Reduction Act (Dennis 2022).

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

5. Results

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

5.1. Reaching net-zero emissions

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

The net-zero scenario achieves global net-zero CO_2 emissions by 2050, with large emissions reductions achieved already by 2035 to meet the Paris Agreement's 1.5 °C goal. Mitigation efforts can vary by region, with some regions achieving net-negative emissions by 2050 to offset residual emissions elsewhere. Brazil, for example, achieves negative emissions through afforestation and bioenergy with carbon capture and storage, while India continues to use fossil fuels to meet its increasing energy needs (UNFCCC 2015). Appendix B provides a brief discussion of primary energy demand in both models and scenarios.

5.2. Socioeconomic impacts of net-zero

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

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

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

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

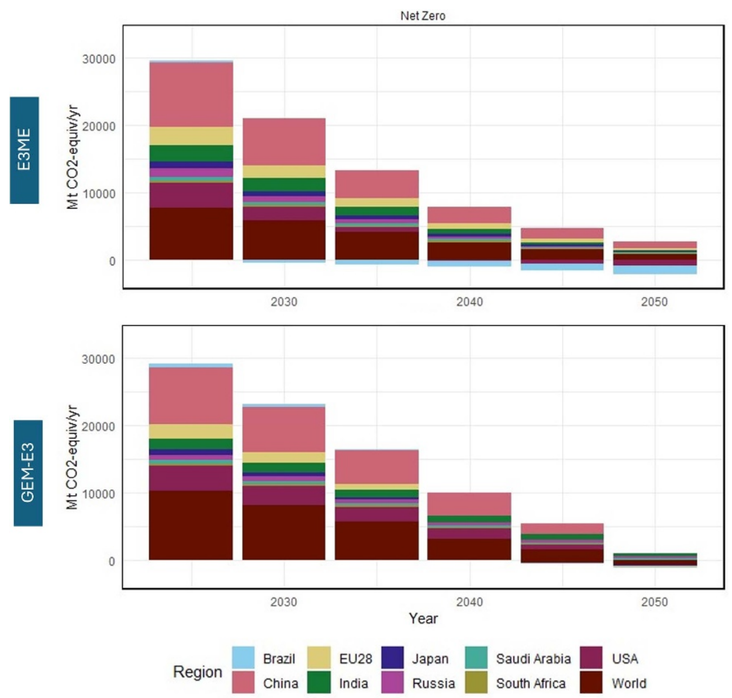

Figure 1. CO_2 emissions in the net-zero scenario. Total emissions across regions in the net-zero scenario in the E3ME model and in the GEM-E3 model.

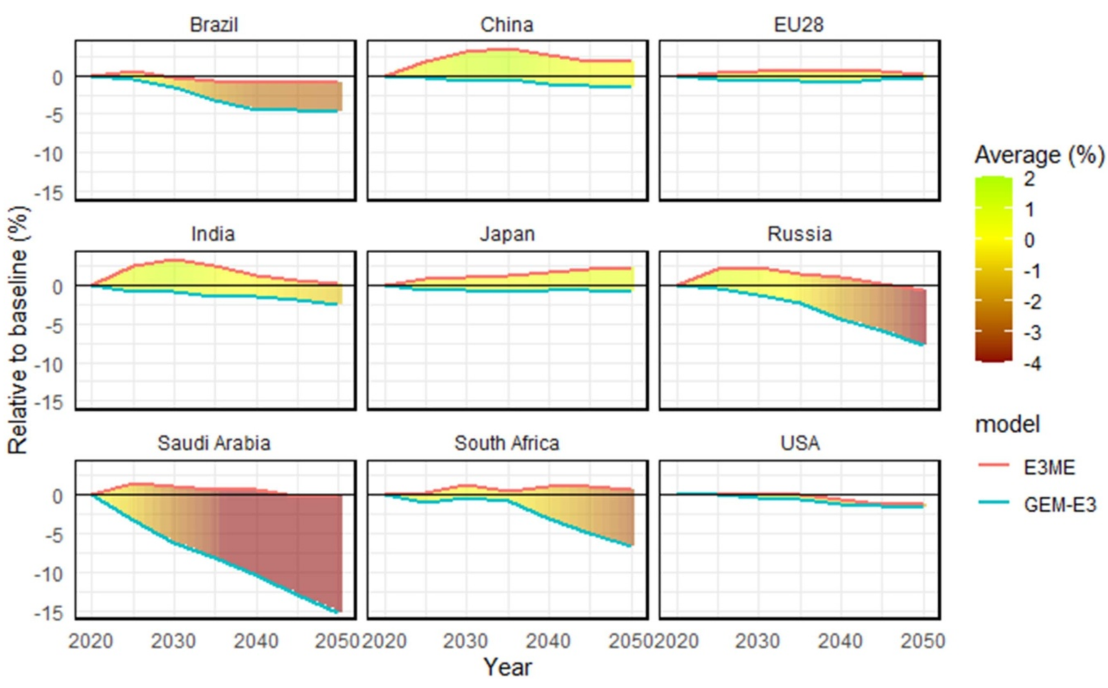

Figure 2. GDP impact of the net-zero scenario compared to current policies. The green-yellow-red shaded area of the figure shows the average difference from baseline (in %) across the two model results. The red (E3ME) and blue (GEM-E3) lines show the two models' estimates.

