



Net0 Pathways through improved IAMs across Sectors, dimensions, and scales

Report on improved representation of economic structural change and its interplay with climate policy

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Executive Summary

The transition to low or zero-emission economies by mid-century requires profound structural macroeconomic changes. The socio-economic implications of decarbonization and especially the distributional impacts across countries, sectors and households have rarely been the focus of IAM-based studies. However, policy makers need insights into the impacts of climate policies on labour markets, competitiveness, and growth to design cost-efficient and societally acceptable low-emission strategies. In addition, the use of carbon revenues has also been widely discussed in the policy debate as this additional government revenue can be used in multiple ways to alleviate the negative impacts of decarbonization, while increasing overall economic efficiency, creating more jobs and/or improving social equity.

The task aims to improve the representation of structural change in climate change scenarios as well as the macroeconomic modelling of structural change and its interplay with ambitious climate policies. During PRISMA, several modelling enhancements have been implemented in a series of macroeconomic Computable General Equilibrium models (GEM-E3, IMACLIM-R) and Integrated Assessment Models (WITCH, REMIND) so that they can explore the interplay between ambitious climate policy and structural economic change at national, European and global levels. In particular, the sectoral granularity of participating models is enhanced and the comparability of model data and results with economic data sources (including GTAP, ILO, Eurostat) is improved. The enhanced models are utilized in a series of studies to assess the macroeconomic and structural change impacts in novel Paris-compatible scenarios aiming for low temperature overshoot. The studies reported in this deliverable provide an improved understanding of how economic structural change, and resulting growth, employment, and trade effects shape mitigation opportunities and vice versa.

In the first study, the research team from AGROPARISTECH showed that low-energy demand pathways necessitate a profound transformation of the global economic structure with new emerging sectors and a lower reliance on industries. Using the enhanced version of IMACLIM-R, four scenarios are explored characterized by a low level of final energy demand and different assumptions regarding the drivers of industrial output and structural changes. The findings indicate that several macro-economic drivers that could shape and challenge low-energy demand pathways, such as the role of material efficiency in production and in capital formation. The role of futures services in the economic structure, driving a large part of the Gross Domestic Product (GDP) increase, and its interlinkage with industries, challenges the idea that low level of final energy can be achieved without undermining economic growth. The analysis shows the need to improve the economic representation in modelling tools, at the sectoral and intra-sectoral scales, as a path towards more consistency between energy and economic growth paradigms in mitigation scenarios.

The socio-economic impacts of different ways to use the revenues from carbon pricing are analysed using four established multi-sectoral macro-economic models with high regional and sectoral disaggregation. The carbon revenues can be recycled back in the economy through multiple channels, including the reduction of taxes on labour (or social security contributions), lump-sum transfers to households, or funding green investment. The study shows that the GDP and employment impacts differ depending on economic narrative behind each model. Using carbon revenues to reduce labour taxes alleviates 40%-70% of mitigation costs in CGE models, while directing them to households through lump-sum payments a positive impact on equity within countries. The study demonstrates the socio-economic benefits of using carbon revenues to reduce distortive labour taxes and social security contributions with clear employment gains globally, while lump-sum transfers to households have the potential to reduce inequality.

The third study quantifies employment vulnerability in coal-dependent sectors in China and India under climate change mitigation scenarios. The analysis shows that the level of climate ambition is



an influential factor in employment risks for coal miners in India and China, but several other factors have an equal or even greater impact, depending on the country and region. The availability of CCS is a major determinant in India, whose development is more dependent on coal. Labour productivity rise in coal mining is a key factor in job destruction with old inefficient mines closing and newer, more productive mines opening. At the subnational level, disparities in mine productivity, coal job concentration, and worker reemployment potential create distinct exposure and vulnerabilities. Although mining regions are among the poorest in both countries, India's high levels of informal work and unemployment make it particularly vulnerable. Finally, the study provides quantitative insights to inform different types of just transition policies, directly or indirectly targeted at coal mine workers suggesting that a more worker-centered approach could reduce the number of workers going into unemployment to ensure Just Transition.

The comparison of socioeconomic impacts of climate inaction and climate mitigation provides policy-relevant insights into the risks and potential economic benefits of pursuing climate action. In this study we use 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 shows that the costs of mitigation are lower and more predictable than the potential climate damage costs. The study reinforces the need for decisive and immediate global mitigation efforts.

In the next study, the research team of PIK extended the global multi-sectoral optimal growth Integrated Assessment model REMIND by incorporating international trade and sector-specific frictions. These advancements enable the model to capture critical mechanisms that shape regional and sectoral outcomes under ambitious climate policy. The study results indicate how trade can mitigate welfare losses from climate policy in certain regions by enabling them to shift the burden of structural adjustment. Similarly, introducing frictions in labour and capital markets reveals their sizable effects on sectoral reallocation and welfare, particularly in low-income regions. These results highlight the value of moving beyond frictionless benchmarks in climate-economic modelling.

Finally, the CMCC team investigated alternative pathways for the transition of the global economy from one dominated by the fossil fuelled (brown) sector to one dominated by the low-emission (green) sector. They modify a well-known integrated assessment model of climate change and economy to consider three transition pathways: Linear, Delayed, and Fast. The results indicate that the main burden of the green transition lies on capital formation, accumulation, and transfers facilitated by full R&D investment in the green sector's productivity. The analysis suggests that transition pathways rely on different mechanisms to achieve their targets. The Delayed pathway relies on the combination of higher green capital investment and an increase in green capital productivity through R&D investment, while the Fast pathway requires substantial transfers of capital from the brown sector coupled with high abatement efforts.



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1. Introduction

Achieving the goals of the Paris Agreement requires a comprehensive transformation of economic systems, entailing not only technological change but also deep shifts in production structures, labour markets, economic growth, trade patterns, income, and labour allocation. Integrated Assessment Models (IAMs) play a key role in evaluating policy pathways that facilitate this transformation, offering quantitative insights into the trade-offs and synergies between environmental goals and economic development. The PRISMA project contributes to the evolution of IAMs by developing model capabilities across several dimensions critical for robust climate policy assessment. A central theme of this effort is the improved representation of economic structural transformation, i.e. how countries reallocate economic activity across broad sectors over time, particularly in response to climate policy. In particular, the task 2.1 of the PRISMA project aims to improve the representation of structural economic change in climate change mitigation scenarios as well as the macroeconomic modelling of structural change and its interplay with ambitious climate policies. As the low-carbon transition deepens, policymakers and other relevant stakeholders are increasingly focusing on the broader socioeconomic, industrial and structural change implications of ambitious climate mitigation strategies that will impact the way that economies and societies operate.

This report focuses on the further development and use of Integrated Assessment Models (IAMs) to assess mitigation measures and systemic transformations towards climate neutrality. IAMs are powerful tools that can help policymakers evaluate the potential environmental and economic impacts of various mitigation scenarios and strategies, including deep electrification based on expansion of variable renewable energy sources (RES), hydrogen uptake, and emergence of Carbon Capture Use and Storage (CCUS). IAMs consider the complex interactions between energy demand and supply, and the environment, but they do not accurately represent the socioeconomic and structural change effects of mitigation given their limited sectoral representation. In the PRISMA project, innovative methodologies to enhance the sectoral granularity as well as the socioeconomic and structural change representation to enable the models provide an enhanced analysis of the potential interplay between climate policy and structural economic change.

The report also puts a specific focus on the macro-economic and structural change implications of the low-carbon transition using a set of established multi-sectoral multi-regional macro-economic models. The socio-economic impacts of decarbonization and especially the distributional impacts across countries, sectors and households have rarely been the focus of IAM-based studies. However, policy makers commonly need insights into the impacts of climate policies on labour markets, sectoral production and competitiveness, and economic growth to design cost-efficient and societally acceptable low-emission strategies. In addition, the use of carbon revenues has also been widely discussed in the policy debate as this additional government revenue can be used in multiple ways to alleviate the negative impacts of decarbonization, while increasing overall economic efficiency, creating more jobs and/or improving social equity.

The second chapter of the report presents a study from AGROPARISTECH showing that low-energy demand pathways necessitate a profound transformation of the global economic structure with new emerging sectors and a lower reliance on industries. The study illustrates the increasing role of services in the global economy and their interlinkage with industries, which challenges the idea that low final energy consumptions can be achieved without undermining economic growth. The analysis shows the need to improve the economic representation in modelling tools, at the sectoral and intra-sectoral scales, to ensure consistency between energy and economic growth paradigms in scenarios.



The third chapter aims to analyse the socioeconomic impacts of different ways to use the revenues from carbon pricing using four established multi-sectoral macro-economic models with high regional and sectoral disaggregation. The study shows that using carbon revenues to reduce labour taxes alleviates 40%-70% of mitigation costs in CGE models, while directing them to households through lump-sum payments a positive impact on equity within countries. The study demonstrates the socio-economic benefits of using carbon revenues to reduce distortive labour taxes and social security contributions with clear employment gains globally.

The fourth chapter explores employment vulnerability in coal-dependent sectors in China and India under mitigation scenarios. The analysis shows that the level of climate ambition is an influential factor in employment risks for coal miners, but several other factors have an equal or even greater impact, depending on the country and region. The availability of CCS is a major determinant in India, whose development is more dependent on coal. Labour productivity rise in coal mining is a key factor in job destruction with old inefficient mines closing and newer, more productive mines opening. At the subnational level, disparities in mine productivity, coal job concentration, and worker re-employment potential create distinct exposure and vulnerabilities.

In the fifth chapter, we compare the socioeconomic impacts of climate inaction and climate mitigation to meet the Paris goals using two macroeconomic models, GEM-E3 and E3ME. The findings indicate that while economic outcomes of decarbonization may vary depending on the model paradigm used, the uncertainties in climate damage projections far exceed those of mitigation costs. The sixth chapter presents a study aiming to extend the global multi-sectoral optimal growth IAM REMIND by incorporating international trade and sector-specific frictions enabling the model to capture critical mechanisms that shape regional and sectoral outcomes under ambitious climate policy. The study results indicate how trade can mitigate welfare losses from climate policy in certain regions by enabling them to shift the burden of structural adjustment.

The seventh chapter presents a study led by CMCC on alternative pathways for the transition of the global economy from a fossil-based paradigm to a low-emission green paradigm. The results indicate that the main burden of the green transition lies on capital formation, accumulation, and transfers facilitated by full R&D investment in the green sector's productivity. The analysis suggests that transition pathways rely on different mechanisms to achieve their targets.



2. Macroeconomic impact of demand-side mitigation strategies: a structural change assessment of material efficiency

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Low-energy demand pathways necessitate a profound transformation of the global economic structure with new emerging sectors and a lower reliance on industries. In this study, we investigate four scenarios characterized by a low level of final energy demand (~325 EJ/yr in 2060) and different assumptions regarding the drivers of industrial output and structural changes. Our findings shed light on the importance of several macroeconomic drivers that could shape and challenge low-energy demand pathways, such as the role of material efficiency in production and in capital formation. The role of futures services in the economic structure, driving a large part of the Gross Domestic Product (GDP) increase, and its interlinkage with industries, challenges the idea that low level of final energy can be achieved without undermining economic growth. We conclude for the needs to improve the economic representation in modelling tools, at the sectoral and intra-sectoral scales, as a path towards more consistency between energy and economic growth paradigms in mitigation scenarios.

2.1 Introduction

Demand-side mitigation options have gathered significant attention in the latest IPCC report as promising strategies aiming at reaching the Paris agreement goals (IPCC, 2023). These consist of a strong reduction in energy services activities and a reduction in the material and energy intensity of economic activities through efficient fuel switching, increased energy efficiency, and lifestyle changes (Creutzig et al., 2022; 2018). Demand-side policies are thus being regarded as a way to accelerate the short-term energy transition, enhance co-benefits and reduce dependencies on carbon dioxide removals (Mundaca et al., 2019; Grubler et al., 2018; van Vuuren et al., 2018).

The feasibility of achieving low-energy demand pathways remains uncertain, particularly due to the macroeconomic transformations they imply. While concerns have been raised about their policy and behavioural implementation (Saujot et al., 2021; Newell et al., 2021), the macroeconomic dimension is still underexplored. One major issue concerns structural change: can economic growth be maintained while reducing the share of industry in economic activity, and can emerging service sectors sustain growth with a much lower material footprint? Demand-side mitigation pathways often rely on a strong dematerialisation of production, assuming a shift from industrial to service-based activities. Yet, industrial production remains central to economic development, especially in emerging economies where it supports infrastructure and capital accumulation (Cunha & Ferrão, 2022; Lautier, 2024; Fisch & Guivarch, 2021; Krausmann et al., 2020). Much of this production involves durable goods (e.g. steel, cement) for buildings and machinery, making it hard to substitute in the short term. While strategies such as material substitution, extended product lifetimes, and digitalisation can ease this pressure (Allwood et al., 2013; Krausmann et al., 2017), the pace of structural change envisioned in low-demand scenarios exceeds historical trends (Semieniuk et al., 2021). Furthermore, the nature and scale of emerging service activities remain uncertain, especially in light of ongoing digitalisation and the rise of artificial intelligence (Freitag et al., 2021; Witt & Gross, 2019). This uncertainty casts doubt on whether a service-based economy can fully support sustained growth while significantly reducing material and energy use.

A second macroeconomic challenge lies in the potential rebound effects of demand-side policies. A reduction in the material content of economic growth, or additional energy efficiency



improvements, could yield productivity gains with direct positive feedback on aggregate economic output (Semieniuk et al., 2021; Brockway et al., 2021; Grubler et al. 2018). In the case of costless efficiency improvements, productivity gains induce lower prices and increase the purchasing power of households. For the case of efficiency measures triggered by dedicated investments, which is the case for energy efficiency or emerging economic activities such as recycling industries, the propagation of productivity gains through the whole economy then depends on the variation of capital and labour costs at the aggregate (Allwood et al., 2011; Peneder et al., 2003). In both cases, the resulting increase in economic activities, sometimes qualified as rebound effects (Grubler et al., 2018; van Sluisveld et al., 2016) challenges the feasibility of demand-side strategies in lowering the final energy demand level in absolute terms (Brockway et al., 2021; Reimers et al., 2021; Skelton et al., 2020; Brockway et al., 2017; Dimitropoulos et al., 2007).

Understanding the macroeconomic implications of demand-side mitigation constitutes a major challenge for modelling, particularly for Integrated Assessment Models (IAMs). Several studies have explored how demand-side measures—such as changes in transport use, housing needs, or consumption of material goods—can reduce energy demand while meeting climate goals (Grubler et al., 2018; van Vuuren et al., 2018; Méjean et al., 2019; van Heerden et al., 2025). These demand-side options assessed span all sectors of the economy (Mundaca et al., 2019) and include actions like car sharing, reduced shipping speeds, or lower indoor temperature setpoints. However, existing modelling approaches often fail to capture the full scope of structural change and rebound effects. Often by construction in IAMs, GDP assumptions serve to derive activity levels of the economy and in turn energy demand, on top of which additional energy reduction measures are scenarised (Kermeli et al., 2021; Grubler et al., 2018). Therefore, low energy demand pathways suggest a strong decoupling between energy and economic growth, without looking back at the potential feedback of this decoupling on the original GDP assumptions, on the economic structure and its associated material content (Lefèvre, 2023; Semieniuk et al., 2021). IAMs typically lack endogeneity in how economic activity levels and structural shifts evolve in response to demand-side policies. Yet final energy demand fundamentally depends on the scale, composition, and productivity of economic activity (Guzzo et al., 2024). Capturing these effects requires representing how industrial goods contribute to GDP—as both final and intermediate goods—and how substitution towards services might occur (Pauliuk et al., 2017; Witt and Gross, 2019). For instance, reducing car ownership through sharing models involves deep changes in consumption patterns and infrastructure, enabled by digital technologies (Shaheen and Cohen, 2012). These interactions between sectors, technologies and preferences remain insufficiently addressed in most current models.

In this study, we assess the macroeconomic implications of low energy demand pathways and show how they matter in driving the final energy level. We illustrate the fact that several macroeconomic realities can exist under a given growth paradigm and yet lead to the same low energy demand level. The inherent consistency between GDP, its economic structure and final energy level is illustrated by five scenarios reaching an aggregate final energy level of 325 EJ/yr in 2060. Each scenario differs in the way structural change reacts to demand-side policies, resulting in various economic structures and sectoral energy intensities, especially regarding industries and services. The scenario differences allow us to shed light on the main macroeconomic mechanisms that have to be considered carefully when designing demand-side mitigation policies. A particular focus is given to the role of the material content of production and capital formation, both acting as GDP multipliers when reduced. We employ the integrated assessment model IMACLIM-R (Briera and Lefèvre, 2024; Méjean et al. 2019; Waisman et al., 2012) in order to capture efficiency measures and activity level reductions into a general equilibrium framework whose macroeconomic dynamics occur at the sectoral scale. A set of common assumptions drives preferences towards a low level of demand for energy services, and a low level of energy and material content of economic activities. However, absolute levels of activities are kept endogenous so that the aggregate GDP is sensitive to each policy measure. This framework allows us to highlight the significance of



macroeconomic mechanisms when considering energy and material efficiency as mitigation options, from which we draw research recommendations for integrated assessment modelling to improve the macroeconomic representation in the design of scenarios.

2.2 Methods and scenarios

The study employs the IMACLIM-R integrated assessment model, which combines a top-down computable general equilibrium (CGE) model with bottom-up sectoral and energy models within a recursive dynamic framework (Briera and Lefèvre, 2024; Méjean et al. 2019; Waisman et al., 2012). The CGE and recursive framework allow for an endogenous representation of the total economic activity and its sectoral components, encompassing the role of energy sectors in aggregated GDP and in industries production costs, as well as the detailed roles of industries and services in economic transformation. Additionally, an input-output structure captures the direct structural effects of material efficiency in supply chains, encompassing the direct reduction of material inputs in production and capital formation¹. Thus material and energy efficiency measures do not only act as a reduction of the physical impact of production but also represent a direct shift of the production frontier, driving as well structural change and economic growth. In IMACLIM-R, potential GDP growth is triggered through two main drivers: an exogenous active population path, and an exogenous path of labour productivity growth for every economic sector. Realized growth, however, depends on the overall economic dynamic which includes relative price variations, structural change and the evolution of annual fixed costs of production (energy and material inputs, transport requirements, etc.). In this study, labour productivity and population growth are chosen so as to reflect in a baseline scenario the GDP of the Shared Socioeconomic Pathway (SSP) 2 scenario when only current climate policies are considered (van der Ven et al., 2023; Riahi et al., 2017; Fricko et al., 2017). However, GDP remains endogenous, neither activity levels nor structural change are prescribed in IMACLIM-R, allowing for example emerging services sectors to absorb any residual economic activity (Lynch et al. 2024; Lefèvre et al. 2022).

We construct five mitigation scenarios, a reference one and four variants, harmonized to a common final energy level of 325 EJ/yr in 2060. All mitigation scenarios have the same labour productivity and population growth as in the baseline, but realized growth could deviate from the GDP trajectory of the SSP2. The reference low energy demand scenario (Im-LED) assumes low level of economic activities and energy intensities by shifting economic agent preferences: households' behaviour, price elasticities driving energy efficiencies, etc. Table 1 and Table 2 describes the various levies employed and the target reached in 2060 in this reference scenario, with a comparison of the MESSAGE-LED scenario of Grubler et al. (2018). Preferences being set in the reference (Im-LED), each of the four variants relaxes a macroeconomic assumption regarding the role of industrial goods as an input in production, in capital formation, or regarding the substitution potential to services. Scenarios ultimately differ in terms of economic structure and energy balance, as a result of endogenous structural changes reactions, price responses and GDP variations to those macroeconomic assumptions. In order to harmonize all scenarios on a 325EJ/yr final energy level in 2060, we change the energy intensity of the services sector by adjusting its energy price elasticity. These differences between scenarios capture the additional energy efficiency effort that has to be made in services to compensate for an upsurge in macroeconomic activities.

The four macroeconomic variants are constructed as follows:

- Im-LED-VA: This scenario is similar to the reference (Im-LED), except that productivity gains resulting from material efficiency improvements (in economic/monetary terms) across all economic sectors are captured through increased profit margins.

¹ Input-output coefficients in IMACLIM-R are calibrated at the base year in US\$2014, with no dual accounting in values and quantities for physical but energy. As such, the value of industrial inputs in 2014 act as a proxy of material inputs, with however an endogenous price.



- Im-Led-noMECAP: This scenario relaxes the assumption of material efficiency in capital formation, and therefore explores the impact of constant material content of capital formation.
- Im-LED-noMEProd: In this scenario, the assumption of increased material efficiency in industrial and other sectors' production is relaxed, so that more intermediate industrial goods are required for global economic outputs and with higher production costs.
- Im-LED-ME2Serv: In the scenario, we assume that material efficiency in production (the material inputs for economic sectors) are substituted by services inputs so that the total cost of production remains unchanged. Thus in this scenario, there are no productivity gains from material efficiency, but also a larger share of services in the total economy.

A sensitivity analysis is conducted on the energy intensity of the services sector for the different scenario variants, still with the same carbon budget but leading to different final energy levels.

All scenarios comply with a carbon budget of 600GtCO₂ over the 2023-2060 period, in line with a 50% likelihood of remaining below a 1.7°C increase compared to pre-industrial levels (Forster et al., 2023). Besides, scenarios are close to net zero in 2060, ensuring the stabilisation of the climate forcing over the following decades. The carbon budget is achieved through global carbon pricing which drives technical change towards low-carbon energy production technologies. Ultimately demand-side policies reduce the final energy level and alleviate the need to rely on low-carbon and negative emissions technologies (NETs) to comply with the carbon budget constraints. Each macroeconomic variant induces GDP, economic activities and structural variations, which affects the extent to which climate policy needs to be strengthened or not. For example, increased transport activities will result in higher short-term carbon emissions, whereas an increased shift from industry to services eases the low-carbon transition through electrification.



Table 1.

	Region	% change in activity levels 2023-2060 (2020-2050 LED)	% change in energy demand 2023-2060 (2020-2050 LED)	Activity in 2060 (2050 LED)	Energy demand in 2060 – EJ/yr (2050 LED)	Preference change drivers	Endogeneity
Housing & Thermal confort	North	-20 (6)	-82 (-74)	54 ¹ (47)	6 (8)	A: income elasticity of housing and maximum housing per capita. E: Additional decrease of the energy intensity of BAU buildings; Increased renovation rate; Higher weight in the logit in favor of more VLE buildings; Lower energy intensity of VLE buildings;	A: Until the asymptote is reached, housing is still endogenous to income. E: Energy intensities of buildings, the market share of VLE, and the renovation rate are still endogenous to energy prices, the CO2 price and investment costs.
	South	88 (63)	74 (-79)	233 ¹ (218)	48 (8)		
Mobility - All	North	61 (29)	-58 (-60)	25.0 ² (25)	20 (16)	A: For the total mobility level, we change the substitution elasticity in the utility function which drives the preferences for mobility compare to other goods. A: For each of the three mode (Terrestrial transport, air and private cars), exogenous forcing on transport infrastructure, which drive congestion and the marginal preference for faster travels.	A: The absolute total level of mobility is endogenous to income. A: infrastructure investments and congestions are still endogenous to the demand and drive the preference for each transport modes, as well as energy prices.
	South	183 (122)	20 (-59)	25.0 ² (73)	27 (12)		
- Terrestrial transport	North	97	-76	8.0 ²	5	E: Additional exogenous energy efficiency.	E: Absolute energy consumption depends on the activity level.
	South	86	-72	45.0 ²	9		
- Air transport	North	41	23	3.0 ²	4	E: Additional exogenous energy efficiency.	E: Absolute energy consumption depends on the activity level.
	South	160	23	3.0 ²	4		
- Private cars	North	49	-69	14.0 ²	9	E: Change the minimum achievable energy intensity of private cars.	E: Absolute energy consumption depends on the activity level, and to some extent on the dynamic of technological progress towards more efficient vehicles (until the asymptote is reached).
	South	1263	252	30.0 ²	16		
- Cycling and Walking	North	/	/	/	/		
	South	/	/	/	/		
Freight - All	WLD	/	/	-51	48	A: None. E: Same energy efficiency gains as for air transport mobility. For shipping, additional energy efficiency gains from speed reduction and port norms implementations.	A: Fully endogenous to the level of trade. E: Absolute energy consumption depends on the activity level.
- International Shipping	WLD	72	68	/	23		
- International Aviation	WLD	-51	-65	/	0		
Production - Agriculture	North	92	45	/	11	A: None. E: Same additional forcings of energy efficiency as in the industrial sector	A: Fully endogenous households demand and income. E: Still endogenous to energy prices and the absolute level depends on the activity level.
	South	200	194	/	32		
Production - Construction	North	174	197	/	5	A: None. E: Same additional forcings of energy efficiency as in the industrial sector	A: Fully endogenous to the demand, mostly capital formation. E: Still endogenous to energy prices and the absolute level depends on the activity level.
	South	360	522	/	9		
Production - Services	North	98	-33	/	16	A: None. E: Same additional forcings of energy efficiency as in the industrial sector	A: Fully endogenous to the activity level (for intermediate consumptions) and to households increasing propensity to consume services as income rise. E: Still endogenous to energy prices and the absolute level depends on the activity level.
	South	475	69	/	26		
Production - Industries - Total	North	-43 (-47)	-25 (-57)	/	33 (26)	A: See detail below E: Exogenous additional forcing to energy efficiency.	A: Fully endogenous to the activity level. E: Still endogenous to energy prices and the absolute level depends on the activity level.
	South	3 (-12)	4 (-23)	/	115 (82)		
- Capital Formation	North	-42	/	/	/	A: 75% reduction of industrial content.	A: Endogenous to the absolute level of investment.
	South	44	/	/	/		
- Households (&PA)	North	-31	/	/	/	A: In the utility function, change of the saturation level of industrial good consumptions.	A: In the scenario variant, the absolute level is still sensitive to changes in relative prices.
	South	-21	/	/	/		
- Intermediate inputs	North	-44	/	/	/	A: 30 and 32% (Global North and South) reduction of industrial intermediate inputs to each sectors.	A: Absolute level endogenous to total activity.
	South	14	/	/	/		
- Exports	North	-52	/	/	/	A: Armington trade elasticity	A: Absolute level endogenous to total activity.
	South	-43	/	/	/		
Total	North	/	-45	/	96		
	South	/	23	/	254		

Assumptions taken for the reference scenario Im-LED. Units: 1 – 10⁹ m²; 2 – 10¹² pkm. A: assumptions for the activity level. E: Assumptions for the energy intensity.
In brackets: selected assumptions of the LED-MESSAGE scenario from Grubler et al. (2018), which consider 2050 as a target.



2.3 Results

2.3.1 The effect of the economic structure on the energy mix

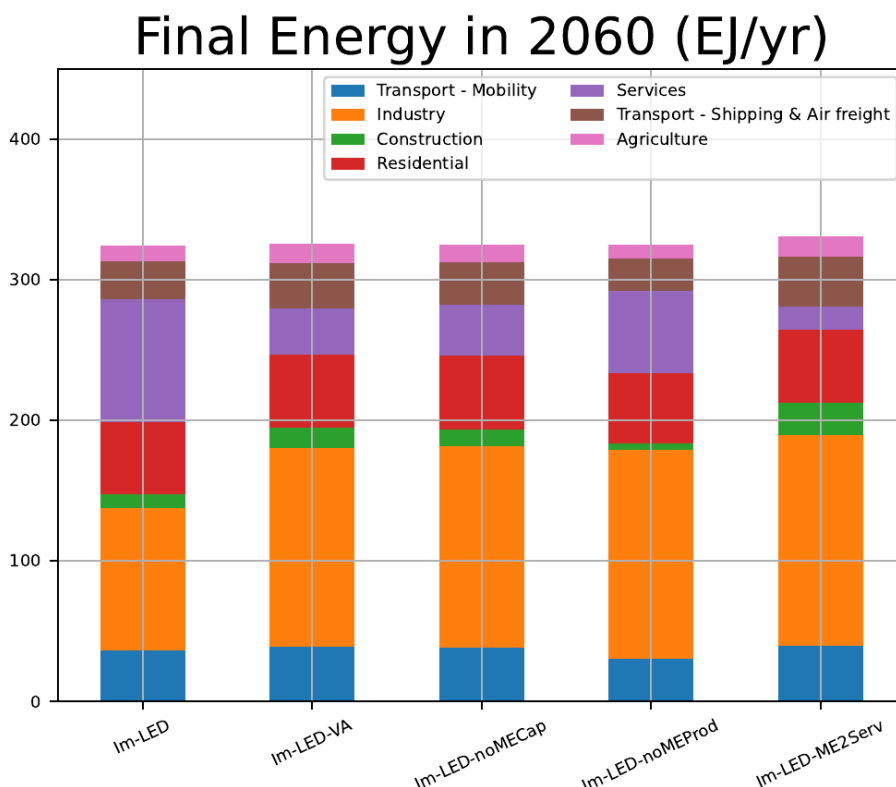


Figure 1. Final energy of the different scenarios in 2060 in EJ/yr, by sector.

Different economic structures and energy balances are compatible with a low energy demand pathway reaching 325 EJ/yr in 2060 (Figure 1). The five scenarios mainly differ in terms of final energy for industries and services accounting respectively for 31 and 37% in the reference scenario Im-LED in 2060. Variations of the other components of the energy balance are also significant depending on economic activity variation (Table 2). For example, the Im-LED-noMEProd scenario exhibits the lowest level of activity for transport, because the no material efficiency assumption leads to a relative decrease in GDP. On the contrary, the Im-LED-M2SERV and Im-LED-VA assumptions result in a relative GDP increase, which translates into larger needs for shipping and air freight (+22.3 and +9.4% increase in energy terms) and construction activities driven by larger investments.

The reference scenario Im-LED reach 101EJ/yr and 87EJ/yr respectively for industries and services in 2060. The four variants have in common a relative increase in final energy for industrial goods production, which is by construction compensated by a relative decrease in services (-59% on average). However, this aggregated result hides different economic structures and activity level variations consistent with the macroeconomic assumptions considered. Fig. 2 shows an LMDI decomposition of the final energy differences with the reference scenario Im-LED. Understanding the differences between scenarios gives strong insights into the economic mechanisms that drive the final energy level, revealing tensions, balancing effects and conditions for the scenario Im-LED to occur.

Impact of Material Efficiency and Servitisation: capturing material efficiency cost savings through increased profit margin (Im-LED-VA) cancels the positive economic feedback impact on the

purchasing power of households. However, it also increases the gross domestic surplus of companies, which boosts GDP compared to the reference scenario. GDP variations would alone be responsible for a +150EJ/yr increase of final energy if everything else were equal, which is here compensated by higher energy efficiency in services (-90EJ/yr) and in other sectors (-45EJ/yr). The substitution of material efficiency by servitisation (Im-LED-ME2Serv) results in a similar GDP boost (+120EJ/yr), but more because of an increased services-led growth than an increase in capital formation.

Achieving Low energy demand without material efficiency: removing material efficiency in capital formation (Im-LED-noMECap) results directly in a relative increase in the demand for industrial goods. The absence of material efficiency does not imply higher costs nor alleviate growth, as it was substituted by service inputs in the reference Im-LED scenario. However, it is by construction replaced by more energy efficiency in services to achieve 325EJ/yr. The resulting energy productivity gain is the main driver of final energy variation, because of an overall GDP boost (+75EJ/yr) through more productive services, despite a slower structural change via capital formation. This scenario highlights how important are each component of industrial goods demand, as industrial inputs in capital formation alone hide a potential rebound effect of 75EJ/yr if material efficiency were missing, adding pressure on services sectors to bear the final energy reduction efforts.

Material efficiency in industrial production (Im-LED-noMEProd) appears to trigger important macroeconomic feedback in demand-side policies. Removing this potential has a strong negative impact on GDP (-220EJ/yr). Relatively to the reference scenario (Im-LED), a lower growth naturally slow down structural change, but the higher energy intensity of industries partially compensates (+47EJ/yr) for the final energy and GDP drop. Lower GDP also slows down capital replacement and the average energy price increase, giving less incentive for energy efficiency in all sectors.

Structural change effects: the effect of structural change appears to be the main driver of final energy variation in all scenarios. Whenever GDP increases, economies shift from industries towards services which are less energy intensive. On the contrary, lower GDP growth is associated with a higher share of final energy from industries. However what matters are the detailed structural change impacts induced by each specific demand-side policies. For example, the servitisation of production (Im-LED-ME2Serv), in substitution to material efficiency, accelerates structural change faster than the scenario with increased profit margin (Im-LED-VA). The latter drives GDP upwards homogenously through increased investments. The strongest macroeconomic effect is caused by the impact of material efficiency in production. The latter concerns all economic sectors, driving fierce deindustrialisation. In every scenario, the fact that industrial goods serve as production inputs or in capital formation creates positive feedback loops on industrial production each time GDP increases, which challenges the targeted industrial output decrease.

$$\Delta FE = \left(\frac{FE_{ind} VA_{ind}}{VA_{ind} GDP} + \frac{FE_{ser} VA_{ser}}{VA_{ser} GDP} + \frac{FE_{oth} VA_{oth}}{VA_{oth} GDP} \right) \frac{GDP}{POP} POP$$

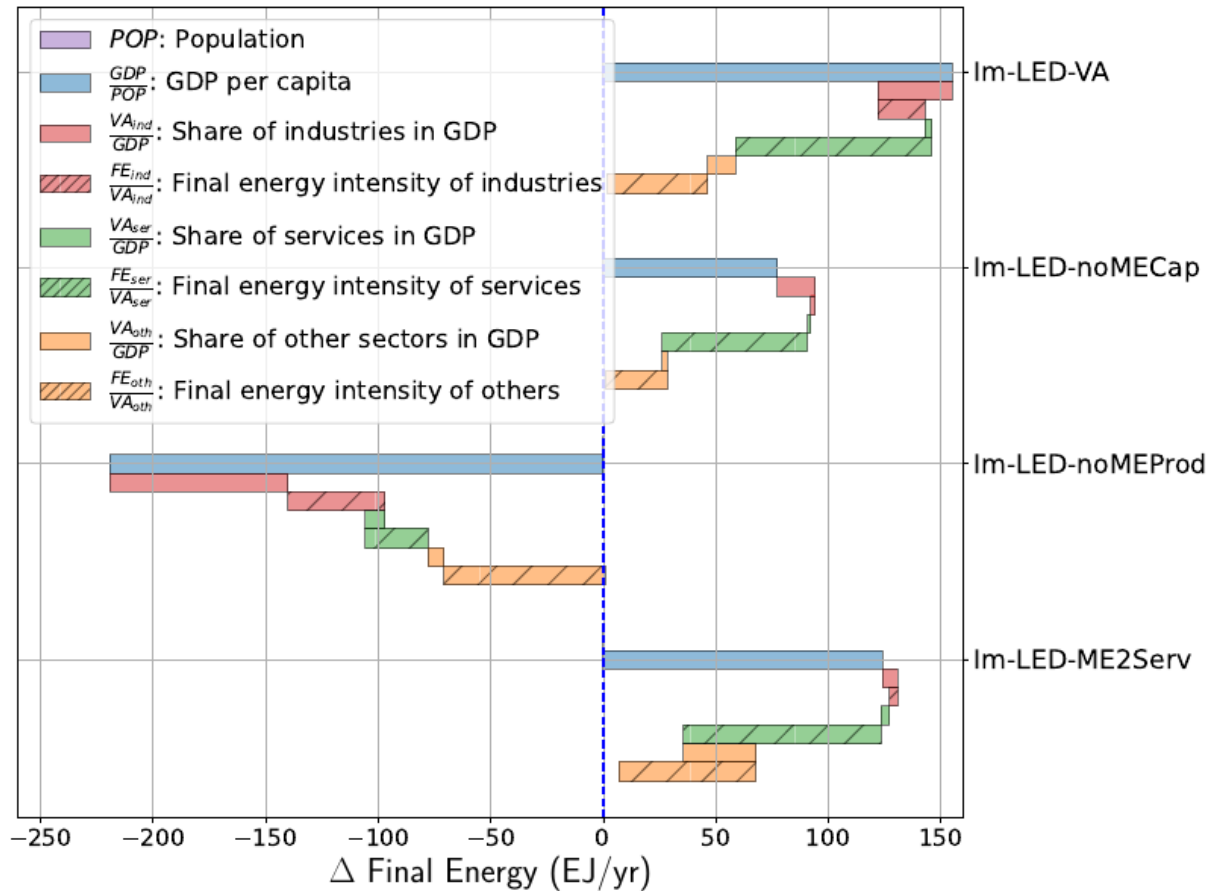


Figure 2. LMDI decomposition (ΔFE) of the difference with the main scenario Im-LED, function of the different drivers: population, GDP per capita, share of value added in GDP and energy intensities of the industrial, services and remaining (other) sectors.

2.3.2 Economic drivers of aggregated industrial good demand

Our scenarios highlight several mechanisms at play that create tensions between policies aimed at reducing final energy and industrial activity levels on one side, and the economic boost resulting from productivity gains, mostly in favour of the services sector on the other side. Channels are not unique and reveal themselves from a complex economic structure, involving the role of structural change from industries towards services as economies grow, the role of the various components of the demand for industrial goods (final households demand, intermediate inputs both in production and in capital formation) and the role of GDP increase triggered by capital investment or household's consumption. Moreover, the main feedback loop involves challenging the decrease of industrial output concerning the emergence of services. The latter are more productive than industries but always trigger industrial good demand because of the degree of materiality of services production and its capital structure. This ultimately challenges the effectiveness of reducing industrial output in absolute terms.

Figure 3 shows the decomposition of the variation of the domestic demand for industrial goods, in the different scenarios. The component that varies the most is industrial goods entering production as intermediate inputs. The relative growth of industrial intermediate goods explains 118% of the industrial domestic demand variation in Im-LED-noMEProd. Obviously in this scenario material efficiency is suppressed which increases industrial output despite a reduction in GDP per capita. In the three other variants, the GDP boost increases the absolute need for industrial

intermediate inputs, explaining respectively 80 and 85% of the variation for the Im-LED-ME2Serv and Im-LED-VA scenarios. On the contrary, suppressing material efficiency in capital good formation (Im-LED-noMECap) increases the industrial good content of investment (+54%). However, the total activity also increases in this scenario so that the share of intermediate inputs in total variation remains high (+38%).

$$\Delta Q_{ind} = Demand_{ind} + CI_{ind} + \frac{K_{ind}}{Inv_{total}} * (Inv_{ind} + Inv_{oth} + Inv_{ser})$$

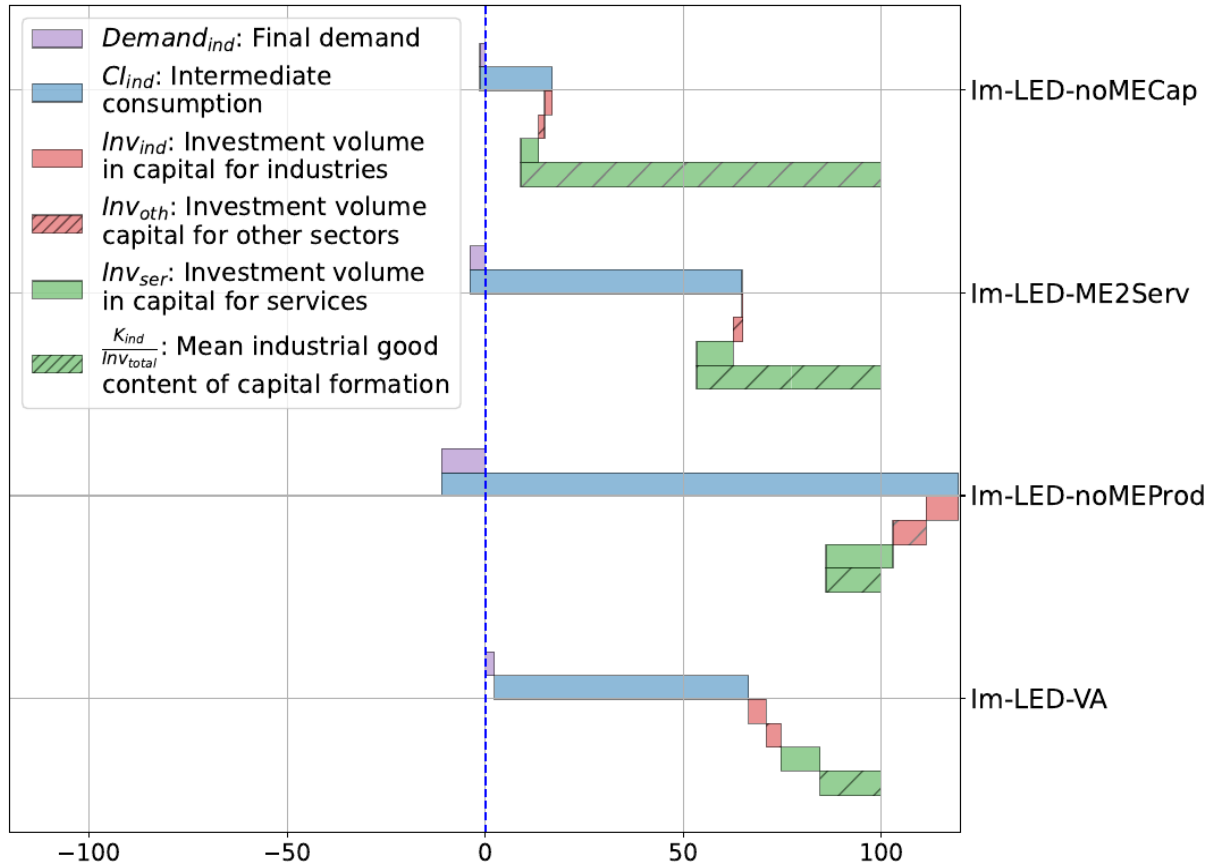


Figure 3. LMDI decomposition of the driver of the domestic demand (delta Q) of industrial goods through its three components: final demand, intermediates inputs, and the demand for capital goods. The latter is decomposed by the average industrial good content of capital formation and by the investment volume in the three aggregated sectors.

2.3.3 Futures services challenging the energy-GDP decoupling

The final energy level of the services sector varies across scenarios. One of the reasons is the alignment with the 325 EJ/year assumption, which is driven by the level of energy efficiency in the services sector. Another reason concerns the level of structural change in each scenario. In this paragraph, we relax the harmonized 325EJ/yr assumption and allow the total final energy level to vary. Figure 4 illustrates the total final energy level in each scenario in 2060, as a function of the energy intensity of the services sector, obtained with different values of energy efficiency price elasticity. We consider a lower bound of 1.5 EJ per dollar of added value based on currently known energy intensities of services sectors. For example, the financial sector in the US exhibits a 1.7 EJ/\$ energy intensity, a sector which only requires heating/cooling of buildings and with high added value. Falling below this threshold would mean that the world economy has an average service sector that is as productive as the US financial sector, but more energy efficient.

Results indicate that the Im-LED-VA, Im-LED-noMECap and Im-LED-noMEProd scenarios were already at really low levels of energy intensities when reaching 325EJ/yr in 2060, reflecting the need to compensate for strong positive economic feedback by a lower energy content of services. The Im-LED-ME2Serv scenario with increased servitisation has the highest final energy level for a given energy intensity. This is explained by the fast-rising share of services in GDP as a consequence of servitisation and the overall macroeconomic boost. Only the reference scenario Im-LED seems to have room for manoeuvre with an average 5EJ/\$ energy intensity at 325EJ/yr in 2060. This scenario is however the most favourable in terms of limiting potential positive macroeconomic feedback due to material efficiency mitigation measures. This raises a first issue concerning the feasibility of low-energy demand pathways: a trade-off appears between an ideal situation in which major economic feedbacks are avoided, and the reliance on strong energy efficiency measures in services to compensate for economic rebounds. If all economic conditions were to be favourable (Im-LED), a low level of final energy demand can be achieved with strong demand-side policies (until 280 EJ/yr in 2060 in our sensitivity numerical simulations). On the contrary, when disruptive economic behaviours appear (increase in the added value of industrial products; failure of material efficiency policies; servitisation as a substitute for material efficiency), pathways to low energy demand can only be achieved if strict energy efficiency gains are made throughout the service economy.

There are large uncertainties about the future of services, and whether they will be as energy-intensive as those of today. None of the services sectors are fully dematerialized, whether they require buildings and heat for commercial activities, or machinery for example for healthcare or leisure parks (Cunha and Ferrão, 2022; Deetman et al., 2020). Also, part of the productivity gains historically observed in industries have been achieved through servitisation, the process of relying on services input in production (Di Berardino and Onesti 2018; Neely et al., 2011). This raises concerns in achieving dematerialisation and having a service-led growth economy without the process of servitisation. A concrete example is how computers support the development and the optimisation of supply chains. In the past few years, ICT has played a major role in economic development, raising the productivity of all economic sectors. The latter requires material inputs and large infrastructure in the form of computers, data centres and networks while being energy-consuming. Overall ICTs seem to result in energy and emissions savings in relative terms but not in absolute (Zhong et al., 2022; Freitag et al., 2021; Lange et al., 2020; Horner et al., 2016), a dynamic far from slowing down with promising productivity gains and new services emerging from AI (de Vries, 2023).



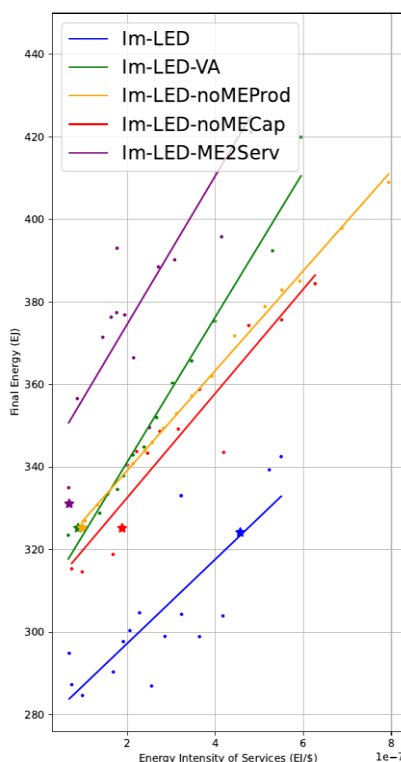


Figure 4. Sensitivity analysis on the energy intensity of services in the different scenarios. The stars represent the five scenario at 325 EJ/yr presented throughout the paper.

2.4 Discussion

2.4.1 Demand side mitigation policies challenged by economic feedbacks

Our scenarios highlight several macroeconomic interventions that appear strategic for the design of demand-side mitigation policies through the form of positive economic feedback. The two main feedbacks involve the material content of production in every economic sector, and the role of services, both as inputs of production and as an emerging sector. Both involved a rise in total economic activity, the first through productivity gains with dematerialisation, the latter through accelerated structural change. Those mechanisms are part of the rebound effects debated in the scientific literature. Instead of providing a quantification of those effects, our study employs a modelling tool to show how they can unfold in low-energy demand mitigation pathways.

Results reveal how material efficiency and servitisation can lead to increased economic activities and final energy consumption, counterbalancing the initial intended structural shifts towards less industrial outputs and energy efficiency measures. The simulations have been designed to maintain a consistent final energy level between scenarios, so that, by construction, demand-side policies are successful to the extent that positive feedbacks are covered by additional energy efficiency measures in services. However, this also revealed the tensions and interactions between the various macroeconomic mechanisms at play, providing insights on the degree of realism of such policies and the feasibility from a pure economic perspective. Our scenarios illustrate the subtle interactions between the economic and energy systems that could challenge the practical implementation of demand-side policies, especially material efficiency in production inputs.

First in order to achieve a low level of final energy demand, material efficiency needs to occur in every production process and part of supply chains, including capital formation and intermediate inputs. The potential to reduce material inputs in capital formation through structural change is limited, as moving from industries to services still requires the construction of infrastructures and

buildings (commercial or business). Eventually, the need for machinery decreases but without going to zero. Secondly, there is no clear evidence that material input reductions will lead to production cost reductions, as they could be replaced by increased capital costs or substituted by service inputs. For example, energy efficiency is generally associated with increased investments and capital costs, whereas servitisation in the industry has often been followed by productivity gains. Both cases (increased capital costs and servitisation) lead to an increase in the total economic activity, playing against the intended effect to reduce material demand.

Finally, reducing the material content of production seems to be the most difficult mitigation option to implement, given that there is many positive economic feedback and that additional efforts are required. Producing goods or services requires material inputs, and the act of economic production by itself requires upstream capital investment. Material efficiency results in productivity gains that ultimately propagate into the economy, through the form of lower purchasing prices for households or capital formation, which in turns raises material demand. A simple numerical model (SMB) shows how this very input-output structure of the economy, encompassing the interdependence of industrial goods with other sectors and capital formation, shows how strong the assumptions on average material savings should be if one wants to reach an average of 20% decrease of industrial output under an average 2% economic growth paradigm. The intuition behind the numbers is as follows: decreasing the material content of the economy should be as large to compensate for pure economic growth on one side, and to compensate for the aggregate economic demand that substitute to industrial production on the other side, as something ultimately “has to grow”.

2.4.2 Building consistent growth and energy scenarios

Our scenarios suggest some limitations in decreasing the final energy level below 325 EJ/yr under a given economic growth paradigm. This raises the issue of the ultimate consistency between growth assumptions, activity levels and final energy levels assumed in low energy demand pathways simulated by global IAMs (Semieniuk et al., 2021; Brockway et al., 2021). Mitigation scenarios often exhibit a strong absolute decoupling between energy, material content and economic growth. The absolute necessity of ambitious climate scenarios to prescribe a decoupling that goes beyond historical facts is not to be questioned, and justified by ambitious policy measures and technological improvement explicitly represented in modelling frameworks.

However, what scenarios tells about future economic activities is another story. More often GDP assumptions in IAMs serve to derive activity levels and energy demand pathways, regardless of the potential feedback that could arise from additional activity reduction measures. Our study shows that in a framework with a more detailed modelling of the macroeconomic dynamics, including the role of input-output structure, capital formation and structural change, demand-side policies give rise to direct macroeconomic feedback and price effects that directly challenge the policy objective. We thus advocate for a continuous effort to improve macroeconomic modelling in global IAMs. For instance, the reporting of the sectoral decomposition of GDP and economic activities would allow for ex-post consistency checks between the economic growth composition and energy systems assumed. Such efforts would provide further understanding of the underlying macroeconomic stories behind mitigation scenarios and allow for further feasibility assessment (Brutschin et al., 2021). Those recommendations also apply to the post-growth scenario literature which often defines economic activities with a bottom-up approach, taking for example decent living standard thresholds, but with a lack of evidence of the actual economic dynamic that could induce such changes (Kikstra et al., 2024; Samadi et al., 2017). A remaining issue that was not fully addressed here is whether or not industries are essential for economic growth in developing countries. Historically industries boost GDP because of the interlinkage with upstream and downstream supply chains, their potential for large economies of scale and because of their capability to absorb large quantities of unskilled labour (Lauriet et al., 2024). As for developed



economies, shifting faster towards highly productive services raises further issues concerning the provision of low-skilled jobs without raising inequalities (Hardt et al., 2021; 2020).

2.5 Supplementary materials

A. Modelling assumptions and mechanisms of the IMACCLIM-R model

Thermal comfort and appliance

End-use service: The energy consumption associated with space heating is aggregated with the one for appliance. Grubler et al. (2018) provide assumptions for the two separately, with respectively 16 and 41 EJ/yr in 2050 (8 and 13 EJ/yr for the Global North (GN); 8 and 28 for the Global South (GS)).

Energy demand levies: The Imacclim-R model project endogenously the dwelling per capita, the energy consumption per square meter and the corresponding energy mix. The IMACCLIM-LED (IM-LED) scenario reproduced the LED scenario assumptions by lowering the income elasticity of per capita floor areas and increasing building energy efficiency (through a higher renovation rate and increasing share of very efficient buildings in new construction).

Feedback effects: Once the parameters are set to reproduce the final energy level and the activity level of the LED scenario, the final energy level will respond to any shocks regarding: energy price movement leading to a different energy mix of energy efficiency level; household's income increase which leads to higher dwelling per capita.

Households Mobility

Households' utility function in Imacclim-R consider the utility provided by mobility services, with direct substitution between total mobility and other goods consumptions, and substitution possibilities between four mobility modes (road private, air travels, other terrestrial transports and zero carbon travel mode such as cycling).

The demand for the three transport modes requiring energy (road private, air, other terrestrial transports) follow the activity and energy demand level described in the LED scenario of Grubler et al. (2018), through increased energy efficiency and reduced demand. The LED scenario of Grubler et al. (2018) assumes 16 and 12 EJ/yr of energy demand for mobility for the Global North and Global South respectively, split into light duty vehicles (LDV), two and 3 wheels (2&3W) vehicles, buses, trains and air travels Supplementary Table 15).

Demand reduction is achieved in through two levies: a change in the elasticity of substitution between transport services and other consumption goods allow for a behavioural change towards less mobility; a reduction in the amount of the infrastructure per transportation mod allow to shift the relative modal share in accordance the LED scenario assumptions.

General feedback effects: Any change in the price of consumer goods shift the consumption frontier towards more or less transport services. Changes in income per capita leads to changes in the level of consumption of the different goods, including transport. Changes in fuel prices of emission content of transports shift the relative modal choices.

Mobility - Road (Private)

End-use service: Private Road mobility in IMACCLIM-R aggregates the use of private cars and the use of 2&3 wheels' vehicles, where the LED scenario gives energy demand and activity levels for the



two separated. The LED scenario assumes 9.8 and 4.9 EJ/yr in 2050 respectively for the GN and GS regions.

Energy demand levies: Beside the elasticity of substitution between normal goods and transports services which allow for a total reduction in household's mobility, a decrease in investments for road infrastructure lead to less mobility though LDV and 2&3W because of congestion.

Feedback effects: In IMACCLIM-R, investment in transport infrastructure are made based on myopic expectations on the future demand for mobility. The IM-LED scenario is constructed by changing those expectations towards less futures needs in infrastructures, still with an endogenous dynamic of investments. However, any departure from the IMACCLIM-LED scenario, for example with a short-term increase of the demand for private road transport, will likely trigger more infrastructure investments leading to less congestion and a slight increase of mobility for this mode. Also, the general feedbacks for private mobility as described above held.

Mobility - Air travels (Private)

End-use service: Energy demand from private air travel mobility in the IM-LED scenario reflects the assumptions of the LED scenario of Grubler et al. (2018), whose assumption is 3.9 and 3.1 EJ/yr in 2050 respectively for the GN and GS regions.

Energy demand levies: Beside the elasticity of substitution between normal goods and transports services which allow for a total reduction in household's mobility, a decrease in investments for air travel infrastructure lead to less mobility because of congestion.

Feedback effects: In IMACCLIM-R, investment in transport infrastructure are made based on myopic expectations on the future demand for mobility. The IM-LED scenario is constructed by changing those expectations towards less futures needs in infrastructures, still with an endogenous dynamic of investments. However, any departure from the IM-LED scenario, for example with a short-term increase of the demand for air travels, will likely trigger more infrastructure investments leading to less congestion and a slight increase of mobility for this mode. Also, the general feedbacks for private mobility as described above held.

Mobility - Other transports (Fret and mobility)

End-use service: Other transports in IMACCLIM-R aggregates public transports from buses and trains, where the LED scenario gives energy demand and activity levels for the two separated. The LED scenario leads to 2.1 and 4.6 EJ/yr in 2050 for passenger mobility, and to 12.9 and 21.2 EJ/yr for fret, respectively for the GN and GS regions. In IMACCLIM-R a single sector provides the other transport services for fret and passenger mobility, so that we only harmonize on the aggregated values (15 and 25.8 EJ/yr respectively).

Energy demand levies: Beside the elasticity of substitution between normal goods and transports services which allow for a total reduction in household's mobility, a decrease in investments for bus and train infrastructures lead to less mobility because of congestion.

Feedback effects: In IMACCLIM-R, investment in transport infrastructure are made based on myopic expectations on the future demand for mobility. The IM-LED scenario is constructed by changing those expectations towards less futures needs in infrastructures, still with an endogenous dynamic of investments. However, any departure from the IM-LED scenario, for example with a short-term increase of the demand for private road transport, will likely trigger more infrastructure investments leading to less congestion and a slight increase of mobility for this mode. Also, the general feedbacks for private mobility as described above held.

Industrial goods

End-use service: The industrial sector of IMACLIM-R aggregates all heavy and light industries. The LED scenario of Grubler et al. (2018) includes details on the material content of the global economy based on various assumptions on the output of the different industries and on material goods consumption from households. Those assumptions lead to 26 and 82 EJ/yr of energy demand in 2050, along with a decrease of 42 and 12 % of the activity from 2020 to 2050, respectively for the GN and GS regions.

Energy demand levies

The LED scenario assumptions are reproduced with IMACLIM-R through two levies, which are energy efficiency improvements and a reduction the demand for industrial goods. Energy efficiency improvements is increased for the three industrial sectors by the same rate (heavy industries, construction, food processing which is aggregated to the agriculture sector in IMACLIM-R), until the final energy demand of the aggregated sector (26 and 82 EJ/yr for GN and GS respectively) is reached. The activity level of heavy industries is controlled as follow.

The demand for industrial goods has four components: (1) the final demand of households; (2) foreign demand (exportations) (3) the demand for intermediate goods consumptions and (4) the demand for industrial goods in capital formation. The general equilibrium framework of IMACLIM-R relies on an input-output structure with an explicit representation of the four components.

Households demand is shifted towards more services through a direct modification of preferences in the utility function. Exports are driven through the trade elasticities.

Each of the twelve sectors of the model consume industrial goods as intermediate inputs (3) in order to produce a given output, including the industrial sector itself. For example, the car industry uses steel. Input-output coefficients are calibrated at the base year. Capital formation (4) is also composed on various goods, including industrial inputs. For example, concrete is required to build factories and steel to build machineries. The composition of capital is also calibrated at the base year based on social accounting matrix of each country. The input-output coefficients of production and those of capital formation are fixed in the baseline, but vary exogenously in the IM-LED scenario so as to reflect the aggregated activity level variations.

The activity level variations of each of those four components of the demand for industrial goods is described in Table 2.

Feedback effects

Accelerating the shift of consumption from industrial goods towards services may diminish the purchasing power of households if services are more expensive. Also, changing slightly the trade elasticity has a small effect on global GDP (more trade increases the specialization of countries).

Changing the industrial input-output coefficient of the twelves output sectors lead to a direct productivity gain as inputs are part of production costs. This impact the overall purchasing power of households, whose consumptions increases, which triggers a second feedback loop on consumption because of the decrease in unemployment. The productivity gain is also reflected by an increase of GDP.

Reducing the material content of capital formation also act as a direct productivity gain through a decrease of the cost of capital. Therefore, more savings are available for investment in productive units. The general equilibrium of IMACLIM-R allows for disequilibrium in the capital market, meaning that it is possible for investments to lead to an excess in productive capacities than what is necessary to satisfy the demand. The supply-demand equilibrium is determined assuming

decreasing marginal returns to productive capacities, so that unproductive investment leads to a decrease of the market price of goods, increasing in turn the purchasing power of households with consequent feedback effect on GDP.

Services (Public and commercial buildings - contingency reserve)

There is no control on the activity level of service. No assumptions are made on this sector regarding assumptions made on public, commercial buildings and the contingency reserve in the LED scenario of Grubler et al. (2018).

The services sector in IMACLIM-R has to be understood as all current and futures non-heavy industries.

The model is calibrated notably on the social accounting matrix data of the GTAP database. The services sector of IMACLIM-R encompasses at the base year the sectors described in the following table, plus energy retailing services. GTAP data in IMACLIM-R are hybridized with energy balance tables of the International Energy Agency, so that the energy sectors only represent the production price of energy, excluding the retail services. The hybridization procedure allows to preserve the balance of the social accounting, by shifting the statistical differences towards the IMACLIM-R services sector.

The projection of the services sector in IMACLIM-R encompasses hypothetically all futures services sectors, including emerging ICTs of other services sectors.

GTAP Sector	Short description	Detailed description
wtr	Water	Water transport
trd	Trade	All retail sales; wholesale trade and commission trade; hotels and restaurants; repairs of motor vehicles and personal and household goods; retail sale of automotive fuel
cmn	Communication	Post and telecommunications
ofi	Financial services nec	Includes auxiliary activities but not insurance and pension funding (see next)
isr	Insurance	Includes pension funding, except compulsory social security
obs	Business services nec	Real estate, renting and business activities
ros	Recreational and other services	Recreational, cultural and sporting activities, other service activities; private households with employed persons (servants)
osg	Public Administration, Defence, Education, Health	Public administration and defence; compulsory social security, education, health and social work, sewage and refuse disposal, sanitation and similar activities, activities of membership organizations n.e.c., extra-territorial organizations and bodies
dwe	Dwellings	Ownership of dwellings (imputed rents of houses occupied by owners)

<https://www.gtap.agecon.purdue.edu/databases/contribute/detailedsector57.asp>

Fret aviation and Shipping



There is no control on the activity level of fret services via aviation or shipping. nor on the final energy demand level of the two sectors. The activity level of both sector is endogenous to the level of international trade in IMACLIM-R.

However, planes delivering fret services are assumed to benefit from the same increase in energy efficiency as air passenger planes.

Construction

There is no control on the activity level of the construction sector, nor of its the final energy demand level. The activity level is endogenous to the total economic activity, with part of the demand driven by households and another part required by capital formation.

However, the sector observes the same increase in energy efficiency improvement as the one of the industrial sector.

Agriculture

There is no control on the activity level of the agricultural sector, nor of its the final energy demand level.

However, the sector observes the same increase in energy efficiency improvement as the one of the industrial sector.

B. Stylized numerical models: the role of the input-output structure

Model

	Q	DF	DI	CI = Alpha * (DF+DI)	Alpha
World	1	0.15	0.15	0.69	2.28
North	1	0.18	0.16	0.66	1.93
South	1	0.12	0.15	0.73	2.73

In this section, we build a reduced numerical model to illustrate how important should be the dematerialisation effort on the various component of the demand for industrial good in order to achieve a certain reduction in total industrial production.

The reduced model is illustrated on the above table, and consist of a very input-output structure. There are no exports, and the production serve to fulfil households demand DF, the demand for material goods entering capital formation DI, and intermediate industrial good CI serving production. We further assume that total intermediate good consumption CI are function of the final demand DF+DI, with the technical coefficient Alpha. The numerical values employed are taken from IMACLIM-R simulations in 2020, normalised to 1 for the Global North, Global South, and the World.

Growth assumptions & target

We compute the industrial production as follow. We assume GDP grows at a 2% rate, which is equivalent to the doubling of economic output between 2020 and 2050. We further assume that household demand DF and capital formation DI grows like GDP. Then dematerialisation coefficients (ME_DF on households' demand, ME_DI&CI on capital formation and intermediate inputs) are

applied to the various component of the demand. We can then compute the final output Q_{2050} as follow:

$$\begin{aligned} DF_{2050} &= DF_{2020} * \%GDP * ME_{DF} \\ DI_{2050} &= DF_{2020} * \%GDP * ME_{DI\&CI} \\ CI_{2050} &= Alpha * (DF_{2050} + DI_{2050}) * ME_{DI\&CI} \\ Q_{2050} &= DF_{2050} + DI_{2050} + CI_{2050} \end{aligned}$$

In the following simulations, we find different values of the dematerialisation coefficient in order to reach the industrial output decrease as in the LED scenario (Grubler et al., 2018): -41% compare to 2020 in the Global North (-141% compare to 2050 in a counterfactual scenario without efficiency / structural change), - 13 in the Global South (-113%) and -20% for the World (-120%). Without dematerialisation, each production values reached 2 in 2050, following GDP growth.

Simulations

In simulation 1 we assumed that dematerialisation coefficients for household's demand DF and other component DI & CI are equals. In order to reach the LED assumptions, dematerialisation need to be respectively -54% and -39% for the North and South. This means, in order to compensate for GDP growth, goods produced for households, for capital formation and the use of material as intermediate inputs needs all to be halved.

In simulation 2 we assume that the reduction of material content of household's demand cannot go further than 20%. This implies directly a -70% of the material content of intermediate inputs and capital formation for the Global North (for a -39% of total production). For the Global South, this implies a -45% material efficiency effort in capital formation and intermediate inputs to reach the -11% shrink in aggregate output.

Those 2 simple examples show that, assuming a 2% growth of the economy, very strong assumptions have to be taken in order to decrease effectively the industrial output. Going lower than -20% of material efficiency in the final demand could involve structural change towards the demand for more services. However, as shown in simulation 1, this still involved indirect production and require a -50% reduction in capital formation, meaning for services sectors, 50% less materials in buildings construction.

Simulation #1

	GDP effect	ME DF	ME DI&CI	DF	DI	Alpha * (DF+DI) = CI	Q – 2050	LED scenario
Global	2.00	0.57	0.57	0.17	0.17	0.45	0.80	0.80
North	2.00	0.46	0.46	0.17	0.14	0.28	0.59	0.59
South	2.00	0.61	0.61	0.15	0.18	0.54	0.87	0.87

Simulation #2

	GDP effect	ME DF	ME DI&CI	DF	DI	Alpha * (DF+DI) = CI	Q – 2050	LED scenario
Global	2.00	0.80	0.45	0.24	0.14	0.39	0.77	0.80
North	2.00	0.80	0.30	0.29	0.09	0.22	0.61	0.59
South	2.00	0.80	0.55	0.19	0.16	0.53	0.89	0.87



Table 2. SM1

	Region	Im-LED activity level	Im-LED- VA (%)	Im-LED- noMECap (%)	Im-LED- noMEProd (%)	Im-LED- ME2Serv (%)	Im-LED energy level	Im-LED- VA (%)	Im-LED- noMECap (%)	Im-LED- noMEProd (%)	Im-LED- ME2Serv (%)
Housing & Thermal confort	North	54.3	0	0	0	0	5.9	0.7	0.7	0.3	0.7
	South	233.3	0.9	0.1	-5.7	0.1	47.5	0.7	0.1	-4.7	0.7
Mobility - All	North	25029	-0.9	-0.8	-6.3	-0.5	19.9	-1.4	-0.8	-6.8	-2.6
	South	77494.7	4.6	0.1	-17.4	8.2	26.6	6.9	0.5	-25.3	-1.9
- Terrestrial transport	North	8351.1	-0.6	-0.4	-1.1	1.1	4.5	1.2	0.3	-2.2	11.2
	South	44805.8	-0.4	-0.9	-3.3	-2.8	8.8	1.4	1.4	4.2	79.1
- Air transport	North	2735.5	-4.4	-3.4	-21.1	-2.1	4.4	-2.7	-1.9	-14.1	-5.1
	South	3093.8	-0.1	0.2	-4.4	-9.1	4.4	-2.7	-1.9	-14.1	-5.1
- Private cars	North	13942.4	-0.3	-0.5	-6.5	-1.2	9.4	-0.6	-0.4	-6.3	-2.8
	South	29595.1	12.6	1.6	-40.2	26.6	16	12.9	1.5	-37.2	-1.6
- Cycling and Walking	North	/	/	/	/	/	9.4	-0.6	-0.4	-6.3	-2.8
	South	/	/	/	/	/	16	12.9	1.5	-37.2	-1.6
Freight - All	WLD	/	/	/	/	/	48.3	9.4	3.3	-17.4	22.3
- International Shipping	WLD	/	-0.3	-0.5	-6.5	-1.2	9.4	-0.6	-0.4	-6.3	-2.8
- International Aviation	WLD	/	-0.3	-0.5	-6.5	-1.2	9.4	-0.6	-0.4	-6.3	-2.8
Production - Agriculture	North	/	2.1	-1.6	-11.1	20	11.4	3.2	-1.6	-12.5	21.2
	South	/	10.2	-0.5	-23.2	28.6	31.5	7.1	0.2	-21.8	20.9
Production - Construction	North	/	3.9	-0.2	-29.9	26.3	5.2	9.9	0.4	-41.4	10.9
	South	/	28.9	6.5	-59.7	103.7	9.1	23	5.2	-63	140
Production - Services	North	/	2.3	-2.3	-16	4	16.4	2.2	-2.9	-17.6	4.7
	South	/	12.8	-3.7	-36.4	-1.1	26.4	11.7	-3.7	-34.8	-0.4
Production - Industries - Total	North	/	1.4	16.4	77.8	11.6	32.8	9.2	14	36.7	-27.5
	South	/	20.7	31.1	41.6	65	115.4	20.9	27.3	23.1	33.1
- Capital Formation	North	/	-0.5	93.5	-21.5	26.9	/	/	/	/	/
	South	/	28.1	129.9	-44.7	90.4	/	/	/	/	/
- Housdholds (&PA)	North	/	5.5	-5.1	-19.2	-13.7	/	/	/	/	/
	South	/	2.5	-0.1	-41.8	7.5	/	/	/	/	/
- Intermediate inputs	North	/	1.8	2.7	129	8.9	/	/	/	/	/
	South	/	22.2	12.6	67.1	65	/	/	/	/	/
- Exports	North	/	-3.9	31.4	67.3	42.9	/	/	/	/	/
	South	/	16.7	34.1	51	65.6	/	/	/	/	/
Total	North	/	/	/	/	/	95.7	5.3	4.7	2.8	-5.1
	South	/	/	/	/	/	254.2	13.7	12.6	-1	25.2

Activity levels and final energy of the reference scenario Im-LED, and variations (%) of the four variants, in 2060.



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3. Assessing the socio-economic impacts of different ways to recycle revenues from carbon pricing

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Summary

Decarbonization will generate large socio-economic implications across regions and sectors, but the revenues collected from a carbon tax can be used to alleviate the adverse societal impacts of the transition. Here, we use four leading macroeconomic models with high regional and sectoral disaggregation to assess the potential economic and structural changes of decarbonization and how these are affected by the use of carbon revenues. We show that the absolute GDP and employment impacts differ depending on economic narrative behind each model, and we derive conclusions that are robust across modelling paradigms. Using carbon revenues to reduce labour taxes alleviates 40%-70% of mitigation costs in Computable General Equilibrium (CGE) models, while directing them to households through lump-sum payments has limited GDP impacts but with a positive impact on equity with the potential to avoid unfair burden sharing within countries.