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

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

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

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

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

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

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

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

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

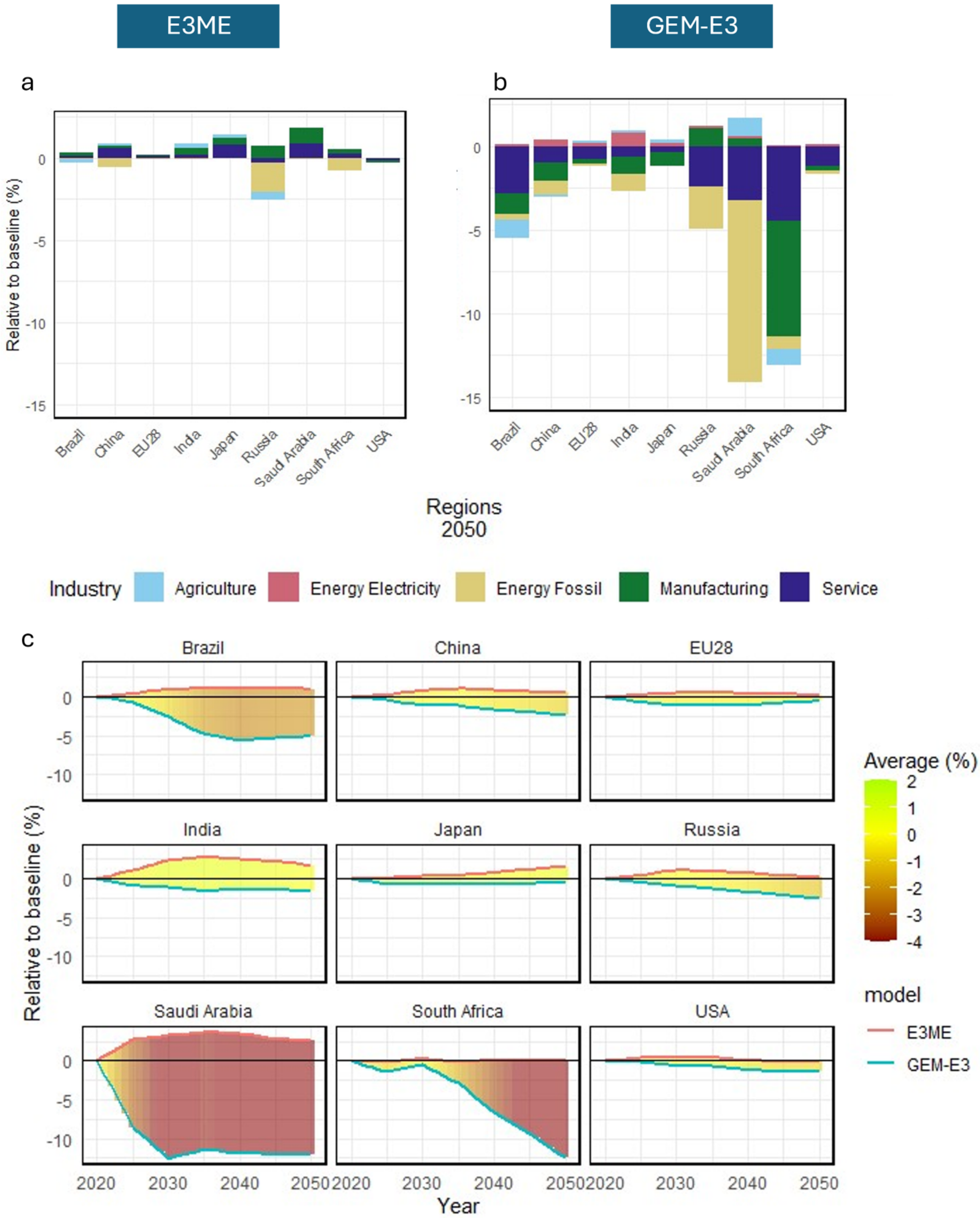

Figure 3. Employment impacts of the net-zero scenario compared to the Current Policies across countries. (a), In the E3ME model in 2050. (b), In the GEM-E3 model in 2050. (c), Employment impacts between 2020 and 2050 in both models. The green-yellow-red shaded area of the figure shows the average difference from baseline (in %) across the two model results. The red (E3ME) and blue (GEM-E3) lines show the two models' estimates.