3.1 Introduction

As the need to mitigate the negative impacts of climate change becomes urgent, an increasing number of jurisdictions have adopted emissions trading schemes (ETS). Today, there are 28 systems around the world in force, and 21 at different stages of development and consideration, cast across different supra-, national, and subnational geographies and economies (ICAP, 2024). The European Union ETS is the world's biggest and oldest carbon market. The ETS is a powerful instrument that can help bring about these necessary changes for the low-carbon transition, as the ETS price signal provides an important incentive to invest in low- and zero-carbon technologies and infrastructure and encourages compliance with emission reduction targets. Emissions trading systems are also a valuable source of revenues, driven by increasing allowance prices and increasing use of auctioning. The European Union ETS generated significant revenues in recent years as the price of permits has risen, with undergoing negotiations to extend pricing to additional sectors (transport & buildings) and to earmark revenues towards a Social Climate Fund. Many governments channel these resources back into further climate action, subsidizing emerging technologies, or supporting lower-income households and protecting the society from high energy prices and their fluctuations.

Leading economists suggest the introduction of general carbon pricing and the use of the resulting carbon revenues as a lump-sum redistribution to households on an equal per capita basis. These carbon dividends could have positive impacts on alleviating inequality and poverty, recently exacerbated by the pandemic and the energy crisis, and thus may increase policy support especially in Middle or Low-Income countries (Dechezleprêtre et al., 2022). Other ways to recycle the carbon revenues have been recently explored. (Zhao et al 2022) found that carbon pricing without revenue recycling increases income inequality, but a progressive individual income tax system can help redistribute income and reduce inequality. (Fragkos et al 2021) and (Feindt et al, 2021) showed that lump-sum transfers and other redistribution schemes allow achieving progressivity of the carbon tax at the EU and Member State level providing double dividends for the EU in terms of achieving net-zero emissions while improving equity. The (World Bank, 2016) has identified five main options to use carbon revenues, including the reduction of other taxes, lump-sum transfers to



households, reduction of public debt and deficit, or funding green investment required for decarbonisation. All carbon revenue recycling options have benefits and trade-offs for the economy, the environment and society. Therefore, the way that carbon pricing revenues are used can impact the economic effectiveness and competitiveness, influence environmental outcomes, reduce inequality, and improve the political acceptability of carbon taxes.

In this study, we explore the socio-economic impacts of using carbon revenues in alternative ways, using four well-established multi-sectoral macro-economic models (IMACLIM, GEM-E3-FIT, E3ME, JRC-GEM-E3). These models have distinct features and integrate different theoretical assumptions on how the economy operates. E3ME-FTT is a demand-driven, non-equilibrium model that assumes that both labour and capital are not fully utilized, whereas GEM-E3-FIT, Imacsim-R and JRC-GEM-E3 are supply-driven, Computable General Equilibrium (CGE) models that assume capital is fully utilised in the baseline scenario. These CGE models, in their standard macroeconomic closure, assume that investment is exclusively financed by savings and there are no savings unused, thus decarbonisation would lead to crowding-out of investment in other sectors. Mercure et. al (2019) and Lefèvre et al (2022) compare in detail the equilibrium and non-equilibrium modelling paradigms. In the current study, these models are used under a common scenario protocol to develop a series of alternative scenarios with increasing climate policy ambition. We explore the macro-economic impacts of different ways to recycle carbon revenues, focusing on the main options suggested by the (World Bank, 2016): 1) reduce labour taxes and social security contributions, 2) provide revenues lump-sum transfers to households based on an equal-per-capita basis.

3.2 Brief description of the models

The current study aims at: i) exploring macro-economic and structural change dynamics of the global economy and major emitters induced by decarbonisation, and ii) assessing the incremental impacts of alternative ways to recycle carbon revenues. With this study we aim to provide new insights about how the global economy could be transformed under Paris-aligned policies and how the revenues from carbon pricing can be used to efficiently promote growth, jobs, and other societal priorities. To do so, we conduct a model inter-comparison exercise using four established multi-sectoral macro-economic models - E3ME-FTT, GEM-E3-FIT, IMACLIM-R, JRC-GEM-E3 - capable of simulating endogenous structural change dynamics and the socio-economic impacts of climate policy.

The GEM-E3-FIT model is a multi-sectoral, recursive dynamic Computable General Equilibrium (CGE) model, which simultaneously represents 46 regions/countries and 51 sectors linked through bilateral trade (Paroussos et al 2020). It is a comprehensive model of the global economy, covering interlinkages between productive sectors, consumption, price formation of commodities, labour and capital, trade, and investment dynamics. GEM-E3-FIT formulates the supply and demand behaviour of economic agents with market derived prices to clear markets, allowing for a consistent evaluation of distributional effects of climate policies. The model is driven by accumulation of capital, equipment and knowledge, features equilibrium unemployment, energy efficiency standards and carbon pricing and can quantify the socio-economic impacts of policies ensuring that in all scenarios the economic system remains in general equilibrium.

Industries operate within a perfect competition market regime and maximize profits. Production functions consider the possibilities of substitution between capital, labour, energy, and materials in each sector and allow for price-driven derivation of intermediate consumption and the services from capital and labour. Households demand, savings and labour supply are derived from utility maximization using a linear expenditure system (LES)



formulation. Households receive income from labour supply and from holding shares in companies. Investment by sector is dynamic depending on adaptive anticipation of capital return and sectoral activity growth. All regions and sectors are linked through endogenous bilateral trade flows, while the allocation between domestic and imported goods is based on the Armington hypothesis that they are imperfect substitutes (Armington, 1969). GEM-E3 is calibrated using the GTAP dataset providing a comprehensive and self-consistent accounting of trade, firms' production structures, households' consumption, gross fixed capital formation and sectoral value added. GEM-E3-FIT includes features that go beyond conventional CGE approach, especially with regard to the bottom-up representation of the electricity sector (with 10 technologies competing to meet electricity requirements), transportation modes (passenger and freight), energy use in buildings (including heat pumps), low-carbon technologies and the integration of technology learning curves (Fragkos and Fragkiadakis 2022). GEM-E3-FIT represents imperfect labour markets, simulated by an empirical labour supply equation that links wages and unemployment through a negative correlation. To adequately capture real-world conditions in labour markets, GEM-E3-FIT represents involuntary unemployment, moving beyond conventional CGE modelling assuming perfect labour markets. GEM-E3-FIT represents labour market imperfections and frictions, so that employees enjoy a premium on top of the wage rate that would correspond to equilibrium between potential labour supply and labour demand. In GEM-E3-FIT the efficiency wage approach (Shapiro and Stiglitz, 1984) is selected to represent involuntary unemployment because of its empirical validation and simplicity, assuming a negative correlation of unemployment levels with wages.

IMACLIM-R is a multi-sectoral Computable General Equilibrium (CGE) model, hybrid with bottom-up sectoral modules (fossil fuel extraction, electricity, buildings, and transport). It represents the global economy as a set of 12 interconnected regional and national economies; each composed of 12 to 19 production sectors (also connected by input-output and trade links). It is primarily based on macroeconomic theory and draws inspiration from the Arrow-Debreu model, specifically in regard to its emphasis on equilibria. It features consistent input-output accounting of both economic and physical energy flows, achieved by reconciling energy balances and national accounting data. The model simulates dynamic trajectories in yearly steps through the recursive and hard-linked succession of static macroeconomic equilibria and bottom-up sectoral modules. It explicitly represents the constraints affecting technical flexibilities and their interplay with macroeconomic trajectories by describing economic patterns in a world with market imperfections, partial use of production factors (labour and capital) and imperfect expectations for investment decisions. Within macroeconomic equilibria, a representative household in each regional economy aims to maximize its utility while considering economic and time budget constraints. In order to meet demand, productive sectors operate under short-term technical and productive capacity limitations. Between two economic equilibria, bottom-up modules use explicit technologies for the electricity and transport sectors to simulate technical adjustments to demand and price changes, considering imperfect foresight. The model utilizes a bottom-up approach for the representation of different power-producing technologies in the electricity sector, while energy-related technologies for buildings and road transport are considered on the demand side.

E3ME-FTT is a simulation-based, demand-driven macroeconomic model consisting of 71 world regions and countries and 43 industrial sectors (71 in the EU and the UK). The economic core of the model calculates demand for goods and services first, using input-output matrices and bilateral trade relationships to calculate supply. E3ME is a non-equilibrium model and assumes that the economy is in a state of constant change, where resources are not fully utilised. The model is also highly path-dependent, meaning that future trajectories are



contingent on previous timesteps. In contrast to equilibrium models, E3ME does not feature a ‘crowding-out’ effect on investment, where resources are diverted away from other areas of the economy to fund the low-carbon energy transition. Instead, the investment-intensive nature of the transition can produce a short to medium-term boost to economic activity and employment in E3ME. For further detail on crowding-out, equilibrium and non-equilibrium models, see Mercure et al. (2019). The FTT (future technology transformation) sub-models simulate technological diffusion through evolutionary dynamics. There are currently 4 FTT sub-models representing the technological composition of the power, heat, steel, and light road transport sectors. FTT uses replicator equations to simulate competition between different technologies, producing S-shaped diffusion profiles. It also captures path dependency, sub-optimal decision-making, and non-marginal change. Currently, 88 technologies are represented across the FTT framework. For further detail on E3ME-FTT, see Mercure et al. (2018).

JRC-GEM-E3 is an applied general equilibrium model (Capros et al., 2013) that covers the interactions between the Economy, the Energy system and the Environment. It is well suited to evaluate climate and energy policies, as well as fiscal issues. The JRC-GEM-E3 model has been used for several Directorates General of the European Commission, as well as for national authorities, contributing to the EU's 2030 Climate and Energy Framework (Weitzel et al., 2023) and to the EU's preparation of the international climate negotiations (Keramidas et al., 2021). The model is able to compare the economic effects of various cost-efficient climate policy instruments, such as taxes, auctioning, various forms of pollution permits and command-and-control policy in the context of climate and energy policies, and various ways of revenue recycling. The JRC-GEM-E3 model is flexible in its regional and sectoral aggregation. Typically, it represents individually the 27 European Member States as well as the OECD and the Group of Twenty (G20) countries. Sectoral aggregation normally covers 30 to 35 sectors and includes a detailed representation of the power sector. The model is calibrated to the latest GTAP database, which is EUROSTAT consistent for the EU Member States.

The JRC-GEM-E3 model simultaneously computes the equilibrium in the goods and services markets, as well as in production factors (labour and capital). The economic agents optimize their objective functions (welfare for households and cost for firms) and determine separately the supply or demand of labour, capital, energy, and other goods. Market prices guarantee a global equilibrium endogenously. The competitive market equilibrium under Walras’ law also includes more detailed equilibria in energy demand/supply and emission/abatement. The structural features of the energy/environment system and the policy-oriented instruments (e.g. taxation) have a considerable level of detail. The geographical regions are linked through bilateral trade. The production of the firms is modelled with a nested CES production function, using capital, labour, energy and intermediate goods. The model allows for different market clearing mechanisms and alternative market structures, in addition to perfect competition. The amount of capital is fixed within each period. The investment decisions of the firms in the current period affect the stock of capital in the next period. The labour market includes involuntary unemployment. Labour is immobile across national borders.

Some of the key model characteristics and differences in theory and assumptions are summarised in the table below. E3ME-FTT is a demand driven, non-equilibrium model that assumes that both labour and capital are not fully utilized in the scenarios, whereas GEM-E3-FIT, Imaclim-R and JRC-GEM-E3 are supply driven, general equilibrium models that assume capital is fully utilised in the baseline scenario. In addition, GEM-E3-FIT, JRC-GEM-E3 and Imaclim-R, in their standard macroeconomic closure, assume that investment is exclusively financed by savings and there are no savings unused. Therefore, decarbonisation that requires larger investment volumes will lead to the “crowding-out” of investment in



other productive sectors. Meanwhile, E3ME-FTT assumes that financing for projects is not constrained by the financing of other projects elsewhere in the economy, and therefore that investment is not directly constrained by the saving behaviour of agents. Involuntary unemployment is recognised in all models. For further comparison of equilibrium and non-equilibrium modelling paradigms, see Mercure et. al (2019).

	E3ME-FTT	GEM-E3-FIT	Imaclim-R	JRC-GEM-E3
Model type	Macro-econometric model	CGE model	CGE model	CGE model
Macro theory branch	Non-equilibrium (Demand driven)	Equilibrium (Supply driven)	Equilibrium (Supply driven)	Equilibrium (Supply driven)
Sector coverage	43 (70 in EU)	52	19	35
Regional coverage	71 countries and regions	46 countries and regions	12 countries and regions	46 countries and regions
Net zero scenario policies	Market based and regulatory	Market based and regulatory	Market based and regulatory	Market based and regulatory

Table 3: Overview of modelling tools used in the study

3.3 Scenario Design

To assess the socio-economic impacts of climate policy and carbon revenue recycling schemes, we start with a scenario that assumes that climate policies are frozen at the status-quo of today's National Policies implemented across countries (NPi_Default) and there is no further strengthening of energy and climate policies. We harmonize the four macro-economic models on the main socio-economic and technical parameters available for SSP2 (regional population and GDP, technology and energy resources availability), whereas the drivers of structural change are based on models' own parameterization. The COVID-19 impacts and the economic recovery that followed are included in the short-term model projections using recent economic data from IMF and the World Bank.

We compare the "Reference scenario" with two scenarios that stabilize global temperature increase to well-below 2°C and 1.5°C and limit the mid-century overshoot in line with the Paris Agreement goals (Luderer et al 2018, Nilsson et al 2021). The models impose uniform carbon pricing policies across all regions, sectors and GHGs in order to achieve the global carbon budget in the most cost-efficient manner. In the 2C scenarios, following the IPCC AR6, a CO₂ emission budget of 1150 Gt CO₂ from 2020 onwards should never be exceeded, i.e. peak as well as end-of-century budgets equal 1150 Gt CO₂, while in the 1.5C scenarios a peak budget of 650 Gt CO₂ is imposed from 2020 to the time of net zero CO₂ emissions. Time profiles of carbon price are not harmonized but fit the requirements of peak carbon budgets (Nilsson et al 2021). Non-CO₂ gases (N₂O, CH₄, and F-gases) should be priced equivalently to CO₂ using GWP100. To minimize temperature overshoot we also implement constraints in Carbon Dioxide Removal (CDR) deployment and net-negative emissions, i.e. cumulated CDR (including AFOLU CDR) until 2100 does not exceed 300 GtCO₂ in the 2C scenarios and 500 GtCO₂ in the 1.5C scenarios. Models that cannot achieve the budget target (especially in 1.5C scenarios) report the lowest budget feasible in their model to ensure comparability of mitigation effort across models.

On top of climate policy targets, we also examined scenarios with different assumptions about the use of carbon revenues building on (World Bank, 2016) suggestions. In particular, we analysed two ways to use the revenues from carbon pricing, namely: 1) reduce labour taxes and social security contributions, 2) provide revenues as lump-sum transfers to households based on an equal-per-capita basis. The alternative carbon revenue recycling schemes will have different socio-economic impacts, which are examined by the four multi-sectoral models presented above. The scenario analysis focuses on the time period until 2050.

#	Name	Mitigation options availability	Climate Target
1	NPi_Default	None	NPi
2	2C_Default	All mitigation options available	Likely 2 °C
3	1p5C_Default	All mitigation options available	1.5 °C with low overshoot
4	2C_Lab	Based on scenario 2, but carbon revenues used to reduce labour taxes or social security contributions	Likely 2 °C
5	1p5C_Lab	Based on scenario 3, but carbon revenues used to reduce labour taxes or social security contributions	1.5 °C with low overshoot
6	2C_Lump	Based on scenario 2, but carbon revenues recycled as lump sum transfers to households	Likely 2 °C
7	1p5C_Lump	Based on scenario 3, but carbon revenues recycled as lump sum transfers to households	1.5 °C with low overshoot

Table 4: Scenarios considered in the study

3.4 Global results

Decarbonisation entails the restructuring of economic production and consumption across sectors and agents. The uptake of low- and zero-carbon technologies, electrification and energy efficiency bring about a shift from high operating expenditures to technology- and capital-intensive processes and higher capital expenditures (CAPEX). Fossil fuels are substituted by low and zero-carbon alternatives, which may cost more in the short-term. This can increase overall production costs with depressing activity impacts especially in CGE models assuming crowding-out of investment (Figure 5). However, this transition can benefit fossil importer countries as low-carbon options are largely produced domestically and fossil importers improve their energy import bill. The higher inertia of the energy system in IMACCLIM-R (imperfect expectations, lower availability of low carbon technologies, etc.) imply that high carbon prices are required, which combined with other market rigidities (e.g. for the labour and capital markets) cause larger GDP losses than in other models. The integration of bottom-up, detailed energy and transport representation combined with faster endogenous technological change reduce GDP losses in the GEM-E3-FIT and JRC-GEM-E3 models. The lack of crowding-out effects in E3ME creates positive economic effects triggered by the assumed investment stimulus and endogenous learning (Paroussos et al, 2020).

Using carbon tax revenues to reduce labour taxes and social security contributions has positive macro-economic impacts in the CGE models with GDP losses caused by ambitious mitigation efforts reducing by 40%-70% across models. This comes from two main channels: reduced labour costs would lower the production cost for firms and existing distortions are gradually removed, so the allocation of resources is more efficient, while additional labour demand would increase household income and consumption. Transferring carbon revenues directly to households on an equal per capita basis can reduce inequality and alleviate



negative distributional impacts of carbon pricing, in particular if their consumption pattern depends on goods and services with a large domestic content. However, this misses opportunities for enhanced productivity and for the creation of new jobs especially in resource-constrained CGE models. In contrast, lump-sum transfers have stronger positive GDP impacts than reducing labour taxes in E3ME as they further increase private demand in the non-equilibrium demand-led modelling framework.

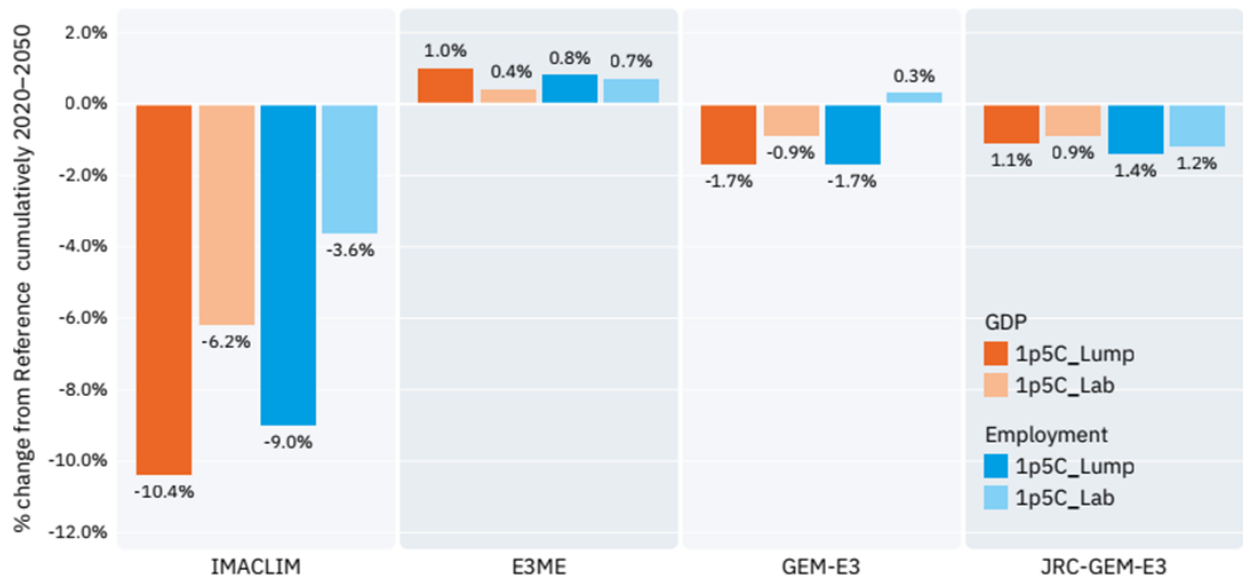


Figure 5. Global GDP and employment impacts of the 1.5°C mitigation scenario across models

As outlined in OECD (2017), the job effects projected by various modelling studies depend on the modelling approach (neo-Keynesian vs. neo-classical), the climate policy ambition, the way to recycle carbon revenues, the flexibility of labour markets and the availability of labour with the right skill set for the emerging green sectors (to avoid mismatch between labour demand and supply). Our study shows that the modelling approach and the specific model assumptions can result in substantial differences in the projected mitigation impacts on the labour market. Figure 5 shows that the mitigation scenarios have limited to moderate impacts on aggregate employment, driven by two contradictory trends: on the one hand, declining economic activity due to expensive mitigation tends to reduce employment (in the three CGE models); on the other, the economy moves toward a more labour-intensive structure as renewable technologies and energy efficiency have higher labour intensity on average compared to fossil fuels (Fragkos et al., 2018). The trade-off between jobs lost in some sectors (e.g. in fossil fuel supply, energy intensive manufacturing) and jobs creation in others (e.g. renewable electricity, biofuels, construction) would lead to a modest impact on economy-wide employment. The LAB scenarios lead to more positive employment effects in all models as they directly reduce labour cost thus increasing labour demand; this effect is particularly pronounced in GEM-E3 showing that this policy can even lead to net creation of jobs globally by 2050 with the potential of double dividends from mitigation. Meanwhile, in E3ME-FTT, the additional demand created through lump sum transfers has a stronger job creation effect than reducing labour taxes because of the demand-driven nature of the model.

In the Labor tax recycling scenarios, the services sector production registers the largest increases compared to Lump sum transfer scenarios in the CGE models accounting for about [50%-60%] of total GDP gains, while industries account for [28%-30%]. This relative positive effect on services is explained by (i) its large contribution on total economic activity in all countries globally, (ii) the services sector is more labour intensive than industries on

average, with a higher labour cost share on total costs, and (iii) services are less carbon intensive than industries so they are impacted much less from climate change mitigation efforts. Regional differences are also observed (with China and Rest of world accounting for about two thirds of the GDP gains) depending on the size and the carbon intensities of the economies, their labour costs and the initial share of industry in GDP.

3.5 Regional results

Modelling results reveal significant disparities in mitigation costs across regions and countries under a 1.5°C scenario with a uniform global carbon price, regardless of the carbon revenue recycling scheme (Figure 6). On one side, high- or middle-income regions with relatively low initial carbon intensity of GDP—such as the USA, EU, Japan, and Brazil—experience mitigation costs in the lower range. These costs span from limited or moderate GDP losses to slight GDP gains, depending on model-specific assumptions. For instance, the magnitude of substitution possibilities between capital, labour and energy (with GEM-E3 embodying greater flexibility than IMACLIM) and the extent of investment crowding-out (ranging from full crowding-out in the three CGE models to none in E3ME) significantly influence the mitigation cost outcomes. In contrast, carbon-intensive economies—particularly Russia, which is also a major fossil fuel exporter—face the highest mitigation costs. The most uncertain outcomes, however, pertain to emerging economies such as India and China. These countries are both significant fossil fuel importers (oil and natural gas) and exhibit high carbon intensities, especially due to their high coal consumption. The range of macroeconomic impacts for these countries depends critically on assumptions about their capacity to phase out carbon-intensive sectors, mobilize low and zero-carbon investments, and develop or reinforce comparative advantages in low-carbon technologies. Differences across models reflect deep structural uncertainties, driven by divergent assumptions on market equilibrium, capital stock inertia, crowding out of investment, labour market flexibility, and the mechanisms of investment dynamics.

At the regional level, as observed globally, recycling carbon tax revenues through reductions in labour taxes and social security contributions generally yields more favourable macroeconomic outcomes in CGE models compared to lump-sum transfers to households. This approach systematically alleviates a large part of GDP losses caused by mitigation efforts, though the extent of this effect varies across regions and countries. Results are consistent across all CGE models (GEM-E3, IMACLIM-R, JRC-GEM-E3), with the EU showing the most substantial reduction in mitigation costs under labour tax recycling. In contrast, the US, Russia, and India experience more limited gains, while Japan, China, and Brazil exhibit intermediate benefits. These variations are closely linked to regional economic structures, particularly trade openness. Switching from lump-sum transfers to labour tax reductions effectively shifts spending from household final consumption to reduced labour costs for firms, which enhances production competitiveness. The macroeconomic benefit of this shift is larger when final consumption has low domestic content and labour-intensive sectors are more exposed to international competition. This is particularly true for the EU, given its high degree of trade openness. Conversely, regions like the US and India—characterized by lower trade openness (beyond energy trade), a stronger reliance on domestically produced goods and services, and less exposure to global competition in labour-intensive sectors—benefit relatively less from this revenue recycling approach. In contrast to CGE models, under the demand-driven modelling framework of E3ME, lump-sum transfers consistently generate better macroeconomic outcomes than labour tax reductions. This result is explained by the model's demand-driven economic foundations, where boosting private final demand drives economic growth more directly in such a modelling paradigm.



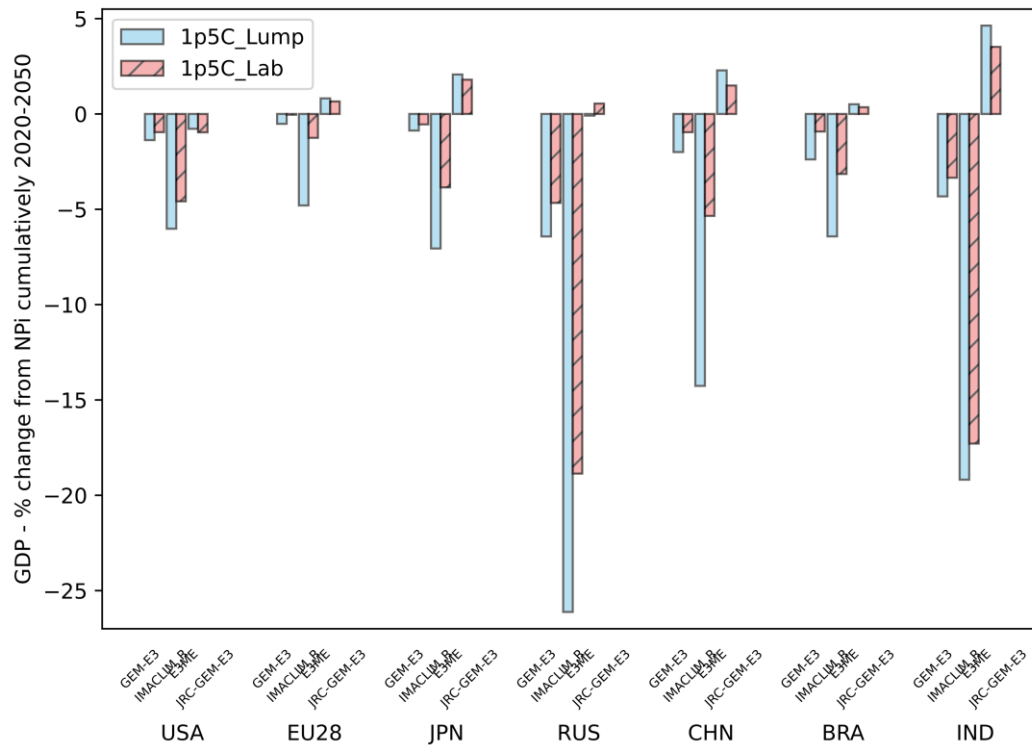


Figure 6. Regional GDP impacts of the 1.5°C mitigation scenario across models

Regional disparities in employment impacts generally mirror those observed for GDP impacts. However, consistently across all regions and carbon revenue recycling schemes, employment effects are smaller in magnitude than GDP effects. This stems from a structural shift toward more labour-intensive economic activities induced by the climate transition, as low-carbon technologies—such as renewables and energy efficiency measures—typically require more labour per unit of output than fossil fuel-based systems. The net employment impact reflects a trade-off between job losses in carbon-intensive sectors (e.g., fossil fuel extraction and processing, energy intensive industries) and job creation in emerging low-carbon sectors (e.g., renewable electricity, biofuels), leading to more limited effects on employment compared to GDP. Moreover, recycling carbon tax revenues through reductions in labour taxes, rather than lump-sum transfers, further moderates employment impacts relative to GDP impacts across all regions. Lowering labour taxes reduces the relative cost of labour, which stimulates labour demand and improves the competitiveness and profitability of labour-intensive production processes. This shift increases the overall labour intensity of the economy, and in many regions—as illustrated by GEM-E3 model results—can even result in net employment gains despite overall positive macroeconomic (GDP) costs. Interestingly, this mechanism produces qualitatively different outcomes for employment compared to GDP across revenue recycling schemes in the E3ME model. In contrast to the GDP results, E3ME shows a relative advantage for labour tax reductions over lump-sum transfers when employment outcomes are considered. As with GDP, India presents the greatest uncertainty in employment projections : CGE models yield some of the most pessimistic outcomes due to India’s high mitigation effort in the 1.5C Paris-aligned scenarios, whereas E3ME suggests optimistic employment trajectories. These discrepancies highlight deep structural and modelling uncertainties, particularly in economies with high carbon intensity and complex labour market dynamics.

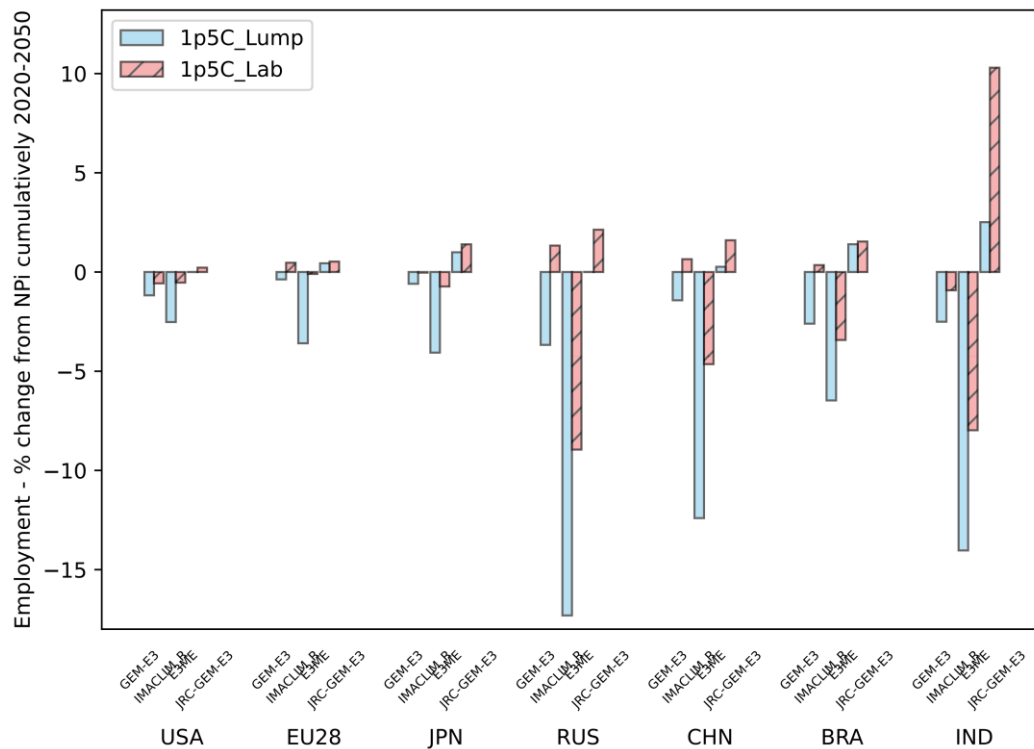


Figure 7. regional employment impacts of the 1.5°C mitigation scenario across models

3.6 Conclusions

Emission trading systems can support governments to achieve ambitious emissions reduction goals and their net-zero targets by mid-century. The generated carbon revenues can be used for various purposes, such as the reduction of other distortive taxes, lump-sum transfers to households, or funding green investment. Each carbon price revenue option has benefits and costs and must be tailored to the specific circumstances and needs of a jurisdiction and aligned with existing policies. Our analysis demonstrates the socio-economic benefits of using carbon revenues to reduce distortive labour taxes and social security contributions, while lump-sum transfers to households have the potential to reduce inequality. Carbon revenues, if carefully and strategically considered, can represent a large financial resource for governments and the EU to support public policy goals, including growth, societal cohesion, decarbonisation or reduced public debt. Robust policymaking processes, including public and stakeholder consultation, can help to determine the most appropriate option for the EU, especially in the light of its new 2040 climate targets. The identification of important priorities and the potential synergies and trade-offs with other policy goals should drive the selection of the preferable scheme to recycle the increasing carbon revenues, while addressing a country or region's unique challenges associated with carbon pricing policies.

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4. Transition costs on labour markets : the case of coal workers and the just transition in China and India

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4.1 Introduction

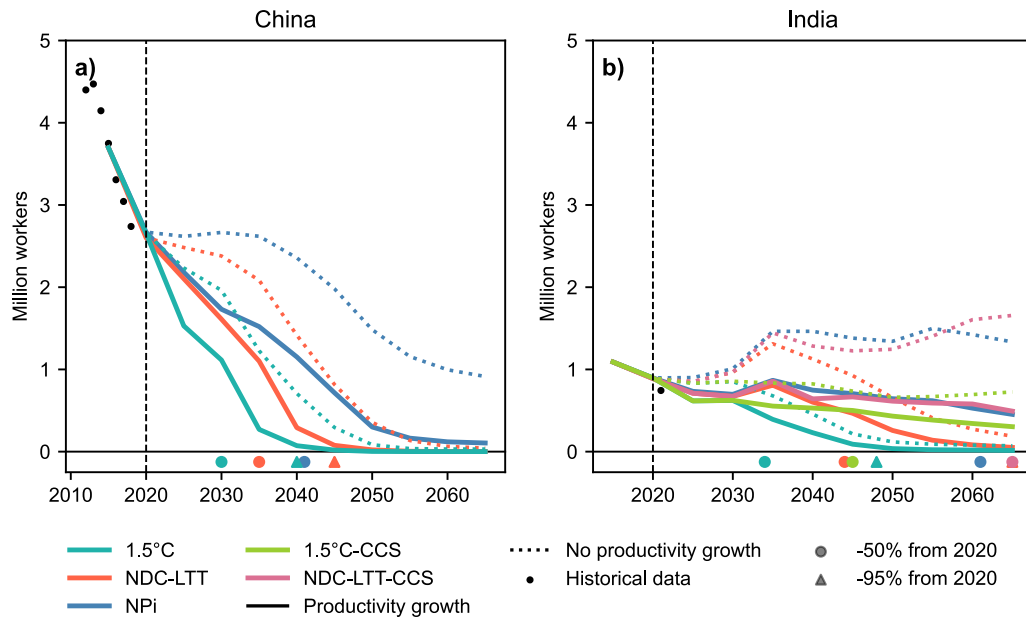
A key obstacle to meeting the objectives of the Paris Agreement is the need for a rapid and drastic phase-down of all fossil fuels, in particular coal, which should decline by at least 80% before 2050 (Achakulwisut et al., 2023). The required pace is largely unprecedented, which casts doubts on the feasibility of such pathways (Vinichenko et al., 2023), especially in coal-dependent countries like China and India, where the majority of primary energy is derived from coal. These concerns over feasibility are largely driven by the central role of coal consumption in the power system and the substantial contribution of coal production to local economies. In particular, the coal mining sector is a significant purveyor of direct and indirect employment (Ruppert Bulmer et al., 2021; Spencer et al., 2018). China and India, the two largest global coal producers, employ around 2.03 million (1.61-2.46) and 0.74 million (0.47-1.00) workers in coal mining, respectively, accounting for 78% of the 2022 global total (IEA, 2023). Globally, coal mining represented 20% of all 2022 fossil fuel-related employment (IEA, 2023).

Employment impacts are among the transition risks that can fuel political and social resistance to decarbonization in coal-dependent regions. While many historical transitions were poorly anticipated (Caldecott et al., 2017), they have led to different outcomes (Harrahill and Douglas, 2019). Many mining regions have experienced similar challenges to other former industrial regions, with long-lasting unemployment and a broad range of social issues, including a lost sense of identity for coal communities (Cha, 2020; Oei et al., 2020). Others, such as Germany's Ruhr region, have proved more resilient through economic diversification and structural change but are still faced with high levels of unemployment and inequality (Reitzenstein et al., 2021). Decarbonisation effectiveness will therefore depend on the alignment of mitigation objectives with the protection and transitional assistance of fossil fuel workers, within a Just Transition framework (Pai et al., 2020a).

This necessitates the detailed understanding of the impact on employment over time and regions to design and size support policies. Mitigation policies will result in job losses across the coal value chain, including mining, transport, and power generation (Clark and Zhang, 2022a; Dsouza and Singhal, 2021a). Job losses and adverse socio-economic impacts are expected to be highly concentrated in coal-producing regions of both China (Clark and Zhang, 2022a; Hamilton et al., 2022; Yang et al., 2024; Zhang et al., 2022) and India (Agrawal et al., 2024; Ordonez et al., 2023; Pai, 2021). Expanding renewable energy in coal-bearing regions could help break dependence and support a just transition (Malik and Bertram, 2022). However, mismatches in skills and renewable resources availability may hinder most coal workers from easily shifting to green jobs (Lim et al., 2023; Wu et al., 2024). A just transition must also focus on non-energy industries for job reallocation (Pai, 2021), broader local economic diversification (Clark and Zhang, 2022a), and policies to support coal workers' resettlement and re-employment (Green and Gambhir, 2020).

Figure 8. Employment trajectories in coal industry, including informal labour in China (a) and India (b) for the five central scenario: 1) NPi : national policy implemented (blue) 2) NDC-LTT: nationally determined





contribution with long term targets (orange) 3) 1.5°C (teal) 4) NDC-LTT-CCS: same as 2 with coal w/ CCS in India (magenta) 5) 1.5°C-CCS: same as 3 with CCS in India (green). Scenarios in dashed lines assume no labour productivity growth after 2020 and are hence aligned with the evolution of coal production. Markers below the x-axis indicate when employment has decreased below a threshold relative to the modelled 2020 value. No historical time series data was available for India.

Subnational employment impact analyses in low-carbon scenarios typically rely on analytical models using asset-level datasets (e.g., power plants and mines) (Clark and Zhang, 2022a; Sharma and Banerjee, 2021; Wu et al., 2024; Zhang et al., 2022), employment factors, and input-output models (Ordonez et al., 2023; Xie et al., 2023; Yang et al., 2024). These can be integrated with energy system models (Zhang et al., 2022) and process-based Integrated Assessment Models (IAMs) (Malik and Bertram, 2022; Pai et al., 2021) to outline energy pathways within broader mitigation scenarios. Computable general equilibrium (CGE) models or macroeconomic IAMs (Fragkos and Paroussos, 2018; Garcia-Casals et al., 2019; Pollitt et al., 2015) assess sectoral employment impacts in the wider macroeconomic context, including transitional labour reallocations and unemployment dynamics (Barker et al., 2016; Fujimori et al., 2020; Garaffa et al., 2023). However, these models lack details on particular worker transitions and fail to account for spatial heterogeneity (Lim et al., 2023; Wu et al., 2024) and the specific vulnerabilities it creates, such as concentrated unemployment.

Here, we analyse and compare the future of coal mine workers in China and India under several mitigation scenarios, focusing on the pace of coal job losses and workers' ability to find new employment across time and regions. Our modelling approach integrates downscaling an established general-equilibrium-based IAM (Imaclim-R World (Sassi et al., 2010)) to capture subnational disparities and key determinants of employment vulnerability to coal phase-out. We incorporate detailed productivity dynamics derived from mine-scale analytical modelling, together with region-specific economic conditions and demographic trends within a dynamic employment module. A forward-looking assessment of coal workforce trajectories and localised vulnerabilities under mitigation scenarios can provide critical insights for designing targeted transition policies.

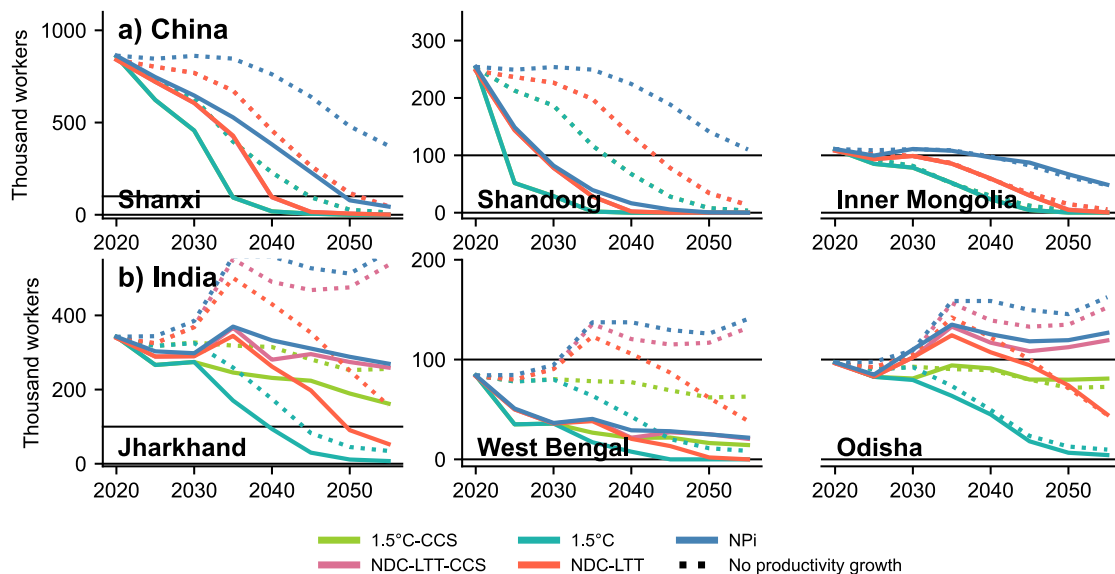
We investigate futures for coal workers and the climate by designing five scenarios: one scenario where current national policies are implemented (NPi), two scenarios of achieving

Nationally Determined Contributions with Long-Term Targets (NDC-LTT with or without Carbon Capture and Storage [CCS] in India), and two scenarios of compliance with the Paris Agreement (1.5°C, with or without CCS in India).

4.2 Results

4.2.1 Phasing down Chinese coal labour is unavoidable ; India is at a crossroads

Figure 9. Subnational employment trajectories for key regions including informal labour in China (a) and India (b) for the five central scenarios. Note that pathways in Shanxi and Jharkhand have been plotted with a different y-axis scale (in red). Dashed lines show pathways if labour productivity growth stopped in 2020, that is in line with subnational productions. The difference between the full and dash line hence shows the number of jobs destroyed by productivity growth.



In China, the production slowdown and labour productivity increase imply a rapid destruction of coal employment (Figure 8). In all five scenarios, the 2020 workforce would be halved before 2035 and as early as 2027 for the 1.5°C scenario. This rapid labour transition is consistent with the pace of employment destruction of the past decade, where coal labour was halved. This was notably pushed by the removal of low-productivity mining capacities during the 13th Five-Year Plan de-capacity period (Andrews-Speed and Xu, 2022; Hao et al., 2019). Rapid employment destruction continues with 95% of 2020 jobs disappearing before 2040 and 2045 for 1.5°C and NDC-LTT, respectively (Figure 8).

Continued NPi production through the 2020s implies slower job destruction in India, hence larger additional efforts to reach 1.5°C. All scenarios necessitate significant job cuttings (20-27 thousand/annum against 94-154 in China) in the next decade, but cuts are maintained until 2045 to reach 1.5°C without CCS (Figure 8). Under NPi, Indian coal production plateaus below 1,900Mt/year (30EJ/year) before an eventual resource-constrained decline. NDC-LTT production peaks by the mid-2030s. CCS allows production to plateau at the peak level in both climate scenarios.

Our modelling enables separating the proportion of job losses resulting from productivity gains alone and identifying the effects of production trajectories on changes in average productivity across time and regions (See Appendix). Productivity gains reduce the potential 2035 NPi Chinese (Indian) coal employment by 41.2% (67.1%) of its 2020 value. In the NDC-LTT scenarios, the contributions of productivity growth and output decline to job losses in 2040 are roughly equivalent at the national level for both countries. Under 1.5°C, the



contribution of productivity gains is lower in 2040 (around 30%) both because output declines are greater and because productivity gains are slower in this context. Rising labour productivity condemns Chinese coal mining employment. In India, however, labour productivity increase slows down in key mining regions during the 2030s as the most productive surface mines are unable to satisfy demand.

4.2.2 A few regions face unique transition challenges

A large share of the labour transition is concentrated in the Chinese province of Shanxi and the Indian State of Jharkhand. The rates of employment destruction in both regions are largely consistent with those of the national levels. Reaching 1.5°C with limited CCS involves a near total phase-out by 2038 in Shanxi and 2047 in Jharkhand (Figure 9). By then, coal labour must diminish by 74% and 58% (19% with CCS) to achieve NDC-LTT goals, in Shanxi and Jharkhand, respectively. Both regions are also the most relatively exposed, with 5.6% and 4.3% of the 2015 labour force working in the coal sector. Even with CCS, under 1.5°C, Jharkhand sees 1% of its labour force laid off between 2020 and 2035. These regions also concentrate high numbers of workers in coal-adjacent sectors like power plants, steel and bricks (Clark and Zhang, 2022a; Dsouza and Singhal, 2021b; Hamilton et al., 2022).

The coal productivity nexus assumes current known mine reserves and that the national coal supply is met by the country's most economically efficient mines (see appendix). In addition to the employment decline of Shanxi driven by both productivity increase and production cuts, Figure 2a highlights two additional archetypes. Eastern regions such as Henan and Shandong see a rapid decline in employment driven by the closure of labour-intensive mines. Both regions reach a 95% labour phase-out between 2032 and 2045, depending on the scenario. Northern regions of Xinjiang and Inner Mongolia can maintain their smaller workforce until the mid-century thanks to the high productivity of their mechanised surface mining.

Similar to Eastern Chinese provinces, the Indian state of West Bengal shows a rapid employment decline because of the low productivity of its underground mines. Simultaneously, employment is on a gradual phase-down path across Western and Central States. Meeting short-term rising demand induces a rise in labour during the 2030s. This is incompatible with the global 1.5°C goal. Regardless of CCS availability, moving from NDC-LTT to the 1.5°C scenario implies foregoing limited net positive employment gain in mining regions for significant employment destruction. Furthermore, such a peak in labour under the NDC-LTT scenario implies hiring a new generation of workers before a sharp labour decline in the 2040s.

4.2.3 Vulnerability beyond exposure

Job destruction numbers alone are insufficient to characterize an unjust transition. Access to a livelihood, changes in wages, or job quality matter. For a more comprehensive view of employment-related mitigation risks, we draw on the concept of vulnerability (Carley et al., 2018; McDowall et al., 2023), which is structured around three components. First, exposure is measured by the concentration of coal mine workers in each region. Second, adaptive capacity relates to agents' response to the transition, first of which is governments, e.g. through their ability to diversify regional economies. Finally, sensitivity is characterised by the ability of coal workers exiting the sector to access a livelihood. We assess it with two factors. First is the accordance of the employment destruction rate with the rate at which workers naturally age out of the sector. Second, is the ability of working-age coal workers exiting the sector to find new employment (Fig. 3), referred to here as



labour mobility. It is the result of competition for a limited number of job vacancies at the local level (see Appendix 4.5).

By 2030, in the 1.5°C scenarios, we find that 30% and 38% redundant workers can leave into retirement rather than be laid off in Chinese and Indian regions, respectively. Increasing retirements by adapting the transition pace to the natural workforce retirement rate is considered desirable as it limits social cost associated with workforce-age unemployment even in cases where retirees have no access to formal pensions. However, in many regions, even the NPI scenario is incompatible with such rates and leads to high vulnerability. Overall, because of their phase-out rate, large mining regions are less vulnerable than less productive ones, such as Henan or West Bengal.

Laid-off workers -those unable to leave into retirement- are found to be more sensitive to unemployment in India than in China. Between 2020 and 2050, we estimate that 48.4% (41.7%) of laid-off workers may not find new employment within 2 years in India (China) under the 1.5°C scenario. This figure is largely dependent on higher initial unemployment in India as well as enhanced macroeconomic impact from the transition, according to the macroeconomic IAM used. The increased sensitivity in ambitious scenarios is diminished over longer time horizons. Despite higher Indian sensitivity, higher exposure still leads to greater vulnerability in China, with 667 thousand workers leaving into unemployment before 2050 under 1.5°C (150 thousand in India). There are large subnational heterogeneities, highlighting increased sensitivity of mining regions, with 70% of Shanxi layoffs (446 thousand workers, Figure 10) and 82% of Jharkhand layoffs (199 thousand workers) leaving into unemployment.

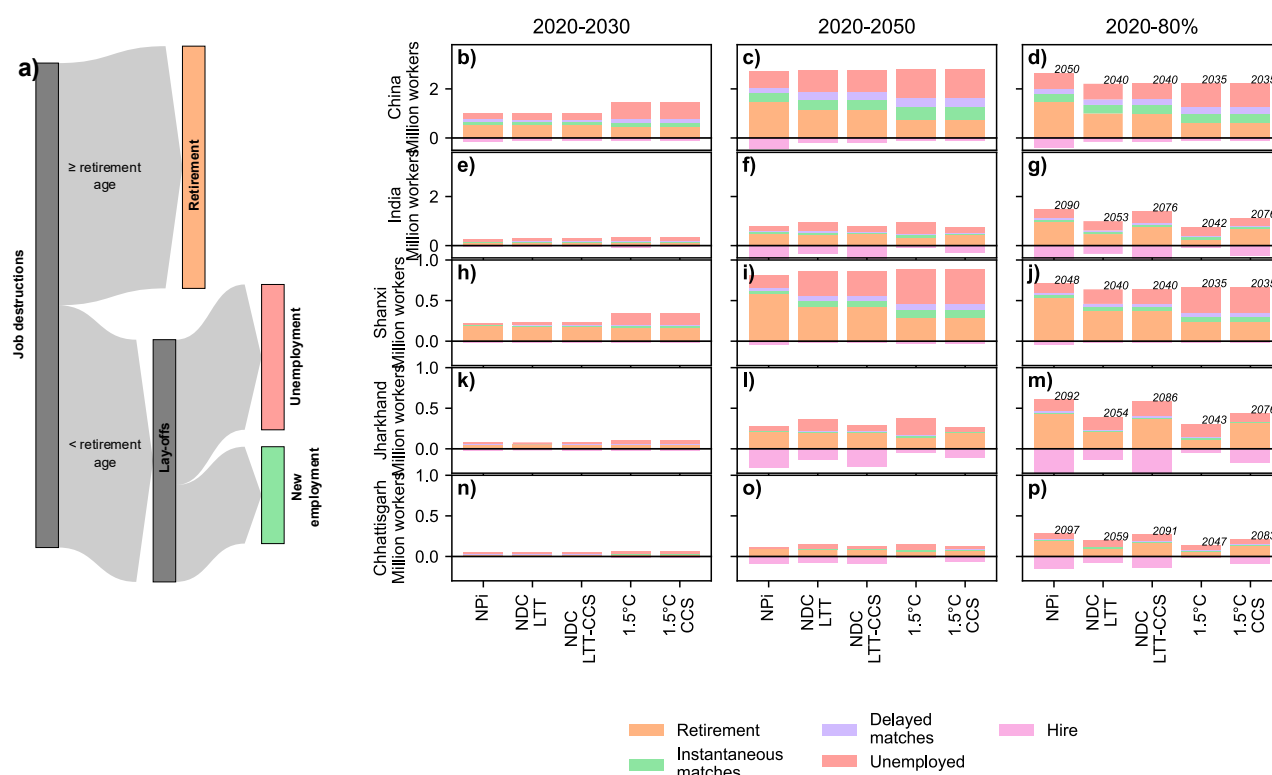


Figure 10. Mobility of laid-off coal workers between 2020-2030, 2020-2050 and 2020 and the year at which 80% of 2020 labour has been destroyed. Instantaneous matches refer to those happening within a year of the worker losing their job. Dates in *italics* on the right panel refer to the year the 80% threshold has been passed

4.3 Discussion and conclusion



By quantifying employment vulnerability in coal-dependent sectors under climate change mitigation, we highlight the critical importance of forward-thinking action. Just Transition must align with development priorities and cannot serve as a discourse of climate inaction. While the level of climate ambition is an influential factor in employment risks for coal miners in India and China, several other factors have an equal or even greater impact, depending on the country and region. The availability of CCS is a major determinant in India, whose development is more dependent on coal. Labour productivity rise in coal mining is a key factor in job destruction with old inefficient mines closing and newer, more productive mines opening. At the subnational level, disparities in mine productivity, coal job concentration, and worker reemployment potential create distinct exposure and vulnerabilities. Although mining regions are among the poorest in both countries, India's high levels of informal work and unemployment make it particularly vulnerable.

Most importantly, this study provides new quantitative insights to inform different types of just transition policies, directly or indirectly targeted at coal mine workers. This can first help assess the costs of mine closure scenarios that consider factors beyond mere economic performance, such as social costs and equity criteria²². A more worker-centred approach of subnational allocation could aim to reduce the number of workers going into unemployment to ensure Just Transition. Previous studies have proposed different subnational extraction budget allocation methods for China (Wang et al., 2020; Yu et al., 2023).

Such quantification also helps to assess the scale of provisioning required to implement transitional assistance measures, which target workers directly. Facilitating early retirement access is a flexible policy to assist workers and facilitate a Just Transition. This is still largely underutilised in China compared to other regions (Gong and Lewis, 2024), even if the social protection system has gained reach and coverage. The structure of Indian coal pension funds operated by the industry (Pai, 2021) complicates such policies. Provisioning those funds could be facilitated by international transfers akin to Just Energy Transition Partnerships. Extending levels of coal transition compensation to the required level in China and India would surpass present climate finance (Nacke et al., 2024). Prioritising targeting workers unable to find new employment or moving into early retirement would ease Just Transition for a fraction of this cost.

4.4 Appendix

We model coal production trajectories under five decarbonisation pathways with the global IAM Imaclim-R world. Those pathways are then downscaled across China and India by two ex-post modules. First, the labour productivity module allocates coal production and employment across regions. Then, the coal labour nexus compares subnational employment to demographics and rest-of-the-economy dynamics to evaluate coal workers' labour mobility.

4.4.1 Imaclim-R

Pathways analysed here are derived from the Imaclim-R World V2.0 multisectoral macroeconomic Integrated Assessment Model (Waisman et al., 2012; Bibas et al., 2015). The model is based on a hybrid structure where bottom-up modules modify the technical coefficients used in calculating a computable general equilibrium at each yearly time step. Imaclim-R offers several advantages for the present analysis. First, Imaclim-R considers several market imperfections such as imperfect foresight. Most importantly, unlike most IAM, the model considers the possibility of labour underutilisation and labour market imperfections. A fixed number of workers $l_{k,i}$ is required to produce a unit $Q_{k,i}$. This leaves a proportion z_k of the labour force L_k of region k unemployed.



$$z_k = 1 - \frac{\sum_i l_{k,i} \cdot Q_{k,i}}{L_k}$$

Sectoral labour productivities l_k are driven by a convergence mechanism in which all regions gradually catch up to a productivity leader. The leader's productivity follows exogenous growth assumptions and is identified as the United States. The speed of convergence for each of the eleven other regions depends on their productivity gap relative to the U.S., allowing the model to reproduce region-specific growth paths consistent with the SSP scenarios.

Wages are related to unemployment in the model by a wage curve defined in the equation below. As unemployment increases, wages fall. Multiple factors can explain this trend. First, as unemployment grows, workers have less bargaining power. But this can also be interpreted from the firm's perspective, whereby it sets the wage to avoid losing workers.

$$\frac{w_k}{pind_k} = a_w \cdot \frac{w_k^{ref}}{pind_k^{ref}} \cdot f\left(\frac{z_k}{z_k^{ref}}\right)$$

Another advantage of Imaclim-R for this exercise is that it represents the coal supply sector explicitly in its general equilibrium. Investments in the supply of coal are made based on the sector regional's expectations. Expectations are made on the basis of historic production to meet local and international demand through trade. The coal price is set as a function of production level and a set of asymmetric elasticities. The price of coal is more reactive to a rise in production than to a drop. These elasticities of coal are calibrated to be consistent in the long term with the supply curves provided by Bauer et al (Bauer et al., 2016).

Coal serves as an intermediary consumption for other sectors within the I-O framework. First, the electricity generation sector is, unsurprisingly, a major coal consumer. In total 26 electricity generation technologies are represented from a bottom-up approach. Out of them, 7 are coal-powered, including 3 with CCS. The use of coal in the electric sector is determined by the installed capacity of these technologies, which is assumed to have a lifetime of 40 years. The choice of input of the sector also depends on a load curve, which distinguishes the need for base and peak power generation. This influences, in turn, the expected profitability of coal generation. Alongside imperfect foresight regarding fuel price and demand, this conditions the investment in different generation technologies.

Second, the industry sector is also a major coal consumer. Energy efficiency in the industrial sector is driven by exogenous trends which can be accelerated with rising energy prices. The relative price between different fuels then induces substitution among them. The model also considers the possibility of coal liquefaction for use in the terrestrial and air transport sectors as well as the consumption of coal for home heating. Those have a lesser influence on scenarios considered here.

4.4.2 Downscaling

Previous coal transitions have highlighted that the associated challenges were localised (Diluiso et al., 2021). This motivates an analysis of future coal labour that accounts for heterogeneity within coal-producing countries. In this study, coal and economy-wide employment trajectories have been downscaled from pathways modelled nationally by an IAM in a manner similar to that first proposed by McDowall et al (McDowall et al., 2023). This allows for the comparison of employment across the energy sectors and the rest of the



economy to identify job prospects for leaving coal workers in different regions. Indeed, geography has been identified as a challenge to the relocation of fossil fuel jobs employment into green jobs (Lim et al., 2023).

The number of workers by sector and subnational region is found by assuming that the intranational spatial distribution of production remains constant. This is motivated by an analysis of expected structural change showing that each region's contribution to national sectoral production is unlikely to change significantly.

Furthermore, we assume that non-coal sectors labour productivity evolves at a homogeneous rate across the regions of each country. This rate is calculated endogenously by Imacim based on convergence assumptions. This means that evolution in sectoral labour between regions is solely determined by the evolution of national sectoral production. Labour productivity is also assumed to be homogeneous at the reference year which allows for the downscaling constants to be calibrated on value-added shares. This differs for all energy sectors except coal, where the downscaling constant is calibrated on regions' volumetric production.

Hence, the number of workers $L_{k,m}$ in region m of country i working in sector k is found from:

$$L_{k,m} = s_{k,m} L_{k,i}$$

Where $s_{k,m}$ is a downscaling constant equal to the share at the reference year.

Such that:

$$\sum_{m \in i} L_{k,m} = L_{k,i}$$

Finally, and similarly to productive sectors, the number of unemployed people in each region at the calibration year is determined by downscaling the nationally determined number of unemployed people. However, unlike productive sectors, the number of people in the unemployment pool is calculated locally as the difference between the labour force and the number of employed people. The sources of the main variables are shown in the Supplementary Information.

4.4.3 Bottom-up coal mining module

We developed a bottom-up coal mining module as the spatial distribution of production and changes in labour productivity in the coal mining sector are first-order determinants of subnational employment trajectories. Compared to existing estimates (Agrawal et al., 2024; Clark and Zhang, 2022a; He et al., 2020b; Yang et al., 2024), this approach captures the dependence between productivity growth and production trajectories. If output declines rapidly, the least productive mines (and therefore the most employment-intensive) will close more quickly, increasing the rate of productivity growth. In addition, the modelling of productivity growth rate is produced at the subnational scale, thus considering disparities between provinces or states: effective output, available reserves, inertia linked to the stock of existing mines, or the dynamics linked to the opening and closing of mines.

The module is micro-founded and data-rich. It consists of adopting a detailed description of the dynamics of mine openings and closures on a micro-scale, by representing the known stock of mines as exhaustively as possible. The module explicitly represents all the coal



mines described in the Global Coal Mine Tracker (Global Energy Monitor, 2024) from the Global Energy Monitor. It is an international database of coal mines and projects under development. It provides detailed information at the asset level, including operational status, coal type, production capacity, workforce size, available reserves, methane emissions, and geographical location. We used the April 2024 release and its September 2024 supplement.

The module dynamics follow a set of rules. The most economically efficient capacities are exploited as a priority until the expected production (exogenous to the module, determined by Imaclim-R World) is met. If the resource is exhausted in a mine, it is closed permanently (no longer exploitable). If production cannot be met by existing mines, current projects are brought on stream, and if there are no more known current projects (in the Global Coal Mine Tracker database), new capacities are built (by considering known subnational reserves and recent capacity development trends).

4.4.4 Labour sectoral mobility

We contribute to the literature by proposing an approach to evaluating subnational vulnerabilities to unjust transition based on the ability of fossil fuel workers to find new employment. To do so, we explicitly calculate labour sectoral mobility (i.e. the number of coal workers reemployed in another sector). Sectoral mobility depends on demographic trends and job vacancies in the rest of the economy.

First, we track the number of coal workers ageing out of the sector each year in each region m . The remaining workers whose jobs have been destroyed are assumed to be laid off and searching for a job S_m . This is put in perspective with demographic trends in the rest of the economy. Retiring workers in non-coal sectors (L_m^{60}) increase the number of available jobs. On the other hand, labour force entrant (L_m^{15}) also compete for available vacancies.

Second, the number of available job vacancies (V_m) is found by downscaling Imaclim-R non-coal employment at the subnational level (see section 4.3 and SI 1.3). Available vacancies are assumed to be competed for not only by laid-off coal workers and labour market entrants but also the existing unemployed population of the region (U_m).

Finally, the coal labour nexus tracks for one year leaving coal workers who were unable to be matched to a job in the year of their lay-off. At this point, they re-enter the competition for limited vacancies and may once again be matched to a job or enter the pool of unemployed workers in the region. Hence, the number of instantaneous matches can be found as:

$$M_{0,m}^t = (V_m + L_m^{60}) \cdot \frac{S_m}{S_m + z_m L_m + L_m^{15} + (S_m^{t-1} - M_{0,m}^{t-1})}$$

And the number of delayed matches as:

$$M_{1,m}^t = (V_m + L_m^{60})$$

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5. Comparing Economic Impacts of net-zero transition with Climate Damage Uncertainties Using a Dual-Model Approach

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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 shows 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.

5.1 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 & 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 & Sylvan, 2020), computable general-equilibrium (CGE) models (Kompas et al., 2018), econometrics (Burke et al., 2015); Kalkuhl & Wenz, 2020); Kotz et al., 2024), and meta-analyses of several studies (Nordhaus & Moffat, 2017), each with unique strengths. Recent studies, such as Kalkuhl & 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 (Dafnomilis et al., 2023; DeAngelo et al., 2021; Fragkos et al., 2020; Pollitt & Chyong, 2021; Van Soest et al., 2021). 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 (macro-econometric non-equilibrium model) and GEM-E3 (CGE equilibrium model) multi-sectoral macroeconomic models to cover a range of probable economic outcomes, as they are characterised 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, Stiglitz, and Taylor (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 like DICE (Nordhaus, 1993), REMIND (Baumstark et al., 2021), or MESSAGEix-GLOBIOM (Krey et al., 2020) are equilibrium models. Mercure (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 decarbonisation 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 modelling approaches provides policymakers with guidance on navigating diverse economic impact assessments and understanding the overarching conclusions of the model-based study.

5.2 Climate damages

The economic impacts of decarbonisation discussed in multiple studies (Dafnomilis et al., 2023; DeAngelo et al., 2021; Fragkos, 2020; Pollitt & Chyong, 2021; Van Soest et al., 2021) 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 1.5-2°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 2.5-3°C are considered the most likely scenarios if current policies and trends continue by 2050 (IEA WEO, 2024). Nevertheless, even less probable situations, such as temperature increases exceeding 4°C in the longer term, should not be ruled out.

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

Keen (2020) has criticized economists' forecasts of climate change damages for being overly optimistic. Economists often underestimate damages due to assumptions that GDP



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

5.3 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 & Jacques, 2024). Both models are types of Integrated Assessment Models (IAMs), with a particular emphasis on robust economic representation. Furthermore, both models are founded on Input-Output (IO) tables derived from the national accounts system. An IO-table consists of multiple sectors and captures the economic activity happening between those as well as the imports and exports by sector. Building on the initial information captured in the IO-tables, main macroeconomic indicators are derived, such as intermediate demand, consumption, capital formation, employment and compensation of employees, trade, etc. Both models capture the complex interlinkages between economy (based on the IO structure), energy system and environment, which are connected to the core economic representation through bottom-up representation of energy system dynamics (at the sector level, focusing on electricity supply, industries, transport and buildings) and emission calculations, the accumulation of which results in global warming. Recently, E3ME and GEM-E3, along with the IMAGE model, have been applied to assess the economic impacts on the Russian-Ukrainian war (Harmsen et al., 2024). Furthermore, the two models have been utilised 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 modelling outcomes. A key distinction is that GEM-E3 is an equilibrium model, assuming that the economy remains in an optimal equilibrium in each scenario, whereas E3ME is a non-equilibrium model, acknowledging that the economy is not always in equilibrium (Mercure et al., 2019).

Equilibrium models ensure a closed system approach that allows a consistent comparison across scenarios of different policy options and an explicit comprehension of system dynamics and long-term structural changes. While a new generation of hybrid equilibrium models, like GEM-E3, incorporate empirically estimated behaviours of markets, for example by featuring endogenous unemployment, decisions still comply 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 & Mercure, 2018). However, more recently, hybrid CGE models, like GEM-E3, include different financing considerations, as described in Paroussos et al. 2019 and 2020, allowing for alternative financing options (e.g. bank behaviour, 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 & Jacques, 2024). However, crowding-out effects can diminish under favourable financing schemes even in equilibrium models, as demonstrated by Fragkos & Paroussos (2019), 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.

Table 5. Overview of the key macroeconomic model similarities and differences

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

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 and GEM-E3) or endogenously (in GEM-E3) set to meet emission reduction targets.
- **Emission caps:** With the tax level endogenously determined to clear demand and supply for emission permits.



- **Market-based instruments:** Such as emissions trading systems (ETS) and subsidies for clean technologies.
- **Regulatory instruments:** Including energy efficiency standards, renewable energy targets, CO₂ standards for vehicles, and phase-out policies for high-emission technologies.
- **Trade-related policies:** Like the Carbon Border Adjustment Mechanism (CBAM) and industrial tariff adjustments to mitigate competitiveness impacts on trade-exposed sectors.

5.3.1 E3ME Model

The E3ME model is a tool designed to analyse 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, labour market reforms, and technological support measures such as initiatives for electric vehicles. 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 analyse 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 behaviour and outcomes over time.

E3ME has been applied to analyse 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).

5.3.2 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 labour dynamics. By incorporating market-derived prices, the model



evaluates the socioeconomic and distributional effects of various types of policies (including energy, climate, labour 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 (ICE), plug-in hybrids, and battery electric vehicles (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 labour market, industrial policies, and decarbonization measures, providing insights into how climate policies can balance economic growth and environmental sustainability while ensuring a just transition.

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

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

Further policy measures in the Net-Zero scenario include caps on new fossil fuel capacities, a phase-out of unabated coal power by 2050, and afforestation investments. Biofuel blending rates are set to reach 100% by 2050, and substantial subsidies are used to



support decarbonizing industrial processes through electricity, hydrogen, and CCS technologies. These coordinated efforts aim to significantly reduce emissions and achieve the average temperature rise of 1.5°C, while transitioning to a sustainable, low-carbon future. More detailed description of the scenario design is provided in Appendix A.

5.5 Results

We analyse 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 greenhouse gas emitters are China, the USA, India, and the EU.

5.5.1 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 11).

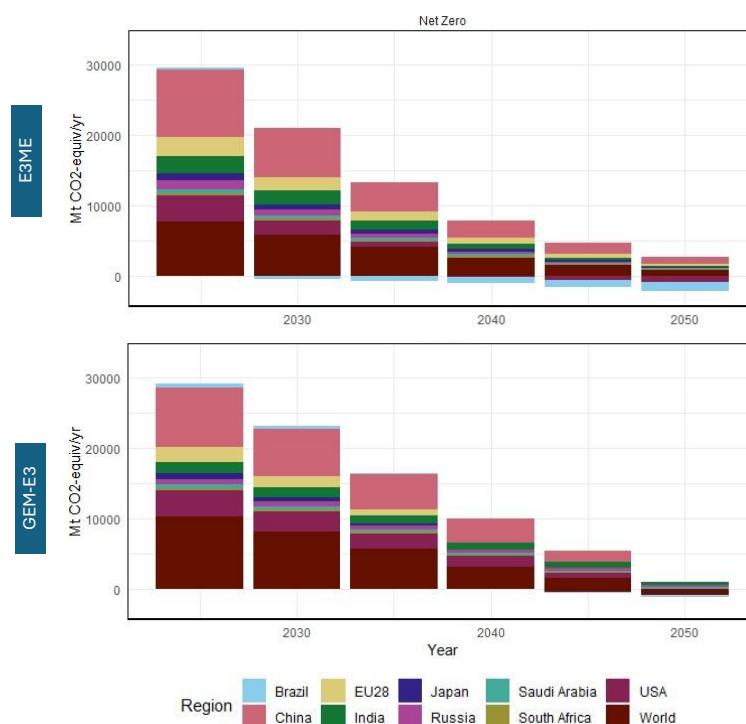


Figure 11. CO₂ emissions in the Net-Zero scenario. Total emissions across regions in the Net-Zero scenario in the E3ME model and in the GEM-E3 model.