6. Comparison of economic impacts and climate damages

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

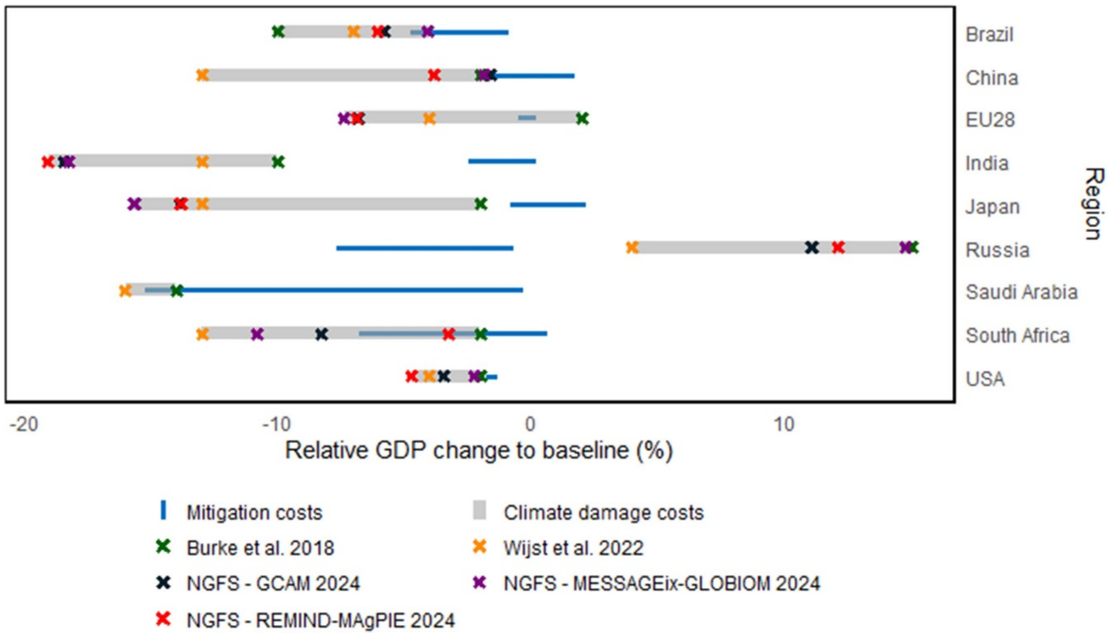

Figure 4. Range of GDP outcomes based on economic and climate modeling. The climate damage costs shown in the figure represent the additional climate damages in a single year, 2050, compared to a 1.5 °C scenario. This specification ensures comparability with the mitigation costs derived from our dual-model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

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

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

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

The costs associated with lower climate ambition, as estimated using different climate damage functions, cover a much larger range than the mitigation costs derived from the dual-model analysis of the net-zero scenario in all regions. This indicates the much higher uncertainty of the potential economic damages from climate change compared to the potential economic impacts of a transition towards global net-zero. However, the greater variability in damage cost estimates may, in part, be attributable to the broader and methodologically more diverse estimates on damage costs, in contrast to the mitigation cost estimates considered in this paper, which are derived from only two models.

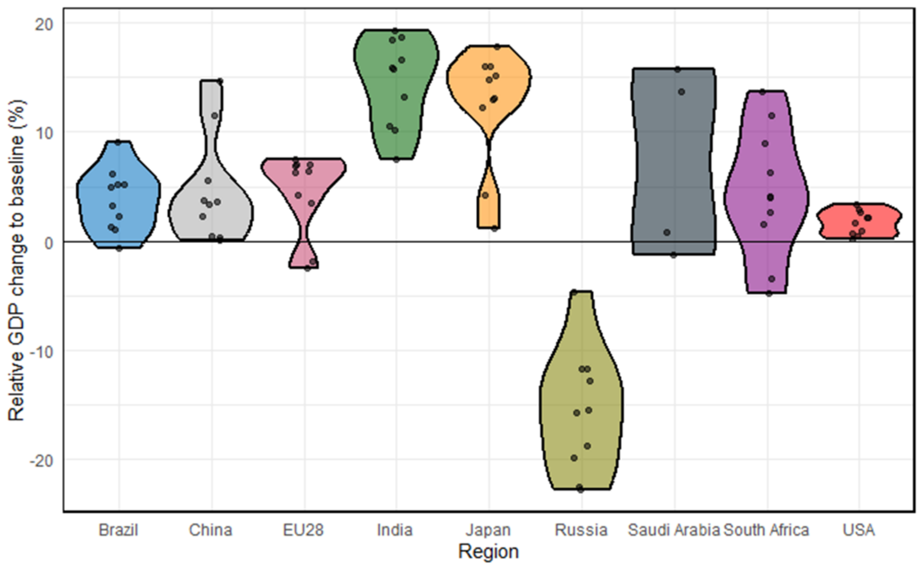

Figure 5. Combined impacts of mitigation and climate damage costs by region in 2050. The combined impacts for each region in 2050 are calculated by subtracting the climate damage costs under the Current Policies scenario from the mitigation costs associated with the net-zero pathway. These estimates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

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

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

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

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

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

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

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

7. Conclusions

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

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

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

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

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

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

Data availability statement

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

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

Declaration of generative AI in scientific writing

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

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