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



5.5.2 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 decarbonisation investment, reducing the productive investment in other activities. In contrast, E3ME anticipates short-term growth driven by investment stimulus given its money creation assumption, followed by a period of slowdown during debt repayment, before stabilizing in the long run.

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

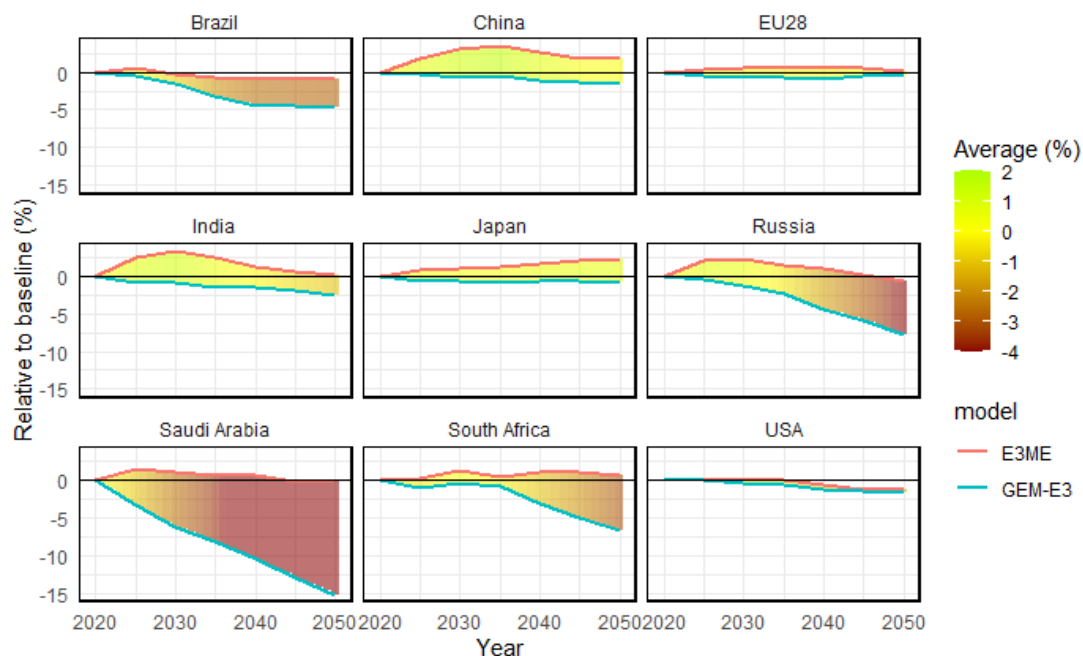


Figure 12: GDP impact of the Net-Zero scenario compared to Current Policies without climate damages. The green-yellow-red shaded area of the figure shows the average difference from baseline (in %) across the two model results. The red (E3ME) and blue (GEM-E3) lines show the two models' estimates.

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

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

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

Unlike the EU, the USA faces small relative GDP losses according to both models due to its extensive shale oil industry that is hit by ambitious climate regulations. E3ME and GEM-E3 indicate a limited reduction in country's GDP as strict assumptions on oil phase-out affect the USA's oil export reliance. Europe, leading in climate action with the European Green Deal, shows initial GDP growth as a result of reduced fossil fuel imports. E3ME 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 decarbonisation towards global net-zero, unless they are efficient producers like Saudi Arabia (Prince, 2023). Zubair et al. (2019, 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 favourable economic trajectories due to investments in renewable energy. In contrast, the USA faces relative GDP losses attributed to its shale oil industry, though existing climate policies mitigate the impact. According to both models, Europe experiences a marginal GDP impact. Oil-exporting countries, especially Saudi Arabia, face significant GDP risks, with substantial losses predicted from reduced fossil fuel export revenues.

Employment trends mirror GDP impacts, closely tied to economic output (see Figure 13). 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 decarbonisation 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).

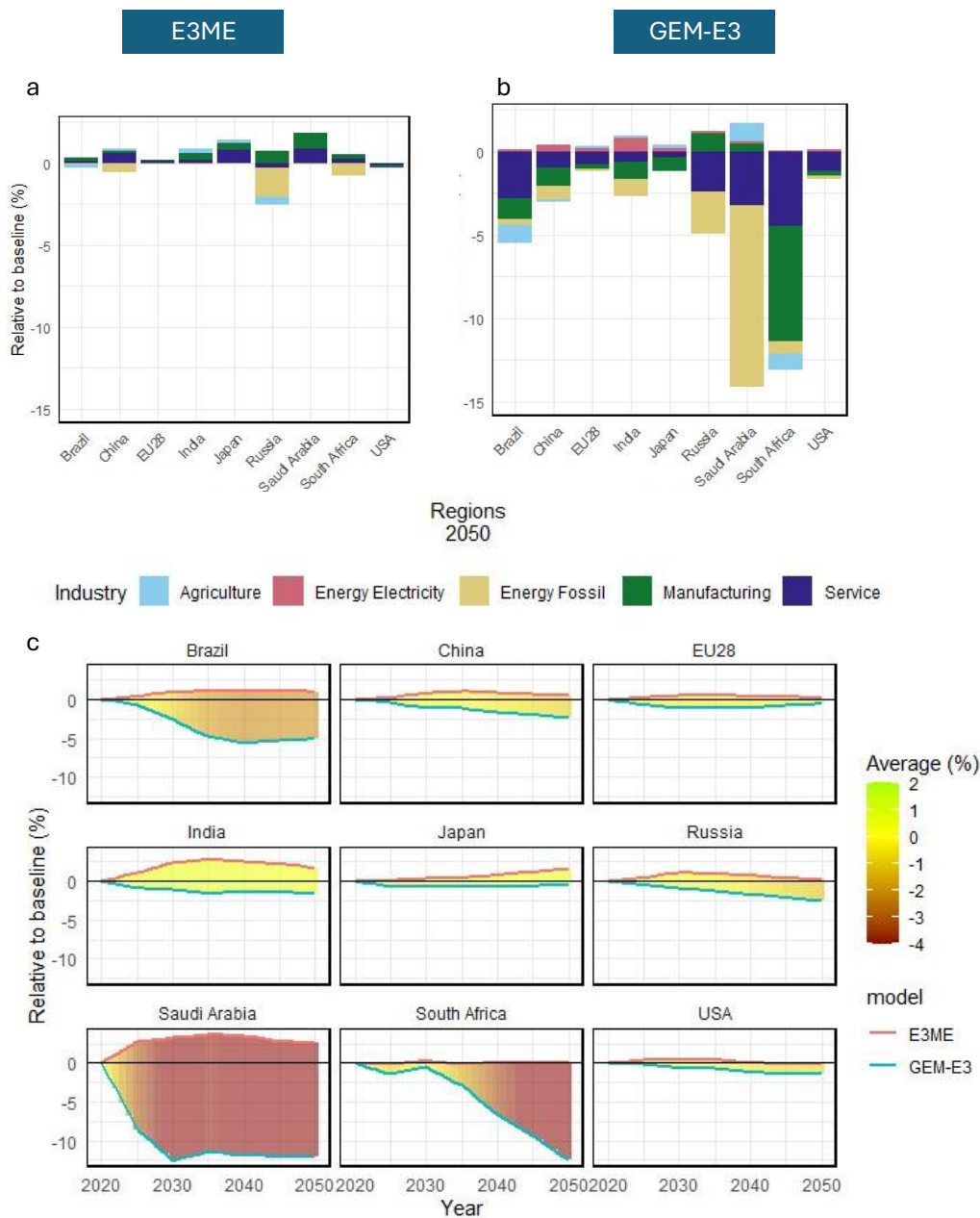


Figure 13: Employment impacts of the Net-Zero scenario compared to the Current Policies across countries. a, In the E3ME model in 2050. b, In the GEM-E3 model in 2050. c, Employment impacts between 2020 and 2050 in both models. The green-yellow-red shaded area of the figure shows the average difference from baseline (in %) across the two model results. The red (E3ME) and blue (GEM-E3) lines show the two models' estimates.

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 decarbonisation 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.

5.6 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 14 presents a regional breakdown of the estimated economic impacts of climate change. 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. 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. Besides the larger



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

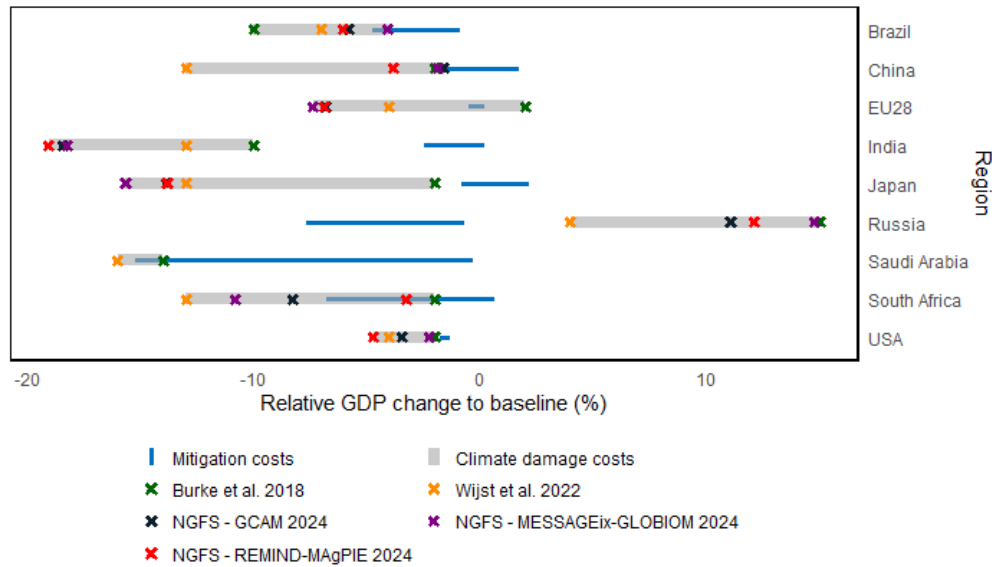


Figure 14: Range of GDP outcomes based on economic and climate modelling. The climate damage costs shown in the figure represent the additional climate damages in a single year, 2050, compared to a 1.5°C scenario. This specification ensures comparability with the mitigation costs derived from our dual-model analysis. The blue range illustrates the mitigation costs and benefits associated with emissions reductions in the net-zero scenario, while the grey range represents the additional climate damages under the Current Policies scenario (3°C).

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

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

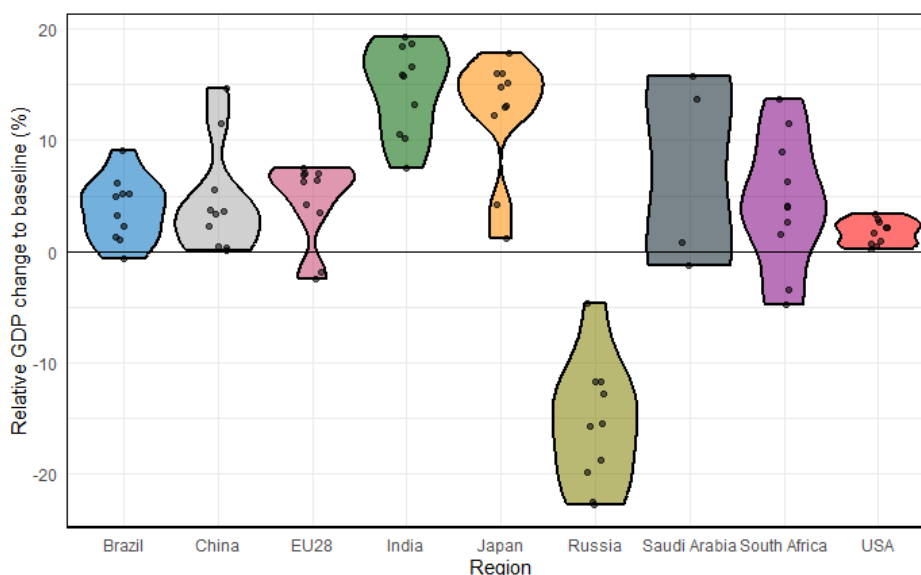


Figure 15: Combined impacts of mitigation and climate damage costs by region in 2050. The combined impacts for each region in 2050 are calculated by subtracting the climate damage costs under the Current Policies scenario from the mitigation costs associated with the net-zero pathway. These estimates are based on both the E3ME and GEM-E3 models, as well as the climate damage cost estimates from the studies referenced in Figure 5. This results in 10 values per region (2 mitigation cost estimates $\times$ 5 climate damage cost estimates). A violin plot is then used to visualize the distribution of these combined total economic impacts of the net-zero pathway.

Figure 15 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.

5.7 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 analysed (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.

5.8 Appendix

5.8.1 Scenario design

In the net-zero scenario, a comprehensive set of policy measures are implemented to achieve significant emissions reductions across various sectors. A summary of the policies is presented in Table A.1. In both models, a uniform carbon price is introduced globally, reaching around \$450-500/tCO₂ by 2050, applying to all sectors, including energy supply, industry, road transport and residential areas. Immediate taxes and mandates, such as a significant energy tax on middle distillate use in road transport and biofuel blending mandates for multiple transport modes and industries, are enforced. The scenario also includes investments in advanced technologies to reduce energy dependency and extensive subsidies for biobased, geothermal, and CCS technologies, with specific support timelines. Vehicle-related policies involve taxes on non-zero emission vehicles and subsidies for electric vehicles, with strong regulation to not allow new petrol or diesel vehicles allowed after 2025/2030 (depending on each economy). Additionally, fossil-fuelled boilers face increasing taxes, while renewable boilers receive subsidies phased out by 2050.

Specific cornerstone climate policies are "The European Green Deal" for the EU (Green Deal for short) and the "Inflation Reduction Act" (IRA) in the USA policy packages. The Green Deal and corresponding "Fit for 55" package that aims at 55% reduction in emissions by 2030 compared to 1990 levels, were endorsed and implemented within the European Union in 2020/2021 (European Commission, 2020). These directives are geared towards positioning the European Union as the pioneer in achieving net-zero emissions by 2050, along with a 55% emissions reduction target by 2030. The Directives encompass a spectrum of policy instruments, spanning from the ETS carbon pricing mechanism that puts a price on every emitted ton of CO₂ in specific industries to the facilitation of coordinated efforts among



member states for efficient emission reduction. Similarly, the IRA was introduced in the USA to mitigate the effects of high inflation at the time, and includes extensive policies targeted at investing in domestic energy production and promote green energy sources (Dennis, 2022). Both the IRA and the EU's Fit for 55 package are included in the net-zero scenario.

Further regulatory measures include caps on new capacities of oil, coal, hydro, and biobased power plants, with a complete phase-out of unabated coal power by 2050. Afforestation investments are made, with emission removals accounted for off-model. Fiscal policy adjustments are designed to balance government budgets by redistributing policy costs and revenues. Biofuel blending rates are set to reach 100% by 2050, entirely replacing middle oil distillates. In the industrial sector, electricity and hydrogen use receive substantial subsidies, phased out between 2045 and 2055, to decarbonize hard-to-abate industrial processes. CCS applications benefit from immediate subsidies, phased out from 2035 to 2050, and hydrogen-based steelmaking also receives investment subsidies phased out by 2063. These coordinated policies and investments aim to drive significant emissions reductions, ensuring a transition towards a sustainable, low-carbon future.

Table 6. Summary table of policies included in the net-zero scenario design

Policy Name	Description	Details
Carbon Pricing	Introduced progressively after 2025 to achieve cost-efficient global transition towards net-zero emissions by 2050.	Gradually increases until 2050, affecting all sectors.
Energy Taxes	Additional taxes imposed on energy to encourage decarbonization.	Supports clean technologies and reduces reliance on fossil fuels.
Biofuel Mandates	Mandates blending rates of biofuels in energy systems.	Target blending rates set to reach 100% by 2050.
CO ₂ Standards and Regulations	Targets emissions reductions in vehicles and boilers through stricter standards and regulations.	Encourages adoption of cleaner technologies in transport and heating sectors.
European Green Deal 2021	Comprehensive EU climate policy for achieving ambitious emissions reductions.	Includes measures such as renewable energy targets and carbon neutrality goals.
U.S. Inflation Reduction Act (IRA)	Major U.S. climate legislation supporting decarbonization and clean energy investment.	Focuses on subsidies and incentives for clean technologies and carbon reduction.
Caps on Fossil Fuel Capacities	Restrictions on new fossil fuel capacities to limit emissions.	Encourages investment in renewable energy sources.
Phase-out of Unabated Coal Power	Gradual elimination of coal power plants without carbon capture by 2050.	Aims to reduce heavy emission sources and promote cleaner alternatives.
Afforestation Investments	Initiatives to plant forests to absorb CO ₂ and improve biodiversity.	Supports achieving net-negative emissions in regions like Brazil.
Subsidies for Decarbonizing Industrial Processes	Financial support for industrial decarbonization efforts using electricity, hydrogen, and CCS technologies.	Encourages transition to low-carbon manufacturing processes.



5.8.2 Additional results

Trade Impacts

Changes in the trade balance of impacted countries is an important indicator of how the comparative advantages of certain countries change within the net-zero scenario and thereby sheds light on the transformative impact of the clean energy transition. Furthermore, the export potential is a key driver of the country's economic development potential and a determinant of how the energy transition is likely to impact it. Note that the export potential of a country is not directly linked to the question of crowding-out effects which is the main fundamental difference between the two models, and therefore the export projections show relatively similar patterns in both models.

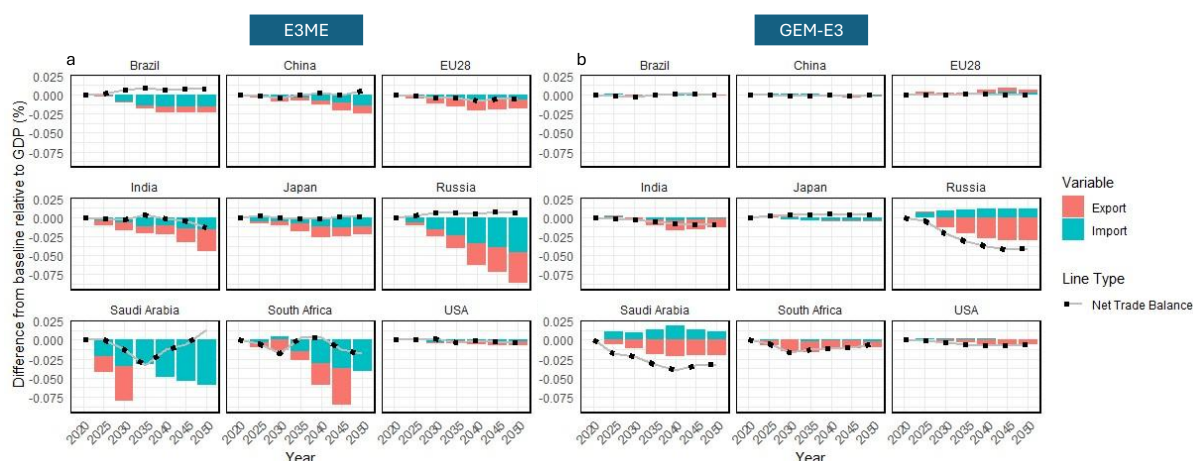


Figure 16. Trade impacts of the Net-Zero scenario compared to the Current Policies across countries. a, In the E3ME model between 2020 and 2050. b, In the GEM-E3 model between 2020 and 2050.

The countries that have the most anticipated potential economic growth in the Net-Zero Scenario, which are China and Japan, are expected to experience only slight negative changes in their export potential, according to both modelling results (see Figure 16).

Brazil and the EU show relatively low export changes in both models. E3ME results predict almost no change in total exports of the EU, while the imports of fossil-based sectors such as coal and manufactured fuels are reduced significantly. In contrast, GEM-E3 projects a somewhat bigger drop in total EU exports, which is caused by the lower productivity in other sectors, due to the crowding-out effect of net-zero investments. While Brazil shows similarly low levels of export changes, it follows a different pathway throughout the transition period. Brazil is currently Latin America's top oil producer, and it has the world's largest recoverable ultra-deep oil reserves (ITA, 2023). The country relies heavily on its oil investments, which it plans to leverage and further increase oil production. E3ME predicts an increase in oil and gas exports up until 2038, when it starts to fall to reach approximately zero by 2050. This export growth in fossil sectors is balanced by the strong decrease in basic metal exports. GEM-E3 shows the same pattern and by projecting lower export changes until mid-2030s, and as fossil investments and exports start to decrease, the country's overall export potential does so too.

Both models project a strong decline for today's fossil exporters who rely heavily on fossil energy exports. This includes Russia, Saudi Arabia, South Africa and the USA. The magnitude of the fall in export levels depends on how much the country's economy is reliant on the export revenues of fossil industries. The relative impact is the highest in the case of Russia and Saudi Arabia, with an export decrease within the magnitude of 10-15% in both models. The other countries are able to mitigate the decline in their export potential over time by



effectively developing their green industries (e.g. EV, solar, wind turbines) during the transition period, which can offset the reduced export income potential from fossil industries.

Primary Energy Demand

The primary energy mix is a key determinant of CO₂ emission levels and therefore it is important to fully understand the emission pathways of the Current Policies and the Net-Zero scenarios. Furthermore, the energy mix is a strong indicator of the transformative impact of net-zero policies as it outlines what will be the share of green and fossil energy sources and sectors in the future.

In the Current Policies scenario (Figure 17), countries largely continue to rely on their traditional energy sources. Total global aggregate demand for primary energy sources remains relatively constant over time until 2050. Due to these trends, fossil fuels aren't being clearly phased out. While the share of renewables is growing, it remains low in many areas. Significant growth in energy demand is anticipated, particularly in developing economies driven by factors such as high GDP growth, rising population, and improved standards of living. Africa is significantly increasing its biomass use and China is boosting solar energy thanks to their development plans. Global demand for fossil fuels is dropping overall, yet gas demand in South Asia is rising because of India's significant growth in oil and gas usage. Conversely, a reduction in primary energy demand is observed only in developed countries with robust climate policies in the Current Policies scenario, exemplified by the European Union (EU).





Figure 17. Primary energy demand across countries. a, In the Current Policies scenario in the E3ME model. b, In the Net-Zero scenario in the E3ME model. c, In the Current Policies scenario in the GEM-E3 model. d, In the Net-Zero scenario in the GEM-E3 model.

While the exact route to phasing out fossil fuels can be contentious, these findings indicate that achieving net-zero emissions is unattainable without nearly eliminating fossil fuel usage. This near-total phase-out implies that any lingering emissions could be managed through carbon capture and storage (CCS) technologies. The need to phase-out fossil energy sources has been acknowledged on the global stage for the first time in 2023, at the COP28 Conference (UNFCCC, 2023). While there have not been any legally binding agreements between participating nations on phasing out fossil energy sources, all of them officially agreed to the fact that to reach the mutually accepted targets, all countries need to transition away from fossil fuels. Comparing the results with the emission figures from the Current Policies scenario reveals that regions heavily dependent on fossil fuels, like East Asia and the Pacific with their substantial coal usage, contribute the largest share of total emissions.

The Net-Zero scenario assumptions target these regions to reduce their reliance on fossil fuels. As a result of this, results indicate that total primary energy demand is reduced by approximately 35% from 2023 levels. The decrease is planned to happen gradually and with the phase out of fossils in most of the regions, with a few exceptions. One such example is the South Asia region, where total energy demand is almost the same in the Net-Zero as it is in the Current Policies scenario, driven by relatively high remaining shares of coal and oil. Another example for remaining shares of fossil fuels is in the East Asia and Pacific region,

caused by China's high dependence on coal as its main energy source. In 2023, China alone is responsible for almost half of global primary coal consumption, which is expected to be reduced by 65% by 2050, but will still account for around one third of global coal demand that year. Additionally, oil demand in the country will remain substantial by creating 10% of the total energy demand in 2050. Finally, North America is responsible for the remaining high share of oil in global demand, with oil demand being only half as much as it would be in the Current Policies scenario in 2050.

In spite of these trends, the adoption of renewable energy sources remains robust worldwide. Solar and wind energy are the primary fuels experiencing substantial global expansion, with biomass also seeing an increase to some extent. Similarly to the Current Policies scenario, the contribution of biomass remains important in Africa as it becomes the continent's largest energy source. Furthermore, solar power is deployed extensively in East Asia and Pacific and North American regions. The extensive solar power resource in the Middle East and North Africa region is not leveraged to its fullest potential, because of the region's heavy reliance on natural gas.

Nuclear power follows the same growth trend in both scenarios, accounting for approximately 5% of total primary energy demand in 2050. Even though nuclear power might be considered desirable for climate mitigation, there has been extensive research that highlights the economic inefficiency and high costs of constructing and maintaining nuclear power plants (Göke et al; 2023).

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6. Extending PIK's Multi-Sectoral Growth Model: Structural Change and Climate Policy under Market Frictions

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Achieving the goals of the Paris Agreement requires a comprehensive transformation of economic systems, entailing not only technological change but also deep shifts in production structures, trade patterns, and labour allocation. Integrated Assessment Models (IAMs) play a key role in evaluating policy pathways that facilitate this transformation, offering quantitative insights into the trade-offs and synergies between environmental goals and economic development. The PRISMA project contributes to the evolution of IAMs by developing model capabilities across several dimensions critical for robust climate policy assessment. A central theme of this effort is the improved representation of economic structural transformation, i.e. how countries reallocate economic activity across broad sectors over time, particularly in response to climate policy. This report presents work conducted under Work Package 2, Task 2.1, which targets the modelling of structural change and its interaction with policy in an economy facing frictions. Specifically, we extend a global multi-sectoral optimal growth model by incorporating international trade and sector-specific frictions. These advancements enable the model to capture critical mechanisms that shape regional and sectoral outcomes under climate policy. Early model experiments illustrate how trade can mitigate welfare losses from climate policy in certain regions by enabling them to shift the burden of structural adjustment. Similarly, introducing frictions in labour and capital markets reveals their sizable effects on sectoral reallocation and welfare, particularly in low-income regions. These preliminary results highlight the value of moving beyond frictionless benchmarks in climate-economic modelling.

6.1 Introduction

In the face of mounting climate-related risks, the international community has recognized the imperative to limit global warming and reduce greenhouse gas emissions². However, willingness and capacity to commit to climate change mitigation efforts differ across countries and regions, making it difficult to reach a global consensus and coordinate effective mitigation strategies. Differences in economic development, climate vulnerability, political institutions, cultural contexts, and social aspirations, lead to different development priorities and, specifically, to different perceptions of the risks and benefits associated with climate change mitigation efforts³. For low-income countries in particular, mitigation efforts are balanced against many other development priorities⁴ such as poverty eradication, food security and structural transformation, particularly industrialization. Structural transformation, i.e., the reallocation of economic activity across broad sectors of the economy, is a well-known stylized fact of economic growth, and commonly defined as the reallocation of output and workers across the agriculture, manufacturing and services sectors: as income grows, the shares of output and workers decline in agriculture, increase in services, and follow a hump shape (increasing at lower levels of income and decreasing

² Collective global action was formally agreed upon at the United Nations Climate Change Conference in Paris in 2015 (F. C. on C. C. United Nations 2015). The relevant science is laid out in the reports by the Intergovernmental Panel on Climate Change (IPCC) Intergovernmental Panel On Climate Change (Ipcc) (2023a).

³ Further pivotal issues are those of climate accountability and burden sharing. See, for instance, Bauer et al. (2020) and Leimbach and Giannousakis (2019) for assessment of burden sharing options within climate mitigation, among others.

⁴ The Sustainable Development Goals (SDGs) adopted by the United Nations (2015) embody the most essential development priorities. See Soergel et al. (2021) for an assessment on the synergies between the SDGs and climate change mitigation.



at higher) in manufacturing⁵. Because of this association with economic growth, low-income countries are hesitant to implement policies that may impair the structural transformation process: climate mitigation policies are often perceived as such, because CO₂ prices are thought to endanger the growth of the energy and CO₂-intense manufacturing sector⁶. That being said, the interactions between mitigation policies, climate change and structural transformation are yet not well understood: different regions and sectors of the economy have different mitigation potentials and different vulnerabilities to climate damages, leading to global interdependencies of sectoral emissions, climate impacts and structural transformation dynamics.

Building upon the foundations of both climate-economy modelling and structural transformation research, we develop a framework that integrates global climate-economy interactions and sectoral heterogeneity, enabling a comprehensive analysis of the structural transformation implications arising from climate change impacts and mitigation policies. In keeping with Nordhaus' foundational studies (W. Nordhaus 1992a, 1992b), our framework is a neoclassical growth model augmented with a climate system, and now, additionally, simultaneous regional and sectoral heterogeneity⁷. Our implementation of the structural transformation dynamics draws upon Kongsamut, Rebelo, and Xie (2001), Ngai and Pissarides (2007), Acemoglu and Guerrieri (2008), García-Santana, Pijoan-Mas, and Villacorta (2021), and chiefly Duarte and Restuccia (2010).

A key starting point for our work is the heterogeneity of climate change impacts and mitigation policies across regions and broad sectors of the economy: sectors are affected differently due to their distinct vulnerabilities and mitigation potentials. These differences imply that sector allocations within the economy are likely to change as temperatures increase and mitigation policies are implemented. To study these effects, we develop a global integrated assessment model (IAM) that integrates structural transformation. The world is divided into twelve regions⁸, and each region has three production sectors: agriculture manufacturing and services⁹. By allowing for regional and sectoral interactions, the model enables us to quantify distributional effects across regions and sectors, and evaluate how structural composition is affected by different mitigation and regional-coordination assumptions. For example, to what extent is the structure of the economy affected by a globally optimal emission allocation across regions? Is the structural development of low-income regions hindered by such a policy or enabled?

Our model endogenizes the structural transformation process. It is driven by both demand and supply side characteristics: on the demand side, the model features non-homothetic preferences, i.e., changes in consumption patterns associated with increasing income; on the supply side, the model features different productivities and damage parameters across regions and sectors. Moreover, following García-Santana, Pijoan-Mas, and Villacorta (2021), consumption and investment goods have different sectoral composition, with investment

⁵ The process of structural transformation has been thoroughly discussed in the economic literature. See, for instance, Kuznets (1957), Maddison (1980) and Herrendorf, Rogerson, and Valentinyi (2014), among others.

⁶ For a comprehensive review of the literature on the relationship between economic growth and CO₂ emissions, see Fávero et al. (2022).

⁷ Regional heterogeneity in climate-economy models is not a novel development, with many previously developed models having this characteristic, albeit to varying degrees; see, for instance, W. Nordhaus and Yang (1996), Baumstark et al. (2021), Krusell and Smith (2022) among others. Sectoral heterogeneity, on the other hand, is a more novel development in optimal -growth climate-economy models, with only a few studies venturing in that direction, see Nath (2020), Casey, Fried, and Gibson (2024), Liao and Ye (2023).

⁸ A list of the regions and a country-to-region mapping is provided in Appendix X.

⁹ We follow the literature and divide the economy into the agricultural, manufacturing and services sectors. However, the developed framework is not restricted to three sectors and future expansion is possible.



being more manufacturing-intensive compared to consumption¹⁰. In every sector, the production inputs are capital, labor, and energy. Energy use causes CO₂ emissions¹¹, which accumulate globally, increase the global mean temperature and create a climate externality in the form of an output loss. The magnitude of the output loss is given by a region- and sector-specific damage function (Parrado and Cian 2014; Wijs et al. 2022), reflecting distinct vulnerabilities¹². This characteristic is essential for analysing critical development issues: if the impacts turn out to be disproportionate across sectors, e.g. larger in agriculture and manufacturing than in services, then low-income countries, where the predominant sectors are agriculture and manufacturing, will suffer the adverse effects of climate change more intensely than higher-income countries. This becomes particularly severe in face of the “food problem”: until countries can produce a sufficient amount of food, labor is trapped in agriculture, delaying the process of modern economic growth¹³.

A further, distinct, characteristic of the model is its representation of the energy sector. In our model, energy-use comes at a cost introduced via emulators derived from the REMIND model (Baumstark et al. 2021). REMIND is a well-established IAM featuring a detailed energy system and wide range of mitigation options. The use of the emulators allows us to abstract away from the complexities of the energy system as a whole, while keeping the necessary information on the evolution of energy prices and CO₂ intensities¹⁴. In our benchmark model, we differentiate between electric and non-electric energy and aggregate them in the production function via constant elasticities of substitution (CES). The substitution elasticity between the energy types provides us with an additional channel to model the variation in mitigation potentials that exists across sectors, and we calibrate it lowest in manufacturing. That is because apart from being the most energy-intensive sector, manufacturing is also the sector in which different energy sources (e.g. heat, liquid fuels, solids, gases and electricity) are often linked to specific technological processes and only rarely easily interchangeable¹⁵.

Our model represents CO₂ mitigation similar to Nordhaus’ DICE model (W. Nordhaus 1992a; W. D. Nordhaus 2017) as an endogenous control variable. Yet, the specific implementation is different. In DICE, decarbonization efforts are modelled using marginal abatement cost curves. In our model, they are modelled using energy system investments that reduce CO₂ intensities of energy at rates computed by the REMIND emulator. Further mitigation is undertaken through reallocation of economic activity and switching between energy sources in face of higher energy costs.

¹⁰ García-Santana, Pijoan-Mas, and Villacorta (2021) consider the change in the investment rate as an additional driver of structural transformation.

¹¹ The only emissions that are endogenous to the model are CO₂ emissions from energy use. CO₂ emissions from other sources, i.e., direct industrial processes (e.g., cement and chemical production) and land use, land use change and forestry (LULUCF), and non-CO₂ greenhouse gas emissions are provided exogenously.

¹² In agriculture, extreme weather events like floods and droughts can cause crop failures and shifts in suitable farming regions. Changes in water availability, pests, and livestock health can pose additional challenges to crop and livestock management. The manufacturing sector faces supply chain disruptions and physical damage to facilities from extreme weather events. Moreover, changing consumer and energy demands from shifting weather patterns, can affect production processes. The services sector experiences disruptions in service delivery and infrastructure due to extreme weather events, while the tourism industry is influenced by changing destinations’ attractiveness. For all three sectors, regional variations play a critical role in shaping the extent of the impacts.

¹³ The concept of the “food problem” dates back to Schultz (1953).

¹⁴ Sections X and X provide more detailed information on the implementation of the REMIND emulator.

¹⁵ Madeddu et al. (2020) present a comprehensive report on the electrification potential of the European industry sector. They find that close to 80% of the sector’s energy demand is, technically, electrifiable with technologies that exist today. However, the extent to which this is economically feasible is less certain and depends strongly on the relative prices of the electrification technologies.



In an extensive review of the climate-economy modelling landscape, Ciarli and Savona (2019) find that most models cover few, if any, aspects of these interactions¹⁶. Notable recent exceptions are Nath (2020), Casey, Fried, and Gibson (2024), Liao and Ye (2023) and Lefèvre et al. (2022). Nath (2020) builds a static open-economy model of structural transformation covering 158 countries to evaluate the impact of climate change on sectoral reallocation and aggregate productivity. He finds that openness to trade determines the aggregate consequences of asymmetric sectoral productivity shocks. Casey, Fried, and Gibson (2024) build a climate-economy structural transformation model with five sectors (the classical three plus mining and construction), sector-specific damages, and different sectoral compositions of consumption and investment goods. They find that, when investment is more vulnerable to climate change, consumption is shifted closer to the present. Compared to our model, theirs includes more sectors but only a single region. Liao and Ye (2023) adapt Nordhaus' DICE model, differentiating between two sectors, one producing a consumption good and one producing an investment good. Key differences with our model include the sectoral and regional resolution: one consumption good producing sector instead of three, and a single region instead of twelve. Lefèvre et al. (2022) perform a model inter-comparison study of three multi-sector models, and assess the impact of mitigation policies on economic structure. They find that mitigation has a small impact on the economic structure as a whole, but significant effects inside specific industries, particularly the energy industry. The models they compare differ to ours in that they are not optimal-growth models and do not integrate damages from climate change.

6.2 Introducing Trade

A key objective of Task 2.1 has been to incorporate international trade into our model. Trade is a crucial component in global general equilibrium frameworks, as it enables the analysis of interdependencies between countries, the transmission of policy shocks across borders, and the reallocation of production and consumption in response to changes in comparative advantage. It also allows for the examination of structural shifts across sectors driven by globalization and climate policy. Moreover, trade plays a central role in determining relative prices between countries and terms of trade, both of which are essential for capturing the economic consequences of environmental and industrial policies in open economies.

6.2.1 Theoretical background

Our approach draws on the extensive literature on modelling international trade in computable general equilibrium (CGE) frameworks. Within the climate policy modelling community, widely used tools include multi-region, multi-sector CGE models such as GTAP (Corong et al. 2017), which are typically calibrated using input-output tables and social accounting matrices. A standard feature of these models is the adoption of the Armington assumption, which posits that goods are differentiated by their country of origin (Armington 1969). This assumption helps to explain the empirical observation of 'cross-hauling', i.e. the simultaneous import and export of seemingly identical products by a single country, by treating them as distinct varieties. It differs from the assumption of homogenous goods typically made in traditional deterministic Ricardian and Heckscher-Ohlin models, in which trade is driven purely by competitive advantage gained from differences in technologies

¹⁶ Ciarli and Savona (2019) identify six aspects of structural change that affect climate change: sectoral composition, industrial organization, technology, employment, final demand, and institutions. They compare integrated assessment models (IAM), computable general equilibrium (CGE) models, structural change models (SCM), ecological macroeconomics models in the Keynesian tradition (EMK) and evolutionary agent based models (EABM), regarding the degree to which these aspects of structural change are implemented.



(Ricardian models) or factor endowments (Heckscher-Ohlin models). These models lead to complete specialization and have difficulties capturing the empirical trends.

Under the Armington specification, domestic and foreign goods are treated as imperfect substitutes, with the degree of substitutability governed by the so-called Armington elasticity. This has important implications for both production and consumption decisions. For firms, the choice between domestic and imported intermediate inputs depends on relative prices and substitution elasticities. Imported intermediates themselves are modelled as composites of imports from different trading partners. Similarly, households consume composite goods comprising both domestic and imported varieties. On the export side, each country is the sole supplier of its differentiated product variety in the global market. This structure gives rise to endogenous terms of trade effects: because export goods are distinct by origin, their prices respond to shifts in global demand. For example, a country can only expand its exports if the relative price of its product falls to stimulate additional foreign demand. Consequently, trade liberalization or climate policy shocks can generate significant terms of trade adjustments. These dynamics are a defining feature of CGE models employing the Armington framework, and are critical for capturing the economic and distributional impacts of trade and climate policy interactions in a multi-country setting.

As an alternative to the Armington structure, many modern trade models adopt a Ricardian framework in the style of Eaton and Kortum (2002). These models assume that countries draw productivity levels for a continuum of goods from a common probability distribution, allowing for heterogeneity in comparative advantage. Firms within each sector produce differentiated varieties, but varieties from different countries are perfect substitutes, meaning that consumers and producers care only about price, not origin. Trade occurs because countries differ in their ability to produce particular varieties at low cost, and trade shares respond endogenously to productivity and trade cost shocks. Compared to the Armington model, Eaton-Kortum models offer an arguably deeper theoretical foundation for trade patterns (Ricardian specialization), but often require more data and computational resources, particularly when extended to dynamic or multi-factor settings, without necessarily leading to differences in results (Bekkers et al. 2023).

The arguments for incorporating trade into structural and climate modelling are strong, but the size and nature of trade effects remain debated. Some studies find limited consequences of trade for structural change: for instance, Krusell and Smith (2022) report only minor differences between autarky and open-trade scenarios in a single-sector global model. Similarly, Hassler, Krusell, and Olovsson (2021) abstract from trade entirely in their evaluation of suboptimal climate policies. Even in multi-sector contexts, Nath (2020) find that agricultural specialization is more strongly driven by subsistence food requirements than by comparative advantage. These findings suggest that while trade mechanisms can enrich the model and policy space, their quantitative role may be context-dependent.

6.2.2 Practical considerations

The implementation of bilateral trade in our model presents several non-trivial challenges. First and foremost, introducing trade significantly expands the dimensionality of the model by increasing the number of variables and equilibrium conditions, which raises the computational burden. More critically, it introduces substantial complexity into the model calibration process. Ensuring that the model reproduces observed international trade flows (both in levels and in bilateral shares) across all regions proves difficult, especially under varying model configurations. This aspect of the work remains under active development.



A further complication arises from the model's solution structure. Our model is solved iteratively, with each region initially computed independently. Between iterations, assumptions on energy prices are adjusted to achieve consistency with the outputs of the REMIND emulators. With the addition of trade, it becomes necessary to additionally ensure that global markets clear, that is that exports from each region match the imports demanded by others. This introduces an additional layer of interdependence that complicates convergence. Moreover, because we simultaneously adjust calibration parameters to align trade flows with empirical data, this iterative process becomes especially delicate. To limit complexity at this stage, we have included a general formulation of ice-berg trade costs into the model structure, but have not yet begun to systematically calibrate them. Current simulations use placeholder or stylized values, and we are in the process of assessing whether the resulting trade flows fall within empirically reasonable bounds. If not, more detailed calibration using observed trade patterns and gravity-style estimates will be pursued in subsequent work.

An additional modelling consideration involves the appropriate valuation of trade flows. Since international transactions occur at market exchange rates (MERs), it is essential that trade values be expressed accordingly, rather than in purchasing power parity (PPP) terms - the unit in which regional capital and GDP is otherwise expressed in our model.

6.3 Introducing Frictions

Structural transformation involves the gradual reallocation of labor and capital across sectors as economies develop, adapt to policy changes, or respond to external shocks like climate change induced damages. In theoretical models, this process is often assumed to be frictionless: workers and capital move instantly to their most productive uses in response to changes in prices or policy incentives. While this assumption facilitates analytical tractability, it is at odds with both empirical evidence and observed macroeconomic dynamics.

6.3.1 Theoretical background

The literature has shown that factor reallocation is slow, uneven, and often incomplete, especially during periods of structural change. Labor markets in particular exhibit persistent frictions due to search and matching processes, sector-specific human capital stocks, and regulatory barriers, amongst others (Donovan and Schoellman 2023; Sim and Oh 2017). These frictions hinder workers from moving to expanding sectors even when wage differentials suggest strong private incentives to do so. At the same time, capital reallocation is constrained by planning lags, installation delays, uncertainty, and irreversibilities (Cooper and Haltiwanger 2000).

Desmet and Rossi-Hansberg (2015) provide a compelling case for why frictions matter when economies face spatially and sectorally uneven shocks, such as those induced specifically by climate change. In their spatial model of global warming, the effects of rising temperatures vary dramatically across regions and sectors, implying large shifts in the optimal geographic and sectoral distribution of economic activity. However, when factor mobility is constrained by geography, institutions, or adjustment costs, the economy cannot reallocate efficiently in response to these shocks, leading to substantial welfare losses. Their findings underscore how frictions (mainly inter-regional in their case) shape not only the speed of adjustment but also the distributional consequences of large-scale structural transitions, a core concern in climate policy analysis.



Similarly, Donovan and Schoellman (2023) show that modeling labor market frictions is essential for understanding cross-country differences in structural transformation. They emphasize that persistent wage gaps between sectors - such as agriculture and manufacturing - exist, and that they reflect real mobility barriers. Ignoring these frictions leads to overestimating the speed at which economies can shift labor toward higher-productivity sectors. It also risks understating the long-term benefits of reducing those barriers, whether through education policy, infrastructure investment (to facilitate geographical relocation), or labor market reform (improved information sharing).

There are many ways to model frictions. Some approaches focus on micro-foundations, such as discrete search models or fixed adjustment costs. Others emphasize sector-specific barriers, learning dynamics, or heterogeneous agents. However, in many macroeconomic applications, including the current iteration of the MUSCLE model, it is often desirable to adopt a more aggregated and tractable representation of frictions that still captures their essential effects on the speed and cost of adjustment.

To this end, we introduce frictions as adjustment costs on sectoral labor and capital reallocation, modelled via symmetric and quadratic convex costs on changes in input shares. This formulation has a long history in the literature (Hamermesh and Pfann 1996) and captures the idea that reallocating economic activity is costly and increasing in the magnitude of the change. The specific form is simple for tractability and should be seen as a flexible and transparent first step. It captures the idea that reallocating economic activity is costly and increasing in the magnitude of the change, and allows us to explore how structural change interacts with policy interventions under real-world constraints.

Future developments may consider extending this foundation by incorporating asymmetries or lumpy adjustment costs (Hamermesh and Pfann 1996). However, even in its current form, the model offers a meaningful departure from frictionless benchmarks and enables richer analyses of transition dynamics.

6.3.2 Practical considerations

Introducing frictions into a multi-sector general equilibrium model like ours poses several practical challenges, particularly regarding calibration. In the current implementation, we calibrate the magnitude of adjustment costs (and to be perfectly clear, we consider only intra-regional adjustment costs between sectors, since we do not allow for inter-regional factor reallocations at all) by targeting the average observed differences in wages and capital rents across sectors, that we can back out from the model solution. Specifically, frictions on labor share adjustments are chosen to match mean wage differentials, while frictions on investment share adjustments are tied to differences in sectoral capital returns. This approach offers a tractable starting point and ensures that frictions are economically meaningful in magnitude. However, it does not generate wage convergence over time, which is a stylized fact in some of the empirical settings. As such, this strategy should be seen as an initial approximation, open to refinement as more detailed targets are incorporated.

A second practical consideration concerns the functional form of the adjustment costs. As discussed in the theoretical section, the current specification uses symmetric, convex (quadratic) cost functions for both labor and capital reallocation. This choice ensures tractability and smooth adjustment dynamics, but it is not innocuous. Empirical work suggests that adjustment processes may be asymmetric (e.g., hiring vs. firing costs) or nonconvex (e.g., fixed costs, lumpy investment). Incorporating such features could generate richer behavior, including periods of inaction, overshooting, or threshold effects. However, doing so would also increase computational complexity and introduce challenges for



calibration and stability. For now, the quadratic form provides a practical compromise that facilitates experimentation while remaining grounded in established theoretical work.

A further practical consideration concerns the representation of capital. Introducing capital adjustment frictions requires disaggregating the previously unified capital stock into three distinct sectoral stocks: one for agriculture, one for manufacturing, and one for services. This additional structure allows the model to track capital reallocation dynamics explicitly and to impose sector-specific frictions. For simplicity, we assume uniform depreciation rates across sectors in the current implementation. However, relaxing this assumption could open up a new exploratory channel, enabling the analysis of how sectoral differences in capital longevity or replacement cycles interact with structural change and policy shocks. As the model matures, such refinements will help deepen the realism and flexibility of the capital side of the framework.

Finally, in some applications it may be appropriate to perform the entire model calibration with adjustment costs already in place, rather than introducing them after the fact. However, this must be done with caution: if frictions are large, they can undermine other calibration targets such as sectoral employment shares, GDP, or trade balances. These considerations underscore the importance of designing flexible calibration routines and clearly distinguishing between baseline and policy scenarios.

6.4 Illustrative Dynamics from Early Model Experiments

The model is still under active development, particularly with respect to its treatment of trade and sectoral frictions. The outputs presented here serve to illustrate the type of dynamics the model is capable of generating and should not be interpreted as final results.

To help contextualize the figures, a brief summary and illustration of the model (Figure 18) are provided below.

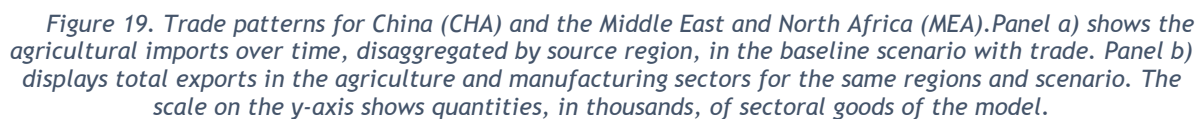
Model summary: The world is divided into twelve regions¹⁷. Each region has three production sectors, agriculture, manufacturing, and services, which require capital, labor and energy as inputs. Regions are endowed with an initial capital stock, and there are inter-sectoral adjustment costs on labor and investment shares. Labor and capital are not mobile across regions. Each region has a representative household that consumes agricultural, manufacturing and services goods, with non-homothetic preferences. CO₂ emissions are a byproduct of energy use and contribute to the elevation of the global mean temperature. The rise in temperature creates a climate externality in the form of output loss, and its magnitude is sector- and region-specific. Mitigation of climate change damages is possible through investments that reduce the CO₂-intensities of energy use. There is trade in the agriculture and manufacturing goods but not in services.

¹⁷ The regions are: United States (USA), Europe (EUR), China (CHA), Russia and Reforming Economies (REF), India (IND), Japan (JPN), Other Asia (OAS), Middle East and North Africa (MEA), Latin America (LAM), Canada, Australia, and New Zealand (CAZ), Sub-Saharan Africa (SSA) and Non-EU European countries (NEU).





To explore the trade module's behavior, Figure 19 illustrates international trade patterns for two representative regions: China (CHA) and the Middle East and North Africa (MEA). Panel a) shows agricultural imports disaggregated by source region, while panel b) displays total exports in the agriculture and manufacturing sectors. Although the trade calibration is not yet finalized, region-specific trade preferences and patterns are already evident. For instance, China and MEA import agricultural goods from distinct mixes of regions, reflecting underlying differences in demand composition. On the export side, both regions are clearly more engaged in manufacturing trade than in agriculture.



To investigate the potential consequences of trade on economic outcomes under climate policy, Figure 20 compares the effects of a carbon tax in two versions of the model: one with trade enabled and one without. Panel a) shows the change in labour allocation across sectors, relative to each model's no-policy baseline¹⁸. The differences are shown in percentage points and remain relatively small in absolute terms. This indicates that while trade modifies the transmission of the carbon price shock across sectors, its effect on domestic sectoral reallocation is modest in these examples. However, there is still variation across sectors and over time, suggesting that trade influences structural adjustment pathways.

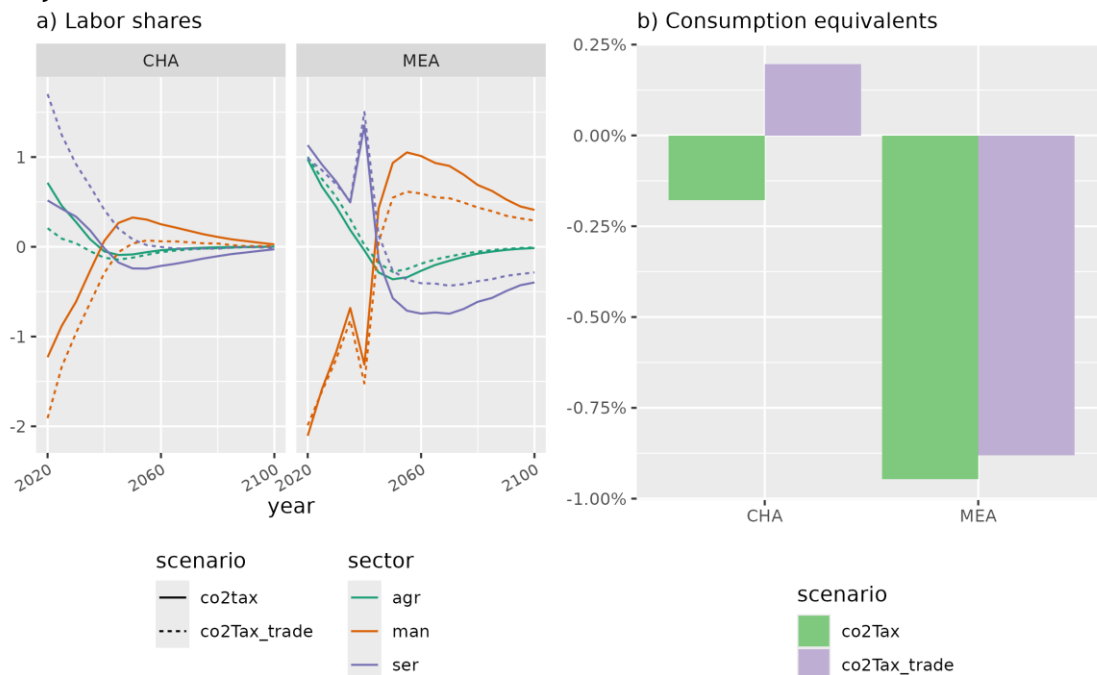


Figure 20. Labor allocation and welfare under a carbon tax with and without trade Panel a) shows changes in labour shares across sectors in China (CHA) and MEA, comparing a carbon tax scenario to each region's baseline, in models with and without trade. Panel b) shows the corresponding welfare impacts, expressed in consumption equivalents.

The welfare impacts of trade, by contrast, appear more substantial. Panel b) of Figure 20 displays consumption-equivalent welfare changes¹⁹ under a carbon tax, again comparing results with and without trade. In both China and MEA, the inclusion of trade changes the welfare outcome significantly. For MEA, the difference is modest, while for China, allowing for trade actually leads to positive welfare effects. This highlights one of trade's key potential roles in the model: as a mechanism for buffering regional adjustment costs, particularly for regions more vulnerable to sectoral or energy system constraints. Even without precise trade cost calibration, this early result already demonstrates how trade can alter the distributional consequences of climate policy.

Taken together, these initial simulations underscore the value of incorporating international trade into multi-sector, multi-region climate-economic models like ours. Even at this stage of development, the trade module introduces meaningful heterogeneity in production and consumption patterns across regions, and affects policy outcomes in ways

¹⁸ In the world with trade, the baseline also has trade enabled. In the world without trade, the baseline does not have trade enabled

¹⁹ The consumption equivalent is the fixed percentage of consumption that would make the household of a region indifferent between two scenarios.



that would be invisible in a closed-economy setup. These early results suggest that trade is a second-order driver of sectoral allocation, but a first-order determinant of regional welfare under policy shocks. These dynamics will be more accurately reflected, as trade elasticities, cost structures, and baseline flows are refined.

6.4.2 Impact of frictions on sectoral allocations, welfare and emissions

To begin exploring the effects of frictions in the model, we simulate a set of scenarios involving sectoral labour and capital adjustment costs, with and without the presence of a CO₂ price²⁰. While the results presented here are not final, they serve to showcase the kinds of economic dynamics the model can generate and to highlight the potential policy-relevant channels that future refinements may investigate. The figures below focus on two illustrative regions, Sub-Saharan Africa (SSA) and the United States (USA), and track sectoral factor allocations, emissions, and welfare under various scenarios.

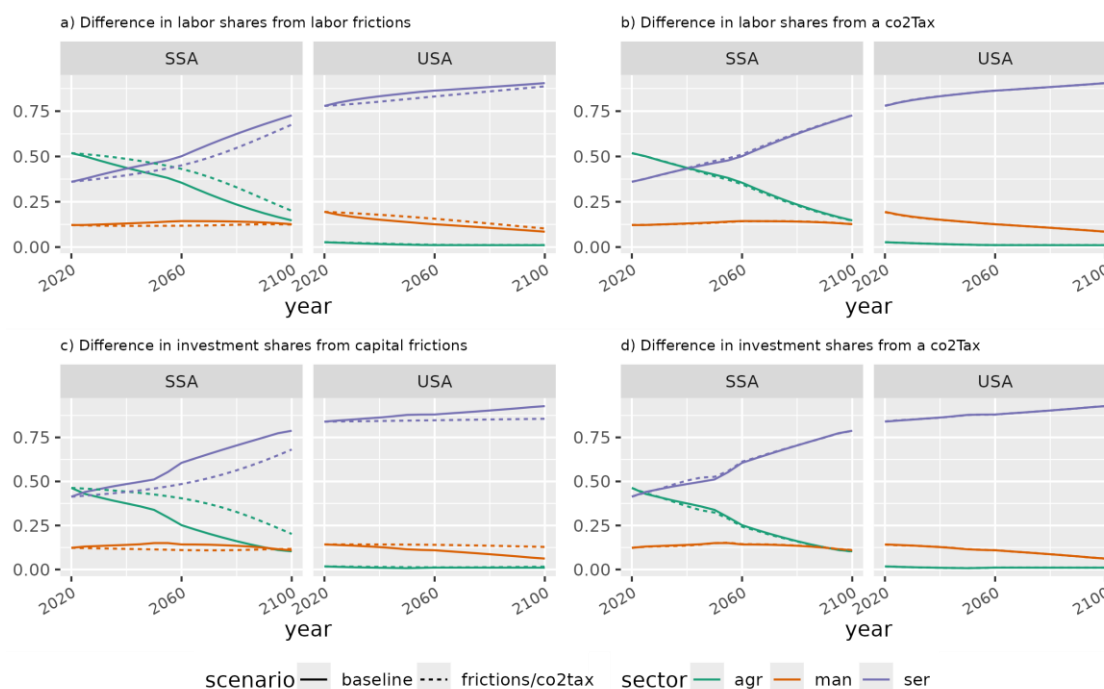


Figure 21. Sectoral labor and investment shares under frictions and carbon pricing scenarios. Panel a) shows the evolution of sectoral labor shares in SSA and the USA, comparing the baseline and a scenario with labor frictions. Panel b) shows labor shares in the baseline and in a scenario with a carbon tax. Panel c) shows investment shares in the baseline and in a scenario with capital frictions. Panel d) shows investment shares in the baseline and in a scenario with a carbon tax.

Figure 21 examines how frictions influence the allocation of labour and capital across agriculture, manufacturing, and services, and how these effects compare with those driven by a co₂ price. Labor shares are affected strongly by labour frictions (Figure 21 panel a), while capital frictions are the dominant force shaping investment shares (Figure 21 panel c). This is consistent with the model's structure: labour frictions directly restrict labour mobility across sectors, while capital frictions impede the smooth reallocation of investment, creating inertia in capital accumulation patterns. Comparing these frictions to the effects

²⁰ Our baseline scenario is an SSP2 scenario with no frictions and no co₂ price.



of a CO₂ price²¹ (Figure 21 panels b and d), we observe an important contrast. While the carbon tax does alter sectoral allocations modestly, especially in SSA, its influence is relatively small compared to that of frictions.

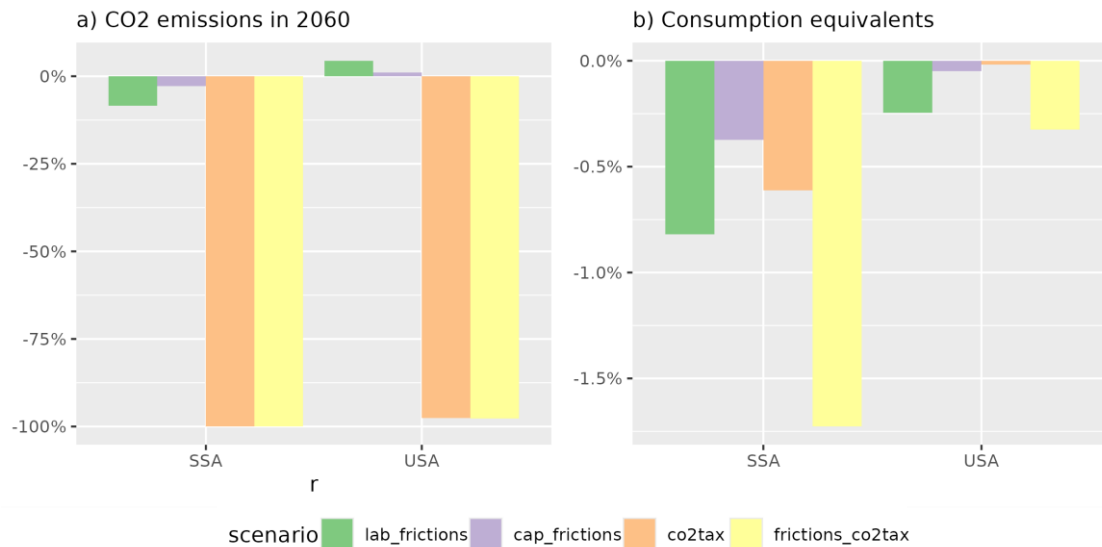


Figure 22. Emissions and welfare under different friction and policy scenarios. Panel a) shows the percentage change in CO₂ emissions in 2060 for SSA and the USA under scenarios with labor frictions, capital frictions, a carbon tax, and their combination, with regards to a baseline scenario with no frictions and no carbon tax. Panel b) shows the corresponding consumption-equivalent welfare changes under the same scenarios.

The reverse is true when looking at emissions in panel (a) in Figure 22: the carbon tax dominates, driving deep emission reductions by 2060 in both SSA and the USA. In contrast, labour and capital frictions on their own have only minor and region-specific effects on emissions, reducing them slightly in SSA, but increasing them marginally in the USA. This suggests that while frictions are key to understanding transitional dynamics and sectoral structure, they are second-order from a mitigation perspective.

Panel b in Figure 22 shows the welfare effects of each scenario in terms of consumption equivalents. These reveal regional heterogeneity in the magnitude of the different channels: For both SSA and the USA, labour frictions generate larger welfare losses than both capital frictions and a co₂ price, however the welfare cost of a carbon tax is lower for the USA than for SSA, underscoring the uneven distribution of climate policy burdens²². When labour and capital frictions are combined with a carbon tax, the resulting overall welfare loss is very close to, but not exactly equal to, the sum of the individual effects. Interestingly, for SSA, the combined effect is slightly higher than the cumulated sum, while for the USA, it is slightly less. This nonlinearity hints at subtle interaction effects that could be explored in the future.

Overall, these early experiments demonstrate the capacity of the model to differentiate between types of frictions and their consequences for structural transformation, emissions, and welfare. The preliminary findings hint at interesting interaction effects with climate policy and important regional differences. Further model development will allow for a richer and more realistic exploration of these dynamics.

²¹ The co₂ price is a global co₂ price—equal for all regions—, implemented as an exogenous tax on co₂ emissions with lump sum transfer to the households. The carbon price pathway is ambitious and consistent with a below 1.5°C warming scenario.

²² Here it is important to note, that the benefits of avoided damages are not included.



6.5 Conclusion

This report has presented key extensions to our multi-sectoral optimal growth model, including the integration of international trade and sector-specific frictions. These features significantly enhance the model's ability to simulate realistic transition dynamics under climate policy, while also allowing for richer analyses of structural change and policy trade-offs.

Preliminary experiments demonstrate that trade has a modest effect on sectoral allocations but a substantial impact on regional welfare, acting as a buffer against asymmetric policy shocks. Sectoral frictions, on the other hand, strongly influence reallocation patterns and welfare outcomes, particularly in lower-income regions that are more dependent on vulnerable sectors. Interestingly, while frictions have a limited effect on emissions directly, they interact with carbon pricing in nontrivial ways, highlighting the need to consider adjustment barriers in mitigation policy design.

These findings underscore the importance of accounting for structural rigidities and global interdependencies in assessing the impacts of climate policy. As the model continues to be refined in terms of calibration, trade cost modelling, and frictions, the insights it generates will support more realistic pathways to global net-zero transitions.

6.6 References

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7. An assessment of different transition pathways to a green global economy

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Transitioning to a green economy is urgently needed to achieve the climate targets by the end of this century. Here we investigate alternative pathways for the transition of the global economy from one dominated by the fossil fuelled (brown) sector to one dominated by the low-emission (green) sector. We modify a well-known integrated assessment model of climate change and economy to consider three transition pathways: Linear, Delayed, and Fast. Our results indicate that the main burden of the green transition lies on capital formation, accumulation, and transfers facilitated by full R&D investment in the green sector's productivity. We also find that transition pathways rely on different mechanisms to achieve their targets. The Delayed pathway relies on the combination of higher green capital investment and an increase in green capital productivity through R&D investment, while the Fast pathway requires substantial transfers of capital from the brown sector coupled with high abatement efforts.

7.1 Introduction

Achieving the United Nations' Sustainable Development Goals (SDGs) and climate targets such as those laid out by the Paris agreement requires a major increase in investments in renewable energy technologies [1], and mitigating emissions from economic activities [2]. Therefore, green industrial policies should aim not only at reducing emissions but also minimizing negative consequences of diverting capital and human resources from fossil-fuelled economic activities [3]. As a result, green growth policies such as the European Green Deal [4] have been explicitly designed to address climate change by decoupling economic growth and fossil-fuel energy consumption [5]. This paper focuses on the issues at the intersection of green transitions, economic growth, and decarbonization. In particular, we are asking “what are the key requirements of green transition pathways in terms of physical and human capital resources?”, “How do research and development (R&D) investments in capital and labour productivity differ across different transition pathways?”, and “How are mitigation efforts impacted by the speed and intensity of the green transition?”. In answering these questions, we show how the transfer of capital and labour between economic sectors can facilitate the green transition and lower the cost of abating greenhouse gas (GHG) emissions in the future.

The green transition requires investment in economic activities and technologies that reduce the dependency on fossil fuels and provide cleaner products or services with lower or no CO₂ emissions [6]. Although possibility of a full decoupling of GDP growth from resource use has been questioned in a series of empirical studies [7], the key premise underlying green growth policies can still be achieved if the green transition also fosters mitigation efforts. Nevertheless, relying solely on renewable energy sources such as solar and wind, despite its appeal [8], has been shown to entail important spatial and temporal mismatches between renewable resource availability and energy demand, which may challenge the reliability of energy systems and hinder the full transition to net-zero emission energy systems [9, 10, 11]. Furthermore, the green transition may not necessarily translate into GHG reductions; there are several socioeconomic and technology-specific factors that may affect the relationship between renewable energy expansion and GHG emissions in long term [12]. Such concerns about the limitations of the green transition have led to a broadening of the concept of the green transition and the recognition of the crucial role of mitigation and carbon dioxide removal in achieving net-zero targets [13, 14]. We build on this evolving field



and consider green transition pathways which include the development and deployment of renewable and low-carbon energy systems, coupled with explicit policies aimed at reducing carbon emissions from both direct and indirect consumption of fossil fuels [15]. Our results indicate a strong coupling between green growth and decarbonization efforts, especially in the Fast transition pathway with high emphasis on early greening of the economy.

As a result, by broadening the implications of the green transition in our framework, we investigate not only investment in clean energy technologies, but also their spillover effect through endogenous technological change on decarbonization methods, as well as the employment opportunities that such a transition may bring about [16]. Empirical evidence has shown that investment in clean technologies coupled with environmental policies and regulations can have positive impacts on overall employment [17] in addition to the reduction of GHG emissions [18]. Furthermore, a systematic review of the literature on the green transition reveals that there is a positive, but relatively small impact from the green transition on net employment and a negative impact on income distribution [19]²³. Our results are in line with such findings, indicating a positive but relatively small impact of green transitions on the green labour share. In contrast, we show that the green transition is mainly driven by capital transfers and green investment decisions.

Another key factor in achieving green growth is technological change driven by R&D investment in physical and human capital productivity and the interactions among the factors controlling such investment decisions [22]. Human capital development has been shown to strengthen R&D capacity [23], while technological progress and education can increase labour productivity [24]. Therefore, R&D investment can be seen as an engine of economic growth and a facilitator of the green transition. In our model, we investigate the critical role of R&D investment allocation decisions in determining the speed and intensity of the green transition and their broader implications for decarbonization. We show that achieving the green transition requires early R&D investment in green sector productivity, with a higher share of such investment directed to enhancing capital productivity as compared to labour productivity.

Integrated assessment models of climate and the economy (IAMs) are widely used for analysing climate change policies and assessing their dynamic costs and benefits. They are built on general equilibrium analysis which aims at capturing the essential dynamics underlying economic activities from production to consumption. These models can be as aggregated and global as the Dynamic Integrated model of Climate and Economy (DICE) model [25] or disaggregated and detailed along different regional (e.g., RICE and RICE50+ models [26]), sectoral (e.g., IMAGE model [27]), and technological (e.g., WITCH [28] and MIND [29] models) dimensions. Regardless of their level of aggregation, one of the key premises of IAMs is that the decision makers such as producers, consumers, and governments, or the central planner in centralised models, are rational welfare-, utility- or profit-maximisers [30]. These models provide a powerful tool in analysing and optimizing climate change policies, assessing their long-term socio-economic and climate impacts, and tracing the mechanisms through which model variables and parameters interact [31]. Nevertheless, there are many critics of IAMs. Compared to input-output models [32], IAMs in general place less emphasis on material and natural resource use and instead, provide more details about technological change. Furthermore, input-output analyses with detailed sectoral and labour market disaggregation, despite often lacking economy-climate feedback loops, can provide valuable insights into how green growth policies can achieve more equitable outcomes [20].

²³ 1Other studies show a trade-off between GHG emission reduction and increases in income inequality and unemployment [20]. It is also worth mentioning that new jobs created as a result of the green transition tend to require higher skills, education, and job training than conventional jobs [21].



What often makes IAMs a preferred choice for policy analysis is their ability to couple climate change dynamics with macroeconomic processes in order to assess the trade-offs between abatement efforts and the economic impacts of climate change. An alternative approach is offered by IAMs built on agent-based macroeconomic frameworks [33]. While these provide a valuable alternative and complement to conventional IAMs, they typically do not allow for the derivation of optimal policies. We believe that adopting a simple IAM framework for the purpose of analysing green transition mechanisms and investigating the trade-offs between transition pathways and optimal mitigation efforts would be more appropriate and useful in this context.

A key feature of IAMs is how they model technological change through targeted R&D investment, which determines the rate of reduction in abatement costs and facilitates the green transition [34]. Despite its importance, some of the most prominent IAMs are equipped with a limited or no endogenous mechanism to account for investment in capital and labour productivity, as well as the interplay between R&D investment, technological change, education, and productivity [35, 36]. For example, DICE has been widely used by the U.S. government to estimate the social cost of carbon [37]. One of the key assumptions of this model is that technological change follows an exogenous path which not only defines the economic growth trajectory but also reductions in the marginal cost of abating CO₂ emissions which is the key driver behind the main findings of the DICE model [38]. There have been several attempts to address this limitation by introducing endogenous technical change in a theoretical framework [39] or by including induced innovation in the energy sector in the DICE model [40] or in the RICE model, the regional version of DICE [41].

Other IAMs such as the WITCH model [28] have an explicit module of technological change and innovation diffusion through R&D investment and learning-by-doing [42]. In the MIND model [29], technological change is endogenized in two parallel fashions: R&D investments, which affect labour productivity and energy efficiency, and learning-by-doing, which affects the cost of renewable energy investments. The results show that these features can reduce abatement costs substantially. They also underline the importance of learning and inertia, which result in smoother abatement with substantially higher early investment efforts [43]. We build on these studies, and apply an endogenous model of abatement cost which depends on productivity growth induced by R&D investment. However, there is no clear best approach emerging from the literature for modelling endogenous technological change [34].

Finally, while a growing body of literature studies technological change through R&D investment [44], there has been less effort to account for endogenized human capital development and labour productivity in IAM frameworks. Here, we aim to fill this gap by decomposing the DICE model into two economic sectors and (a) endogenizing the effect of learning-by-doing on abatement cost, (b) endogenizing the effect of R&D investment on capital productivity, and (c) endogenizing the effect of R&D investment on labour productivity. The results of these improvements to the original DICE model highlight a distinct but less-discussed transition mechanism: early R&D investment in green capital productivity coupled with a steady flow of capital from the brown to the green sector guarantees the growth of the green sector. On the other hand, labour productivity growth and labour transfers play a less prominent role in shaping the green transition. The overall pattern of the results is shown to be robust to changes in transfer cost.

7.2 Results

7.2.1 Modelling the green transition

As in the 2016 version of DICE, our model is a finite horizon dynamic model with 60 time periods (300 years). It includes a representative agent model of the economy with



endogenous technological growth. We assume a two-sector economy including green and brown industries. The transition to a green economy is modelled as a growing share of green output in the composite final consumption good.

In each period (5 years), the central planner decides on how to divide an existing capital stock and labour force between the two economic sectors through transfers. Capital²⁴ and labour are the inputs of the aggregate production function in each sector. The productivity of capital and labour is determined by allocating a share of total R&D investment to each factor in each sector. Similarly to the original DICE model, the abatement rate is another decision variable, which controls the amount of carbon emissions in both sectors²⁵. Furthermore, the marginal abatement cost declines endogenously over time as capital and labour productivity increase through R&D investment.

Emissions accumulate in the atmosphere over time and a portion of the atmospheric carbon stock sinks into the ocean. Radiative forcing - the difference between incoming short-wave radiation and outgoing long-wave energy (heat) - is a function of the atmospheric carbon stock, while global temperature is a function of radiative forcing and past temperatures. The economic and climate models are linked through a damage function. An increase in the global mean temperature reduces net economic output in each sector through sector-specific damage functions. Damage functions such as the one used in the DICE model are intended to represent aggregate climate change damages. Alternatively, one can account for the effects of temperature on different parts of economic production separately [47]. This includes climate change impacts on population dynamics [48], labour markets [49], as well as capital stocks and financial systems [50, 51]. In order to be able to compare our results with the benchmark provided by the DICE model, we keep the sectoral damage functions similar to the aggregate one used in the DICE model. These damages can be avoided by (a) fostering the green transition through the expansion of the green sector and allocating a greater share of economic output to low-carbon green products, and (b) increasing abatement measures to reduce emissions from economic activities in both sectors. However, in our modelling framework the first mechanism is an exogenous assumption (represented by the assumed transition pathways), while the second mechanism is a decision variable (see 'Methods' for detailed description of the model, equations, and the calibration).

We analyse the green transition through 3 representative pathways and compare them to the Baseline pathway with a constant share of green output in the composite final consumption good. Table 7 presents these 3 transition pathways along with the Baseline pathway and their characteristics (see 'Methods' for more detailed descriptions of these transition pathways).

²⁴We have not included natural capital in our model. Some studies have shown that considering the use and non-use value of natural capital can have large implications for climate policy [45, 46].

²⁵ As discussed in 'Methods', we assume that economic activities in the green sector have a lower emission intensity than those in the brown sector.



Table 7. Three transition pathways and the Baseline pathway

Pathway	Shape	Green consumption share		
		2010	2050	2100
Baseline	—	20%	20%	20%
Linear	/	20%	49%	90%
Delayed	⌋	20%	20%	90%
Fast	⌋	20%	90%	90%

The model's central planner aims to generate the maximum utility from composite consumption over the modelling time horizon given a fixed discount rate. As a result of this dynamic optimization, at each time period one can calculate the optimal abatement rate in each sector, the optimal share of output allocated to capital formation in the next period in each sector, the optimal share of capital and labour transferred between the two sectors, and the optimal share of R&D invested in capital and labour productivity in each sector.

Figure 23 shows a schematic diagram of the modified DICE model (see 'Methods' for details). It is worth mentioning that, following the original DICE model, the proposed framework does not include material resources dynamics. Therefore, the results presented here should be treated with caution as they do not consider issues pertaining to material decoupling in the green sector.

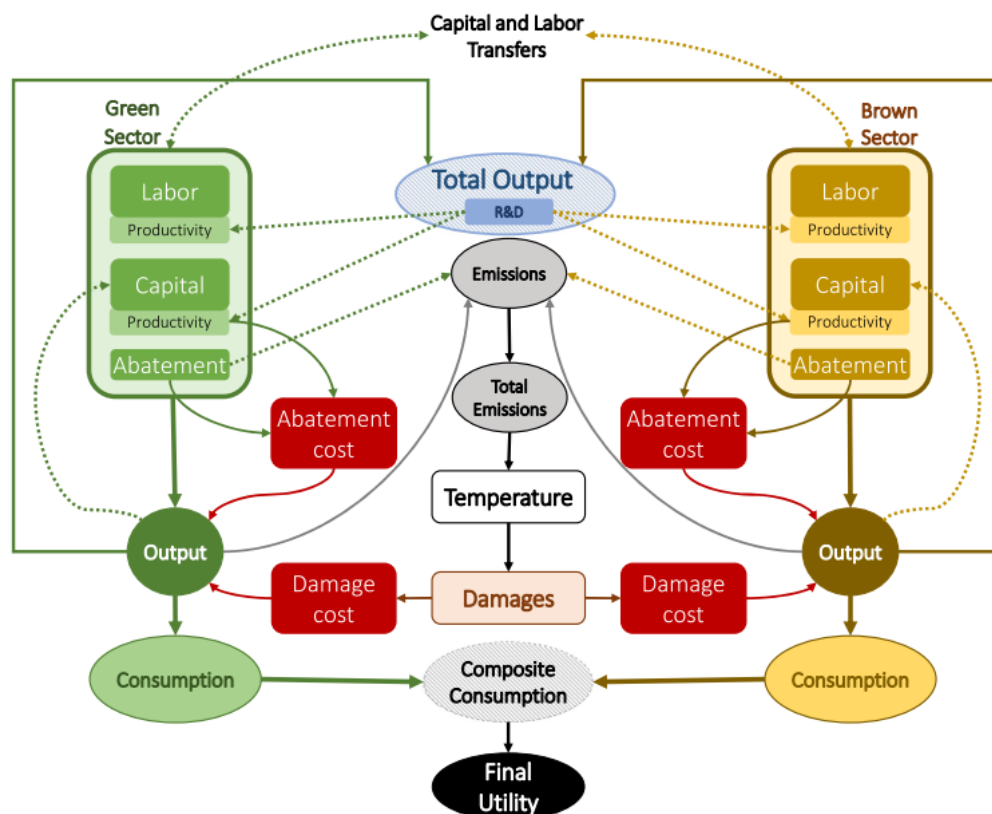


Figure 23. Schematic overview of the 2-sector DICE model. Continuous lines depict relationships between variables while the dashed lines represent the 11 decision variables defining the action space



7.2.2 Assessment of transition pathways

In this section we present the results of three scenarios of future green growth (i.e., three green transition pathways) as described in Table 7 and shown in Figure 24a. The first set, labelled as Baseline, indicates a case where the share of the green good in total consumption is kept at its current level of about 20% until the end of the century. In the Linear case, this share increases constantly to reach 90% by 2100. In the Delayed case, on the other hand, green growth is kept at zero during the first half of the century, but it picks up speed linearly in the second half until it reaches 90% by 2100. Finally, in the Fast case, the consumption share of the green sector grows fast initially to reach 90% by 2050 and subsequently remains at that level until 2100. It is important to note that green transition pathways are green growth trajectories which are concerned with the share of green output in the composite final consumption good. They do not necessarily translate into climate objectives such as the net-zero targets, as the climate implications of each pathway depend not only on the growth of the green sector but also on the stringency of abatement efforts.

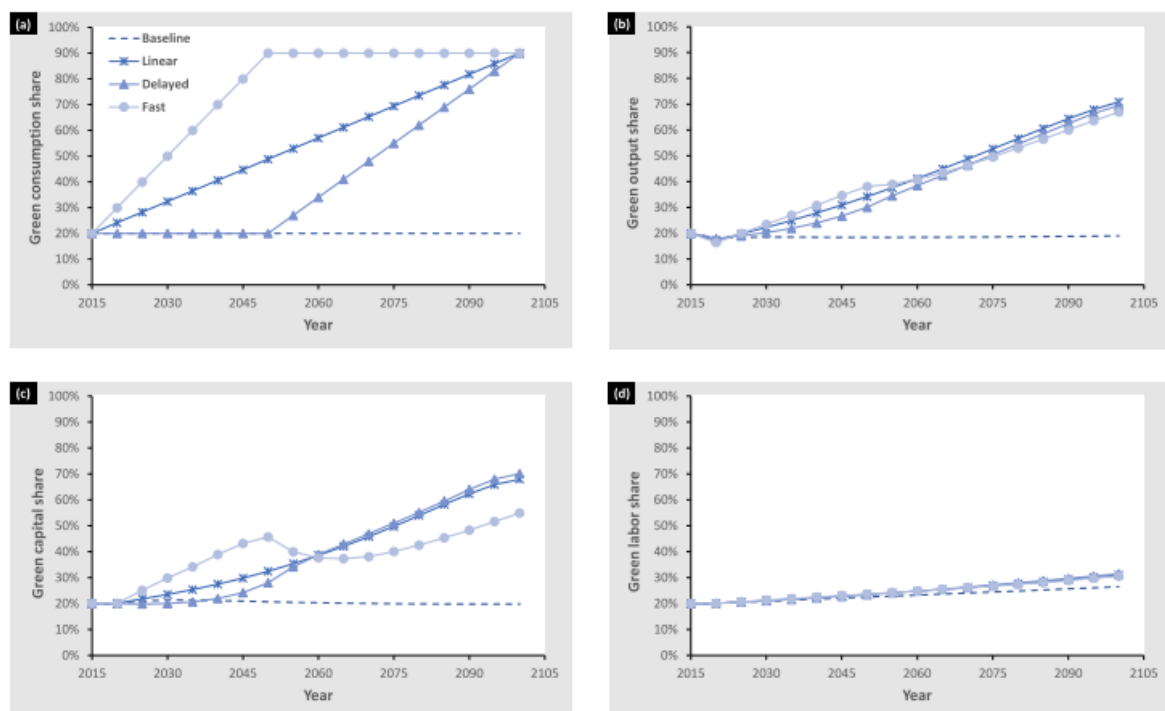


Figure 24. Green growth transition pathways and their consequences. (a) Share of the green consumption good in composite consumption, (b) Share of green output in total output, (c) share of green capital in total capital input, and (d) share of green labor in total labor input.

Figure 24b shows the share of green output in total output under each transition path. Comparing different pathways for green output growth in this panel reveals that they all share a similar increasing trend starting from 20% in 2015 and growing slowly up to about 70% in 2100. The difference between output growth under different pathways, especially between the Delayed and Fast pathways is similar to but less profound than those reported in Figure 24a. This is chiefly due to two factors: a modelling assumption and an optimization result. While the green and brown outputs are linearly combined to generate total output, the final consumption good is a constant elasticity of substitution (CES) function of green and brown output, with their shares following the trends shown in Figure 24a. On the other hand, the magnitude of (green and brown) output which is consumed is derived from production and what is saved and invested in capital formation in the next period. Therefore,

the choice of saving rate (i.e., the portion of output which is not consumed but invested in capital formation) can also affect the transformation of output into consumption patterns.

Transitioning to a green economy requires the expansion of green capital and green labour markets. Figure 24c and 21d, show the shares of capital and labour inputs dedicated to the green sector. While the labour share grows slowly and more homogeneously across the pathways, the green capital share follows the consumption patterns of Figure 24a. As noted above, this again reinforces our conjecture that capital formation dynamics (i.e., capital formation, accumulation, and transfer) are the main drivers of the green transition.

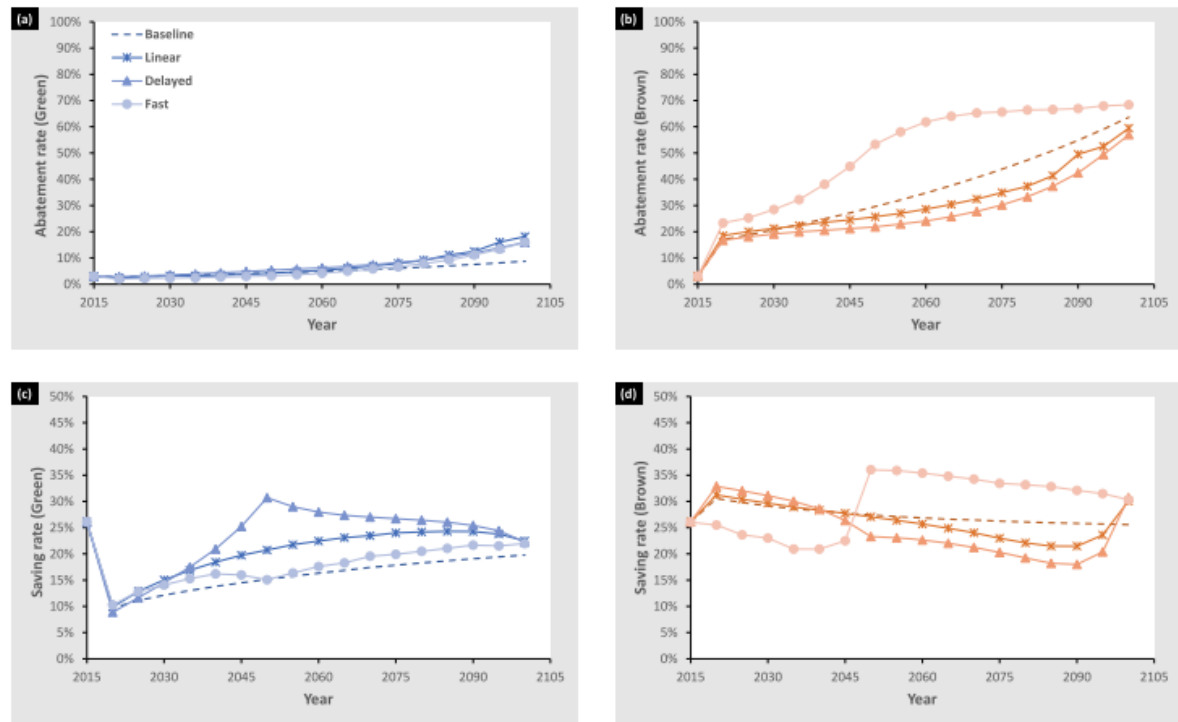


Figure 25. (3) Key drivers of the transition pathways. a Abatement rate in the green sector, (b) abatement rate in the brown sector, (c) saving rate in the green sector, and (d) saving rate in the brown sector.

The green transition will also require a substantial decarbonization of the economy, especially in the brown sector. Figure 25a and 22b show the optimal abatement rates under the three pathways compared to the Baseline case for the green and brown sectors, respectively. By definition, the emission intensity of the green output is much lower than the brown sector. Nevertheless, both sectors are required to undergo some varying degrees of decarbonization depending on the pathways. In both sectors however, the Fast pathway entails higher abatement rates. This difference is more pronounced in the brown sector where under the Fast pathway, the abatement rate reaches about 70% by the end of the century.

Saving rates, by contrast, demonstrate smaller but nevertheless noticeable fluctuations across the pathways in both sectors. Most notable is the optimal saving rate behaviour under the Delayed pathway in the green sector. In this case, the saving rate increases in the first half of the century when the green transition is stalled, in anticipation of the rapid expansion of green consumption in the second half of the century. Another interesting behaviour can be observed under the Fast pathway in the brown sector, where falling saving rates imply that much of the brown capital has already been transferred to the green sector. This is indeed a core feature of our model, which allows for the transfer of production factors (i.e.,

capital and labour) from one sector to another at a cost. The optimal transfers of capital and labour between the two sectors are demonstrated in Figure 26.

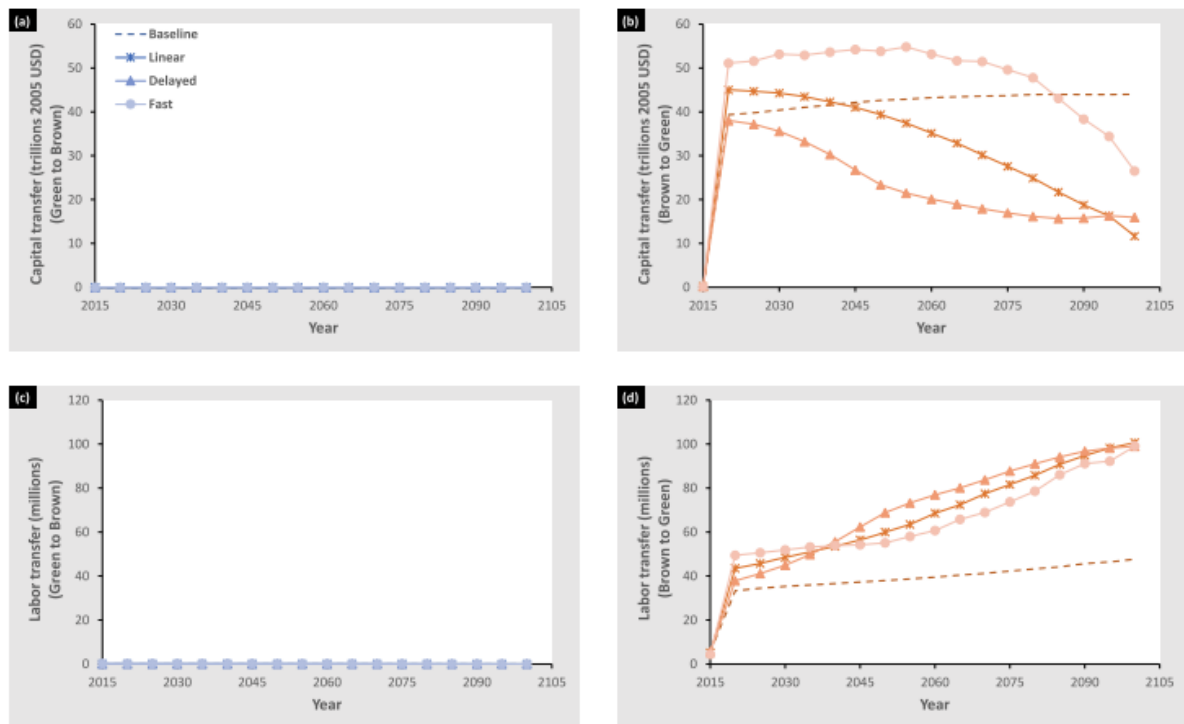


Figure 26. (4) Capital and labour transfers under different transition pathways. a Capital transfers from the green to the brown sector, (b) capital transfers from the brown to the green sector, (c) labour transfers from the green to the brown sector, and (d) labour transfers from the brown to the green sector.

As shown in Figure 26a and 26c, there is no transfer of capital or labour from the green to the brown sector. On the contrary, green transitioning under any pathway, and even the Baseline case without a transition requires some transfer of capital and labour from the brown to the green sector. Panel 4b shows the capital transfer from the brown to the green sector. While the capital transfer is initially the highest under the Fast pathway, it decreases towards the end of the century. This is due to the fact that after initial rapid growth of the green sector, the green sector stabilizes in the second half of the century, reducing its dependency on new capital transfers from the brown sector. The decrease in capital transfers under the Delayed pathway however, is linked to rising saving rates in the green sector which makes it easier for the green sector to accumulate capital endogenously while reducing its dependency on acquired capital from the brown sector. The labour transfer patterns in Figure 26d, on the other hand, appear to follow the overall patterns of the pathways; the Fast pathway requires more labour transfers in the first few decades of the century while the transfers are higher in the second half of the century under the Delayed pathway. Transfer costs (as a share of total sectoral output) along with abatement and climate damage costs are presented in Figure 30, while sectoral economic outputs (gross and net) are shown in Figure 31.

Although the combination of transfers and saving rate results can provide information about the underlying mechanisms driving the green transition in each pathway, their contribution is incomplete without considering the central role of productivity growth and R&D investments which makes the transition possible. Figure 27 depicts the optimal allocation of R&D output to capital and labour productivity in each sector. As shown in Figure 27a and 27c, all transition pathways, regardless of their speed, require a full allocation of

R&D output to green sector productivity. The only exception is observed during the early stages of the Delayed pathway where some R&D output is allocated to the brown sector's capital and labour productivity (Figure 27b and 27d). These allocations, however, are short-lived with a declining trend which goes to zero by 2040. As a result, the green sector enjoys a boost in productivity which helps it achieve the 90% targeted share of total consumption by the end of the century. As shown in Figure 32, the result of heavy R&D investment in the green sector is (a) larger productivity of capital and labour in this sector compared to the brown sector, and (b) higher productivity of green capital than green labour. The combination of these factors, helps increase the share of green output in accordance with transition pathways.

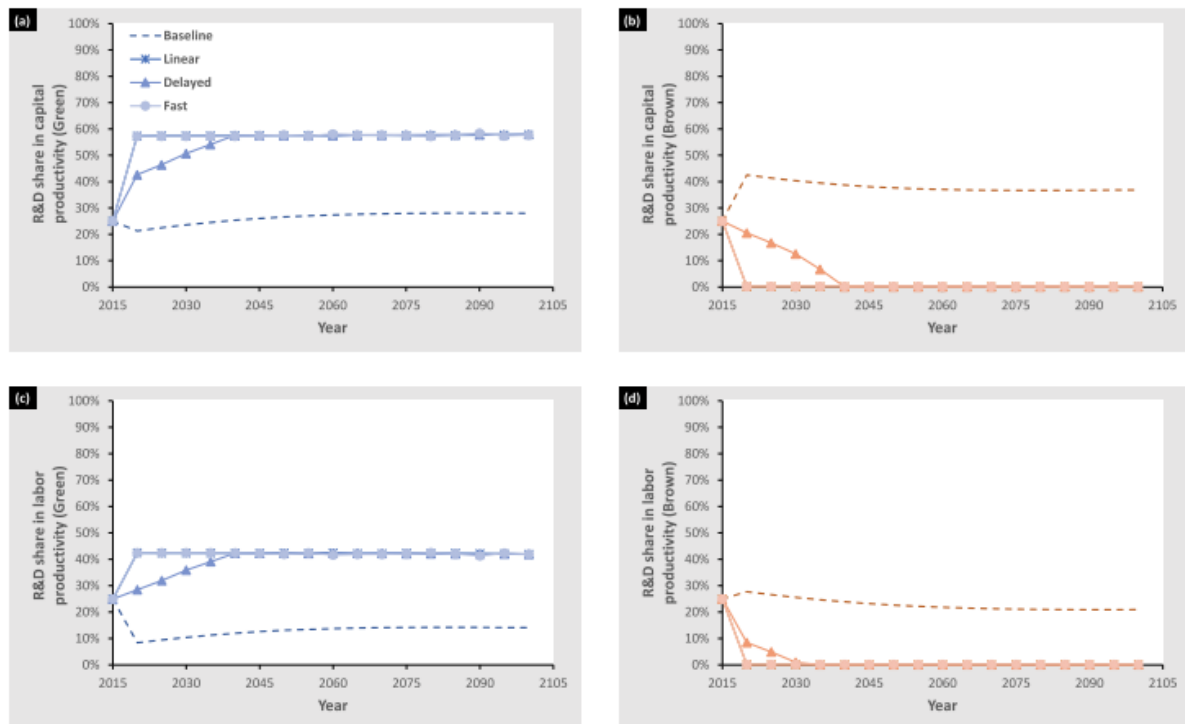


Figure 27. (5) Share of R& D allocated to each sector. a Share of R& D allocated to capital productivity in the green sector, (b) Share of R& D allocated to capital productivity in the brown sector, (c) Share of R& D allocated to labour productivity in the green sector, and (d) Share of R& D allocated to labour productivity in the brown sector.

The magnitude of transfer flows depends not only on the policy forces driving each pathway, but also on the unit cost of transferring capital and labour between the two sectors. Supplementary Note 1 describes a sensitivity analysis of transfer costs. As expected, lowering the transfer cost of a production factor (Figure 33) facilitates the transfer of larger quantities of it from the brown to the green sector. As shown in Figure 34, lowering labour transfer cost, in particular, not only increases labour transfers from the brown to the green sector, but also reduces the need for capital transfer to the point that no capital will move from the brown to the green sector by the end of the century. Despite the adverse effects of lowering transfer cost for one factor on the other factor's transfer quantities, the overall transfer patterns and optimal saving rates (Figure 35) across different transfer cost scenarios remain unchanged.

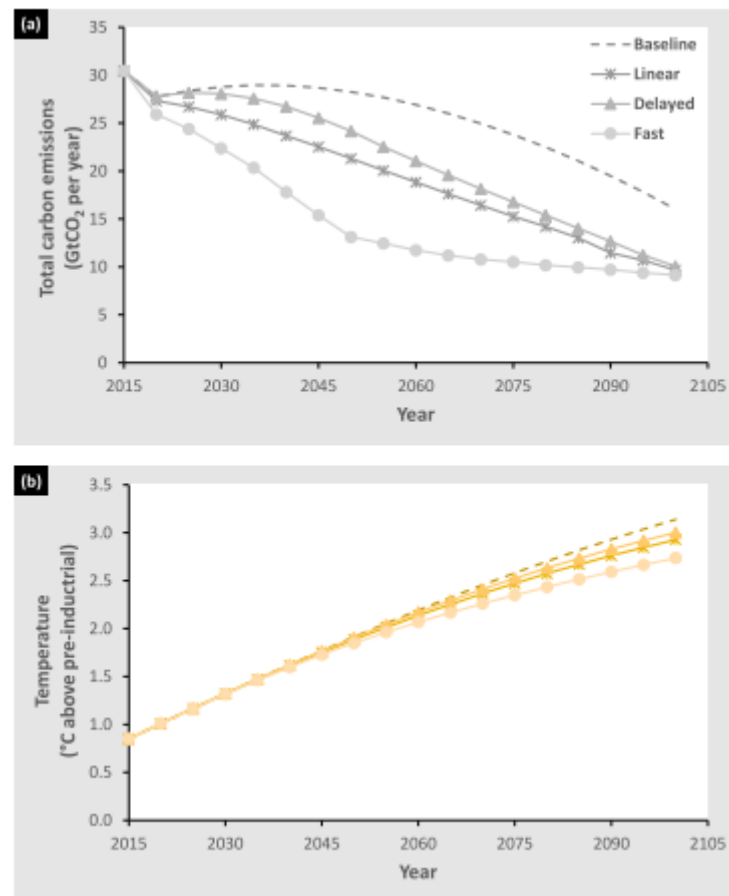


Figure 28. (a) Climate indicators in the transition cases. a Total carbon emissions, and (b) atmospheric temperature change compared to pre-industrial levels.

Finally, we can compare the transition pathways in terms of their broader impact on climate change indicators. Figure 28a displays total carbon emissions. Early investment in the green sector under the Fast pathway manifests itself in lower levels of carbon emissions which stabilize in the second half of the century. After an initial upward trajectory, emissions under the Delayed pathway follow a decreasing trend throughout the rest of the century. A similar trajectory (but without the initial rise) can be observed under the Linear pathway.

The overall impact of the different emission trajectories on atmospheric temperature change is less profound, but nevertheless important, as shown in Figure 28b. The end-of-century atmospheric temperature change reaches 3.1 °C in the Delayed case while it stays just below 2.7 °C in the Fast transition case.

7.3 Conclusion

In this paper we develop an IAM framework to study different green transition pathways (Linear, Delayed, and Fast) and compare them to a Baseline case with no green transition. We decompose the economy into two sectors, namely green and brown, which respectively represent renewable-based and fossil fuel-based economic activities. We investigate the implications of each transition pathway for decarbonization efforts in terms of R&D investment in productivity improvements, capital and labour market transfers, and endogenous technological change.



The results of our analysis highlight some important policy insights for the green transition. First, comparing the trends in labour and capital markets, the results suggest that the main burden of the green transition lies on capital formation, accumulation, and transfer. While the green sector's labour input share increases modestly in all pathways, its capital input share grows dramatically and almost triples by the end of the century driven by the high capital intensity of low- and zero-carbon technologies. However, it is important to note that there are preexisting modelling assumptions and biases that may have contributed to such outcomes. For example, the specific choice of the production function with a higher capital share in the original DICE model underscores the role of capital in the green transition which translates into an increasing trend of saving and endogenous investment in the green sector.

Second, transition pathways appear to rely on different mechanisms to achieve their targets. Under the Fast transition pathway, the rapid growth of the green sector in the first half of the century is mainly accomplished through large transfers of capital from the brown to the green sector. In the Delayed transition pathway however, green capital is accumulated through increased saving rates in the green sector in the first half of the century and is maintained at a high level during the rapid expansion of the green sector throughout the second half of the century. Capital transfer from the brown to the green sector in this pathway, on the other hand, reduces over time, indicating a higher reliance on endogenous capital formation rather than converted capital acquisition. This can further be confirmed by considering the R&D allocations shown in Figure 5, where the R&D investment share in the green sector is low at the beginning, justifying the need to initially transfer some capital from the brown sector. As investment in R&D increases over the first few decades under the Delayed transition pathway, green capital becomes more productive, reducing the need for transferring capital from the less productive brown sector.

This leads us to our third finding, which concerns the transition speed. While the abatement rate in the green sector grows steadily but slowly, decarbonization of the brown sector follows the underlying trajectory of the transition pathways and reaches its highest peak under the Fast transition pathway. This is an interesting consequence of our earlier conjectures, expressed above. The Fast transition pathway requires massive transfers of capital from the brown to the green sector in a short period of time, before the green sector can grow endogenously and sustainably. In other words, the Fast transition implies, quite paradoxically, heavy reliance on the brown sector. As a result and to limit the consequences of relying on the dirty sector, abatement in the brown sector needs to increase rapidly under the Fast transition pathway to limit potential climate change damages. Consequently, the rapid growth of the abatement rate in the brown sector leads to a sharp decline in total carbon emissions and a 0.5°C reduction in global mean temperature change compared to the Baseline case with a fixed share of green consumption.

Finally, it is worth mentioning that the Linear transition pathway lies somewhere between the Fast and the Delayed transition pathways. As a result, while capital transfers from the brown sector decline gradually, the saving rate of the green sector increases steadily, paving the way for a more sustainable and endogenous way to create and accumulate capital in the green sector. Nevertheless, even the linear growth of the green consumption share still requires full allocation of R&D investment to increase the productivity of capital and labour in this sector, similar to the other two transition pathways. This highlights an important fact about the green transition: regardless of the speed of the transition, greening of the economy requires not only a substantial transfer of resources, especially capital, from the brown to the green sector, but also a full allocation of R&D resources to enhance green capital and green labour productivity.



Besides transfer costs and R&D investment expenditures, a sustainable transition, in reality, would also require broad political support and public acceptance at different levels of society. The model presented in this paper does not distinguish between different skill levels of the workforce, nor does it consider structural differences between the two sectors. Therefore, investigating issues at the intersection of climate change and development such as unemployment, inequality, justice, and up-skilling is beyond the scope of the current paper. A more detailed analysis of abatement options and energy transition methods as well as disaggregated climate change impacts on different parts of the production system would provide a better understanding of the transition risks and their broader implications for the economy. Another limitation of our model as well as the original DICE framework is the exclusion of natural resources from the analysis. This shortcoming should be taken seriously and addressed adequately in future modelling developments. Nevertheless, we hope that the 2-sector framework presented in this paper can be a starting point for future research on the interaction between green transition, human capital development, and endogenous technical change. We also acknowledge the fact that there are deep uncertainties in the climate and economic systems that require careful analysis of key parameters and the sensitivity of the main results to their variations.

7.4 Methods

7.4.1 Summary of Modifications to DICE

Here we briefly summarize our modifications to DICE. The model's time horizon spans over 250 years starting from the year 2015 with 5-year time steps. In this paper we report the truncated results up until the year 2100. Therefore, we assume that the time horizon is $t=\{0, \dots, 17\}$ corresponding to the years from 2015 to 2100 in 5-year increments.

- **Economic sectors:** We divide the economy into two sectors (brown sector, and green sector) with each having a designated stock of labour and capital and each factor having a sector-specific productivity. We deploy a two-factor Cobb-Douglas production function to calculate the output of each sector. Total output is calculated as the sum of sectoral outputs.
- **Labor market:** As in the original DICE model, there is only one type of labour input to the production function. We further distinguish between labour working in green and brown sectors. The division of labour between green and brown sector is controlled through the labour transfer mechanism which is a decision variable determined during the optimization.
- **Capital market:** Similarly, capital transfer decision variables are introduced to the model to regulate the allocation of capital to each sector. We assume that the depreciation rate is fixed for capital in both sectors. Sectoral saving rates are also considered as part of the decision variables.
- **Productivity:** We endogenize productivity growth by modelling R&D output allocation dynamics. R&D output is generated from the fixed investment of 2% of total output in every period. This R&D output is then allocated to each sector's capital and labour productivity using new decision variables representing the allocation share to capital and labour in each sector. As the R&D output share allocated to capital and labour productivity improvements in one sector increases, overall output will grow faster in that sector subsequently.

We model DICE similar to a Markov decision process but without uncertainty. This setup includes a state space, an action space, a transition function, and a reward function.

- **State Space:** The first modification to the DICE model is to replace its single sector economic model with a 2-sector model. Each sector has its own stocks of capital and labour. Therefore, the global climate-economy system can be defined as a state with 13 continuous variables comprising 5 climate variables and 6 economic variables. Among the list of climate variables, T_t^{at} denotes atmospheric



temperature (degrees Celsius above the pre-industrial level), T_t^{oc} is the ocean temperature (degrees Celsius above the pre-industrial level), M_t^{at} is the atmospheric concentration of carbon (Gigatons of Carbon, GtC), M_t^{up} is the concentration in upper ocean layers (GtC), and M_t^{lo} is the concentration in deep ocean layers (GtC). Among the list of economic variables, A_t^b and A_t^g denote the productivity of capital in the brown and green sectors respectively, B_t^b and B_t^g are the productivity of labor in the brown and green sectors respectively, K_t^b and K_t^g are the capital stocks (trillions of 2010 USD) in the brown and green sectors respectively, and finally, L_t^b and L_t^g are the labor stocks (millions of people) in the brown and green sectors respectively. Therefore, we can define the state space as $STATE_t = \{A_t^b, A_t^g, B_t^b, B_t^g, K_t^b, K_t^g, L_t^b, L_t^g, T_t^{at}, T_t^{oc}, M_t^{at}, M_t^{up}, M_t^{lo}\}$.

- **Action Space:** At each time step, the central planner decides the levels of the following variables: abatement rate in each sector (a_t^b and a_t^g), saving rate in each sector (s_t^b and s_t^g), capital transfer rates indicating the share of capital transferred from one sector to another (κ_t^b and κ_t^g), labor transfer rates indicating the share of labor transferred from one sector to another (λ_t^b and λ_t^g), R&D output allocation to capital productivity (r_t , with the corresponding share allocated to labor being given by $(1 - r_t)$), each sector's share of the R&D allocation to capital productivity (ρ_t^b and ρ_t^g), each sector's share of the R&D allocation to labor productivity (η_t^b and η_t^g). Note that $\rho_t^g = 1 - \rho_t^b$ and $\eta_t^g = 1 - \eta_t^b$. Therefore the action space is defined as $ACTION_t = \{a_t^b, a_t^g, s_t^b, s_t^g, \kappa_t^b, \kappa_t^g, \lambda_t^b, \lambda_t^g, r_t, \rho_t^b, \eta_t^b\}$ where every member belongs to the interval $[0,1]$.
- **Transition functions:** The gross output of sector $i \in \{b, g\}$ is calculated from the given level of net capital K_t^i , productivity of capital A_t^i , net labor L_t^i , and productivity of labor B_t^i .

$$\bar{Y}_t^i = (A_t^i \times K_t^i)^{\theta^i} \times (B_t^i \times L_t^i)^{1-\theta^i}, \quad i \in \{b, g\}$$

where θ^i is the output elasticity of capital. Net capital and labor in sector i are calculated from the gross values ($\bar{K}_t^i$ and $\bar{L}_t^i$) net of the transfers to and from sector j :

$$K_t^i = \bar{K}_t^i - \kappa_t^i \times \bar{K}_t^i + \kappa_t^j \times \bar{K}_t^j, \quad i, j \in \{b, g\}$$

$$L_t^i = \bar{L}_t^i - \lambda_t^i \times \bar{L}_t^i + \lambda_t^j \times \bar{L}_t^j, \quad i, j \in \{b, g\}$$

Capital transfer costs (Φ_t^i) and labor transfer costs (Ω_t^i) are assumed to have a polynomial form:

$$\Psi_t^i = \eta_K \times (\kappa_t^i)^{\bar{\eta}_K}, \quad i, j \in \{b, g\}$$

$$\Omega_t^i = \eta_L \times (\lambda_t^i)^{\bar{\eta}_L}, \quad i, j \in \{b, g\}$$

where η_K and η_L are the transfer cost scaling factors, and $\bar{\eta}_K$ and $\bar{\eta}_L$ are the transfer cost exponents. As in the original DICE model, we use exogenous population growth projections to obtain the size of the overall labor force in a period:

$$\bar{L}_{t+1}^i = \bar{L}_t^i \times \frac{L_{t+1}}{L_t}, \quad i \in \{b, g\}$$

where L_t is the exogenous population level at time t from the original DICE model. Total output is calculated as the sum of sectoral outputs, and R&D output (R_t) is a fixed share (d) of this total output:

$$\bar{Y}_t = \sum_i \bar{Y}_t^i, \quad i \in \{b, g\}$$

$$R_t = d \times \bar{Y}_t.$$

Capital and labour productivity in each sector evolve through R&D output share allocation:

$$A_{t+1}^i = (1 + \omega_A^i \times r_t \times \rho_t^i)^{\zeta_A^i} \times A_t^i, \quad i \in \{b, g\}$$

$$B_{t+1}^i = (1 + \omega_B^i \times (1 - r_t) \times \eta_t^i)^{\zeta_B^i} \times B_t^i, \quad i \in \{b, g\}$$

where ω_A^i and ω_B^i are scaling factors, and ζ_A^i and ζ_B^i are exponents of the productivity growth functions. Beside improving the productivity of capital and labor through R&D investment, in this model we depict improvements in the abatement cost factor Δ_t^i through learning-by-doing. The functional form of abatement cost is similar to the original DICE model:

$$\Delta_t^i = \gamma_t \times (a_t^i)^{\bar{\gamma}}, \quad i \in \{b, g\}$$

$$\gamma_t = \gamma_0 \times \left(\frac{A_t^b + A_t^g + B_t^b + B_t^g}{A_0^b + A_0^g + B_0^b + B_0^g} \right)^{-\nu}$$

where γ_0 is the abatement cost coefficient, $\bar{\gamma}$ is the abatement cost exponent, and ν is the exponent of the learning curve. Climate change damage cost in sector i depends on the atmospheric temperature change (T_t^{at}):

$$D_t^i = \xi_1^i \times T_t^{at} + \xi_2^i \times (T_t^{at})^2, \quad i \in \{b, g\}$$

where parameters ξ_1^i and ξ_2^i are the damage cost coefficients specific for sector i . The net output of each sector, Y_t^i , is calculated after subtracting transfer costs (Ψ_t^i and Ω_t^i), abatement cost (Δ_t^i), and climate damage costs (D_t^i):

$$Y_t^i = \bar{Y}_t^i - \Phi_t^i - \Omega_t^i - D_t^i \times \bar{Y}_t^i - \Delta_t^i \times \bar{Y}_t^i, \quad i \in \{b, g\}$$

Total consumption in each sector (C_t^i) is calculated after subtracting saving for investment in future capital:

$$C_t^i = (1 - s_t^i \times Y_t^i), \quad i \in \{b, g\}$$

$$K_{t+1}^i = (1 - \delta) \times K_t^i + s_t^i \times Y_t^i, \quad i \in \{b, g\}$$

where δ is the capital depreciation rate and s_t^i is the saving rate in sector i . Finally, composite consumption is obtained as a CES function of green and brown consumption:

$$C_t = [\alpha_t \times (C_t^b)^{\frac{\epsilon-1}{\epsilon}} + (1 - \alpha_t) \times (C_t^g)^{\frac{\epsilon-1}{\epsilon}}]^{\frac{\epsilon}{\epsilon-1}}$$

where α_t is the share of brown output in the composite final consumption good, and ϵ is the elasticity of substitution between brown and green consumption.

We assume that initially, the production of one unit of green output emits α_0 times less than the emissions arising from the production of one unit of brown output:

$$\sigma_0^g = (1 - \alpha_0) \times \sigma_0^b$$

Total carbon emissions (E_t) therefore consist of sectoral emissions (E_t^i) post-abatement, a_t^i , as well as exogenous sources such as land use change (E_t^{exg}):

$$E_t^i = \sigma_t^i \times \bar{Y}_t^i, \quad i \in \{b, g\}$$

$$E_t = \sum_i (1 - a_t^i) \times E_t^i + E_t^{exg}, \quad i \in \{b, g\}$$

where σ_t^i is the carbon intensity of output in each sector, which declines over time according to an exogenous function similar to the original DICE model.

$$\sigma_{t+1}^i = \sigma_t^i \times e^{g\sigma_t^i \times t}$$

$$g\sigma_{t+1}^i = g\sigma_t^i \times (1 + d\sigma^i)^t$$

where $g\sigma_t^i$ is the growth rate of σ_t^i and $d\sigma^i$ is the decline rate of decarbonization. The atmospheric and oceanic carbon concentrations in the $t + 1$ are given by:

$$M_{t+1}^{at} = E_t + (1 - \phi_{12}) \times M_t^{at} + \phi_{21} \times M_t^{up}$$

$$M_{t+1}^{up} = \phi_{12} \times M_t^{at} + \phi_{22} \times M_t^{up} + \phi_{32} \times M_t^{lo}$$

$$M_{t+1}^{lo} = \phi_{23} \times M_t^{up} + \phi_{33} \times M_t^{lo}$$

where $\phi_{12} \dots \phi_{33}$ are carbon cycle transition coefficients. The equations giving the temperature anomalies in period $t + 1$ are:

$$T_{t+1}^{at} = T_t^{at} + \tau_1 \times \{F_{t+1} - \tau_2 T_t^{at} - \tau_3 \times \{T_t^{at} - T_t^{lo}\}\}$$

$$T_{t+1}^{lo} = T_t^{lo} + \tau_4 \times \{T_t^{at} - T_t^{lo}\}$$

$$F_{t+1} = \tau_2 \times \log_2(M_t^{at}/M_0^{at}) + Fex_t$$

where $\tau_1, \dots, \tau_4$ are temperature coefficients and F_{t+1} is the radiative forcing, where Fex_t is exogenous forcing due to anthropogenic emissions of GHGs other than CO_2 (assumed exogenous in DICE).

•

The reward is calculated as the social utility of consumption at each time step:

$$U_t = L_t \times \left[\frac{(\frac{C_t}{L_t} \times 1000)^{1-\psi} - 1}{1 - \psi} - 1 \right]$$

where ψ is the elasticity of marginal utility of consumption and L_t is the exogenous total population coming from the original DICE model. The objective is to maximize the sum of discounted expected social utilities over the modeling horizon:

$$\max \sum_{t=0}^T \pi^t U_t$$

where π is the discount factor.

7.4.2 Calibration of Parameters in the Modified DICE model

We calibrate the model parameters in order to generate results which are comparable to those arising from the original DICE model. First, we develop a baseline model with two identical sectors (i.e., also assuming that both sectors have the same initial emission



intensity of output ($\sigma_0^g = \sigma_0^b = 0.340$). Each sector is responsible for half of the economic output and, consequently, half of the endogenous emissions. The results of this calibration are presented in Figure 29.

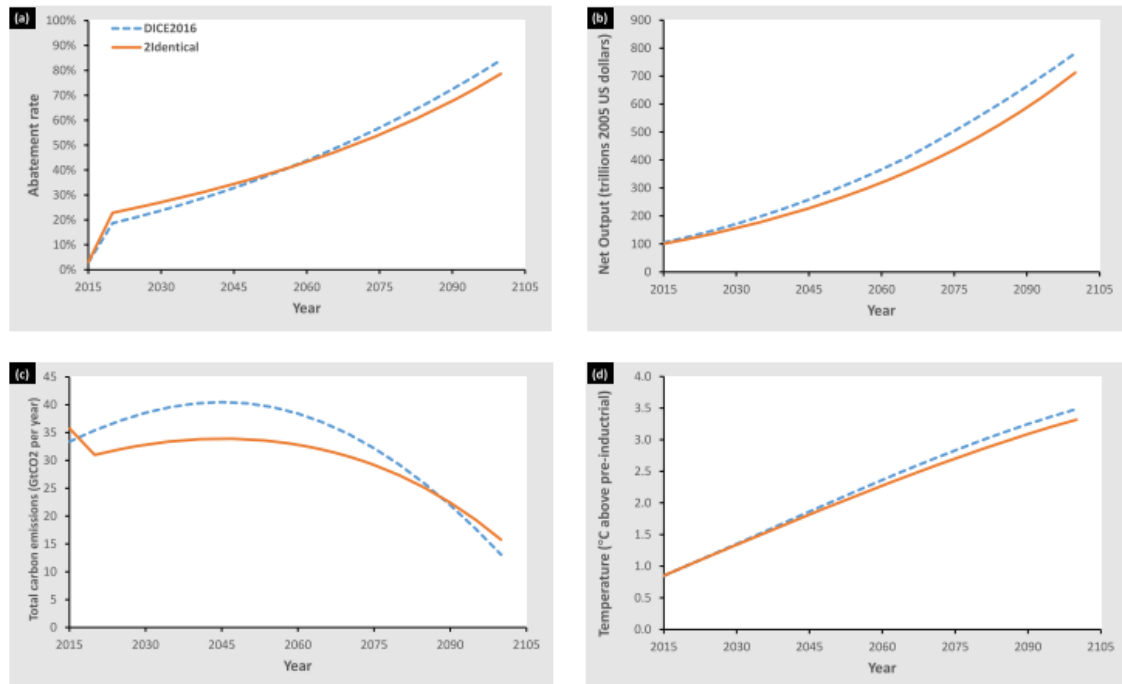


Figure 29. Calibration of the baseline model with two identical sectors based on DICE2016. (a) Abatement rate in percentage, (b) net output, (c) net carbon emissions, and (d) atmospheric temperature change compared to pre-industrial levels.

Beginning from these calibration results, we set the values for the additional parameters in the model. Table 8 lists the key parameters of the model and their values.



Table 8. Key parameters of the 2-sector modified DICE model

Parameter	Description	Value
θ^i	output elasticity of capital (both sectors)	0.3
η_K	capital transfer cost scaling factor	0.001
η_L	labor transfer cost scaling factor	0.001
$\bar{\eta}_K$	capital transfer cost exponent	2
$\bar{\eta}_L$	labor transfer cost exponent	2
d	R&D share of output	0.02
α_0	initial share of brown output in final consumption	0.8
ϵ	elasticity of substitution between consumption goods	0.5
γ_0	abatement cost coefficient	0.1
$\bar{\gamma}$	abatement cost exponent	2.5
ω_A^i	capital productivity scaling factor (both sectors)	$0.5/\alpha_0$
ω_B^i	labor productivity scaling factor (both sectors)	$0.5/\alpha_0$
ζ_A^i	capital productivity exponent (both sectors)	0.5
ζ_B^i	labor productivity exponent (both sectors)	0.2
ξ_1^i	climate change damage cost scaling factor (both sectors)	0.00236
ξ_2^i	climate change damage cost exponent (both sectors)	2
ν	learning rate exponent	0.85
δ	capital depreciation rate	0.1
σ_0^b	initial carbon intensity of brown output	0.340
$g\sigma_0$	initial growth of σ	-0.0152
$d\sigma$	decline rate of decarbonization	-0.001

7.4.3 Green transition pathways

The transition speed to a green economy is controlled by setting a pathway for the share of the brown good in total composite consumption (α_t). We define the four pathways Baseline, Linear, Delayed, and Fast as follows:

- **Baseline pathway:** In this case, the share of green output in composite consumption remains at 20% until 2100:

$$\alpha_t = 0.80, \quad t = \{0, \dots, 17\}$$

- **Linear pathway:** In this case, the share of green output in composite consumption increases from the initial value of 20% in year 2015 to 90% by 2100 in a linear fashion. This translates into a 0.8% annual decrease (or 4.1% decline over every 5-year time step) in the share of brown output:

$$\alpha_t = 0.80 - 0.041 \times t, \quad t = \{0, \dots, 17\}$$

- **Delayed pathway:** In this case, the share of green output in composite consumption remains at 20% until 2050 and then rapidly increases to reach 90% by 2100. This translates into a fixed share of brown output until 2050, followed by a 7% decline over every 5-year time step until 2100:

$$\alpha_t = 0.80 \times t, \quad t = \{0, \dots, 7\}$$

$$\alpha_t = 0.80 - 0.07 \times (t - 7), \quad t = \{8, \dots, 17\}$$

- **Fast pathway:** In this case, the share of green output in composite consumption grows fast up to 90% until 2050 and then remains at 90% until 2100. This translates



into a 10% decline of the brown output share over every 5-year time step until 2050, followed by a fixed share of 10% until 2100:

$$\alpha_t = 0.80 - 0.1 \times t, \quad t = \{0, \dots, 7\}$$

$$\alpha_t = 0.10, \quad t = \{8, \dots, 17\}$$

7.5 Supplementary Material

Transfer costs play a key role in governing the green transition and as a result, changing their assumed values may affect the overall results. In the results presented in the main body of this paper, the values for both capital and labour transfer costs (η_K and η_L , respectively) are assumed equal and they are obtained from the iterative process of calibrating the model with two identical sectors to match the output of the original DICE model. Therefore, it is important to validate the main findings of our model by deviating from this assumption and allowing the capital and labour transfer costs to differ. Here, we define two markedly different scenarios. In the scenario with lower labour transfer cost, we halve the labour transfer cost while keeping the capital transfer cost unchanged (i.e., $\eta_K = 0.001$ and $\eta_L = 0.0005$). Similarly, in the scenario with lower capital transfer cost, we halve the capital transfer cost while keeping the labour transfer cost unchanged (i.e., $\eta_K = 0.0005$ and $\eta_L = 0.001$).

The comparison of the results in terms of capital and labour transfers (from the brown to the green sector) is shown in Figure 34. Despite the adverse effects of lowering the transfer cost for one factor on the other factor's transfer quantities, the overall patterns remain unchanged across different parameter settings. We can further verify this by considering the transfer costs as a portion of gross sectoral output as shown in Figure 33.

Finally, we also investigate the impact of changing transfer costs on optimal saving rates. Here too, although the overall pattern remains unchanged, there are some noticeable exceptions. In particular, saving rates in the green sector are more sensitive to lowering capital transfer costs as shown in Figure 35. In contrast, saving rates in the brown sector show little difference across different parameter settings. In the setting with lower capital transfer cost, for example, saving rates in the green sector are as low as 0% in the initial years. This indicates that cheap capital flows from the brown to the green sector can initially substitute the need for endogenous green investment.



7.5.1 Supplementary Figures

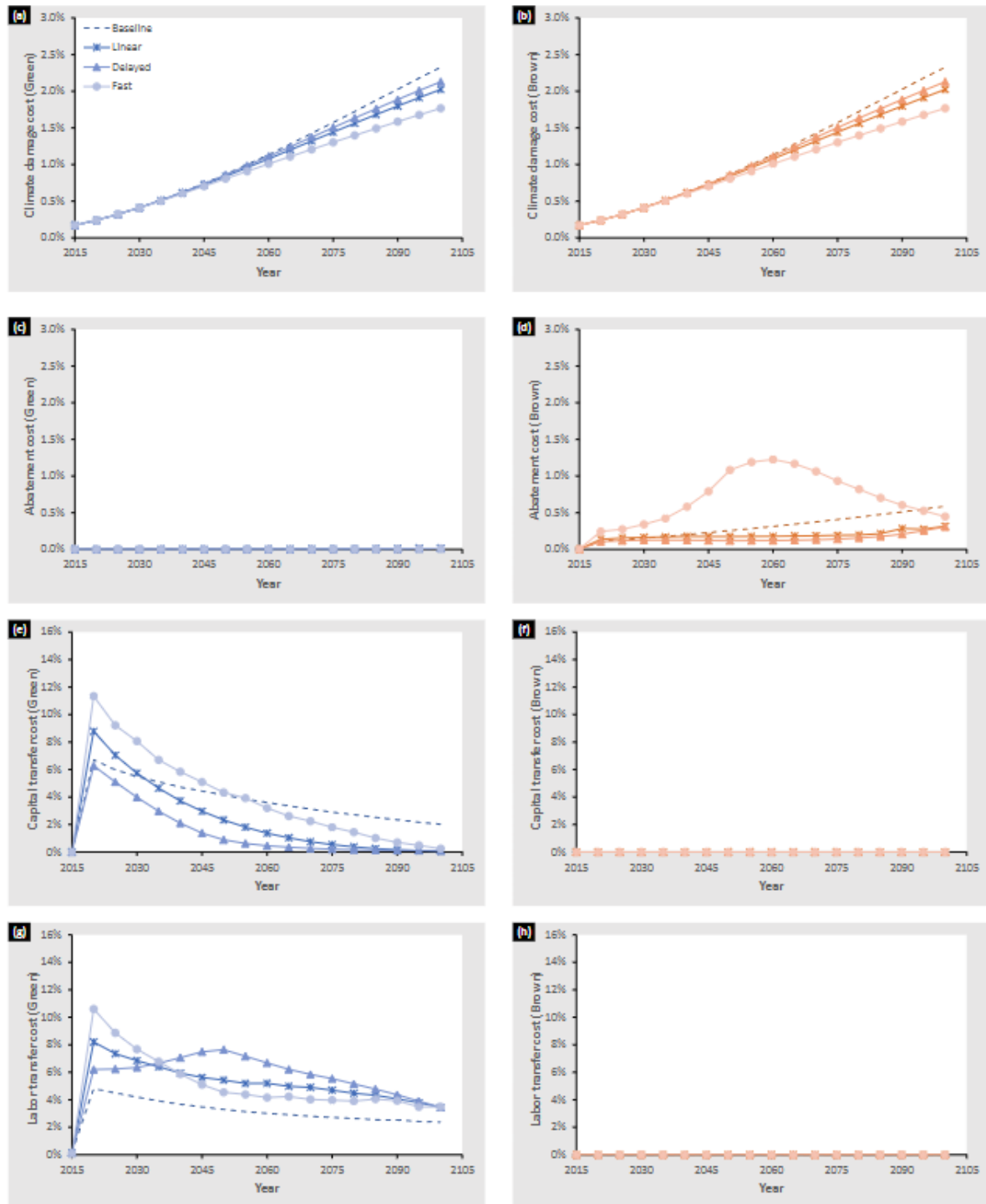


Figure 30. Green transition costs as share of sectoral gross output across different pathways. (a) and (b) Abatement costs, (c) and (d) climate damage costs, (e) and (f) capital transfer costs, and (g) and (h) labour transfer costs.

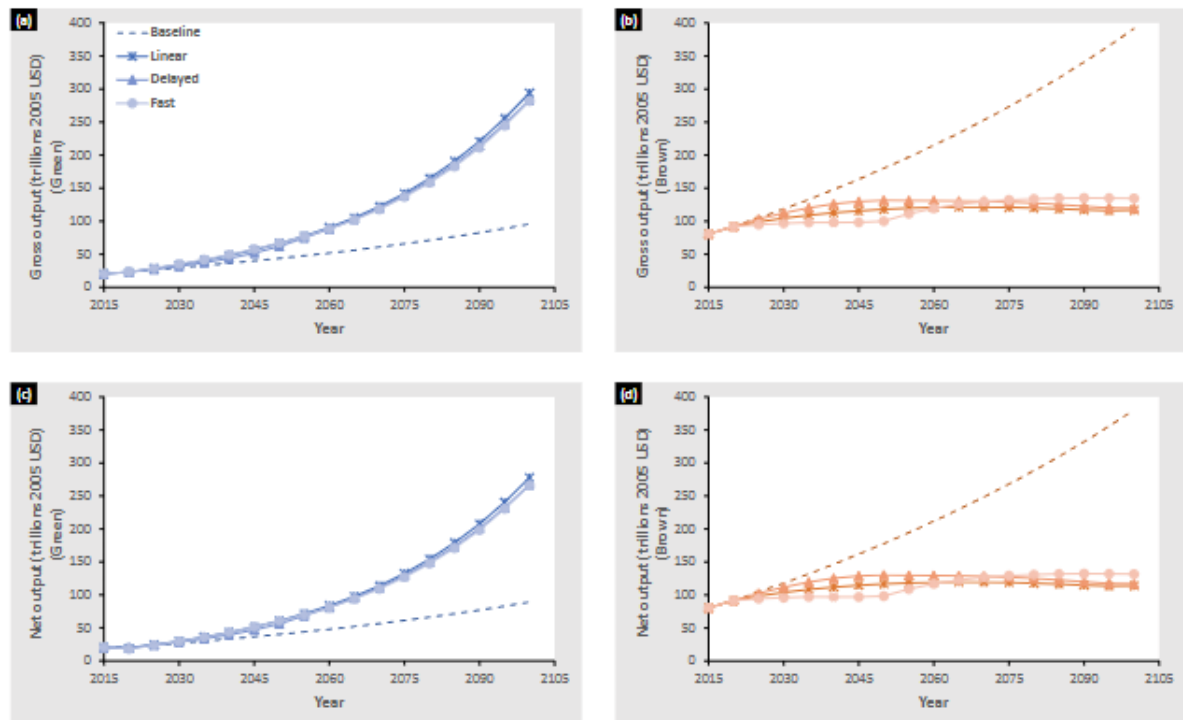


Figure 31. Sectoral output. (a) Gross output in the green sector, (b) gross output in the brown sector, (c) net output in the green sector, and (d) net output in the brown sector.

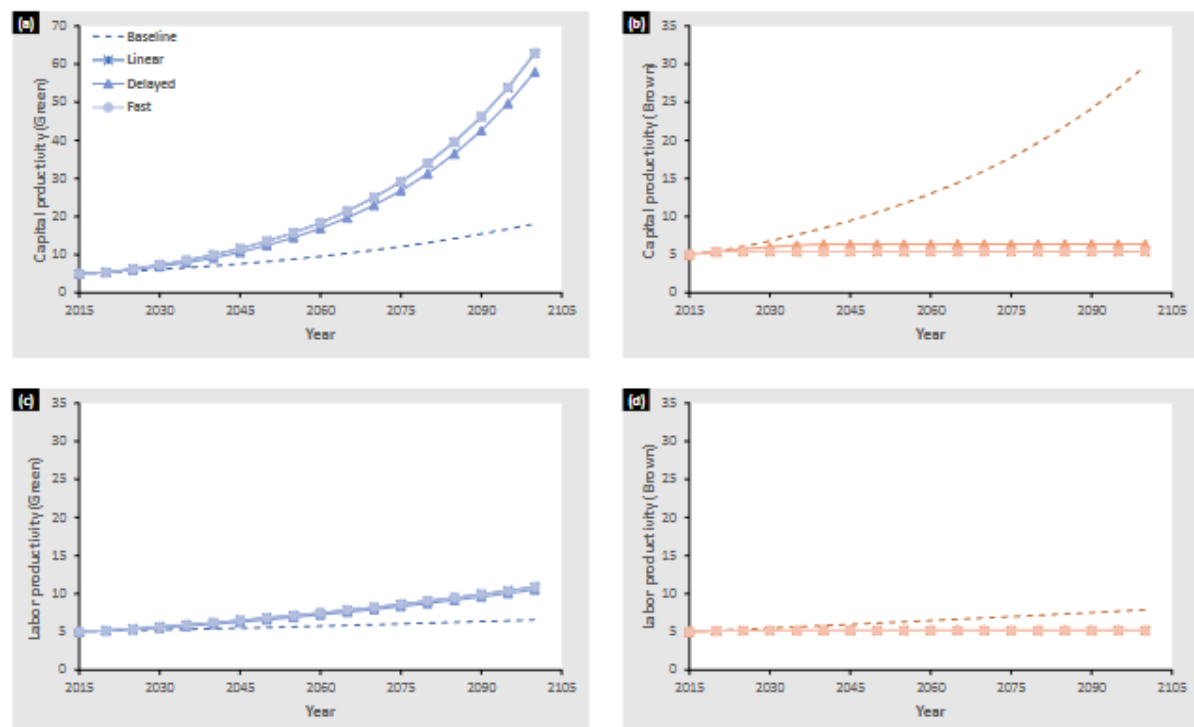


Figure 32. Productivity of capital and labour in each sector. (a) Capital productivity in the green sector, (b) capital productivity in the brown sector, (c) labour productivity in the green sector, and (d) labour productivity in the brown sector.

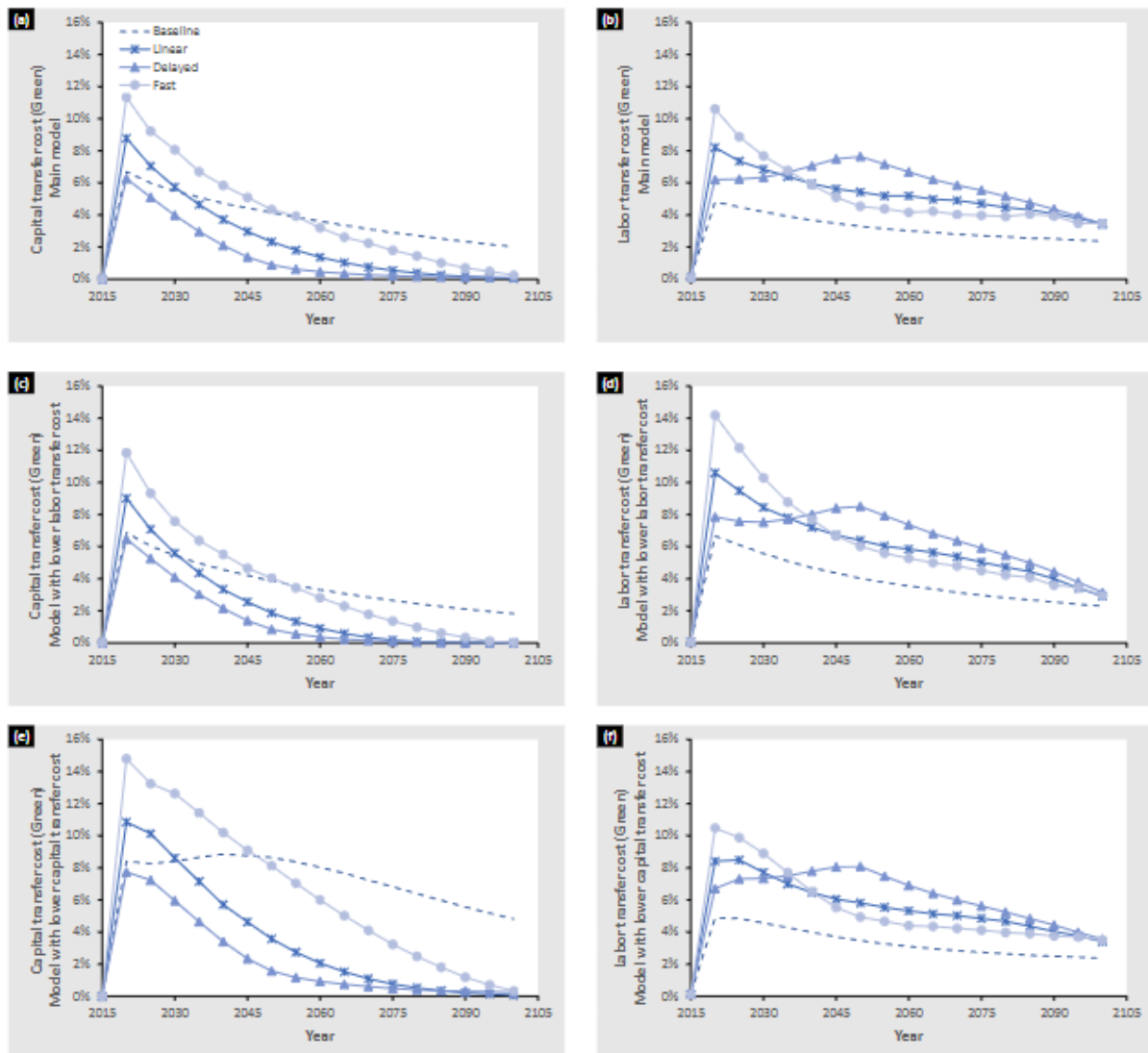


Figure 33. Capital and labour transfer (brown to green) costs as a percentage of gross green output. (a) capital transfer cost in the main model, (b) labour transfer cost in the main model, (c) capital transfer cost in the scenario with lower labour transfer cost, (d) labour transfer cost in the scenario with lower labour transfer cost, (e) capital transfer cost in the scenario with lower capital transfer cost, and (f) labour transfer cost in the scenario with lower capital transfer cost.



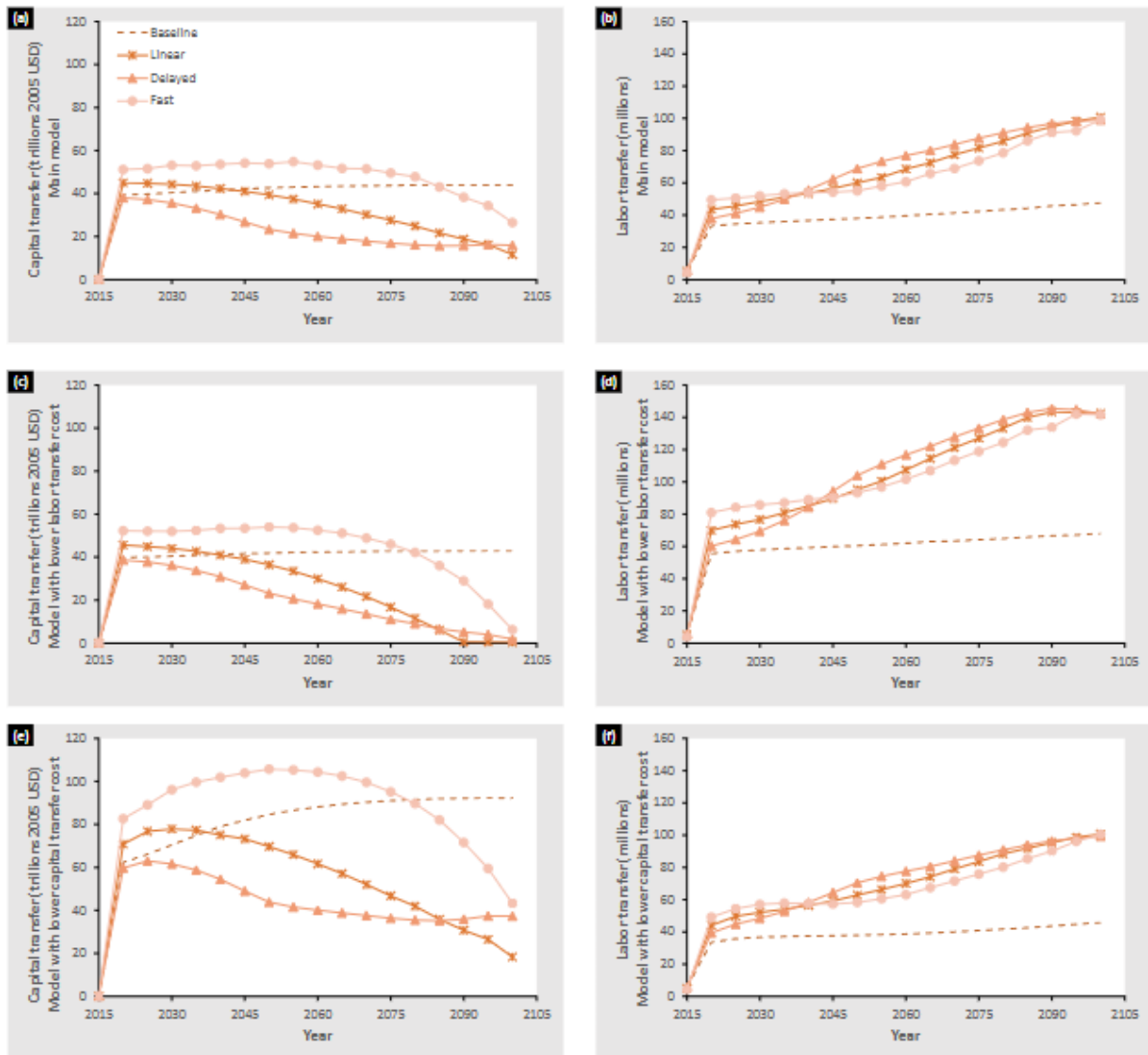


Figure 34. Capital and labour transfers from the brown to the green sector. (a) capital transfer in the main model, (b) labour transfer in the main model, (c) capital transfer in the scenario with lower labour transfer cost, (d) labour transfer in the scenario with lower labour transfer cost, (e) capital transfer in the scenario with lower capital transfer cost, and (f) labour transfer in the scenario with lower capital transfer cost.

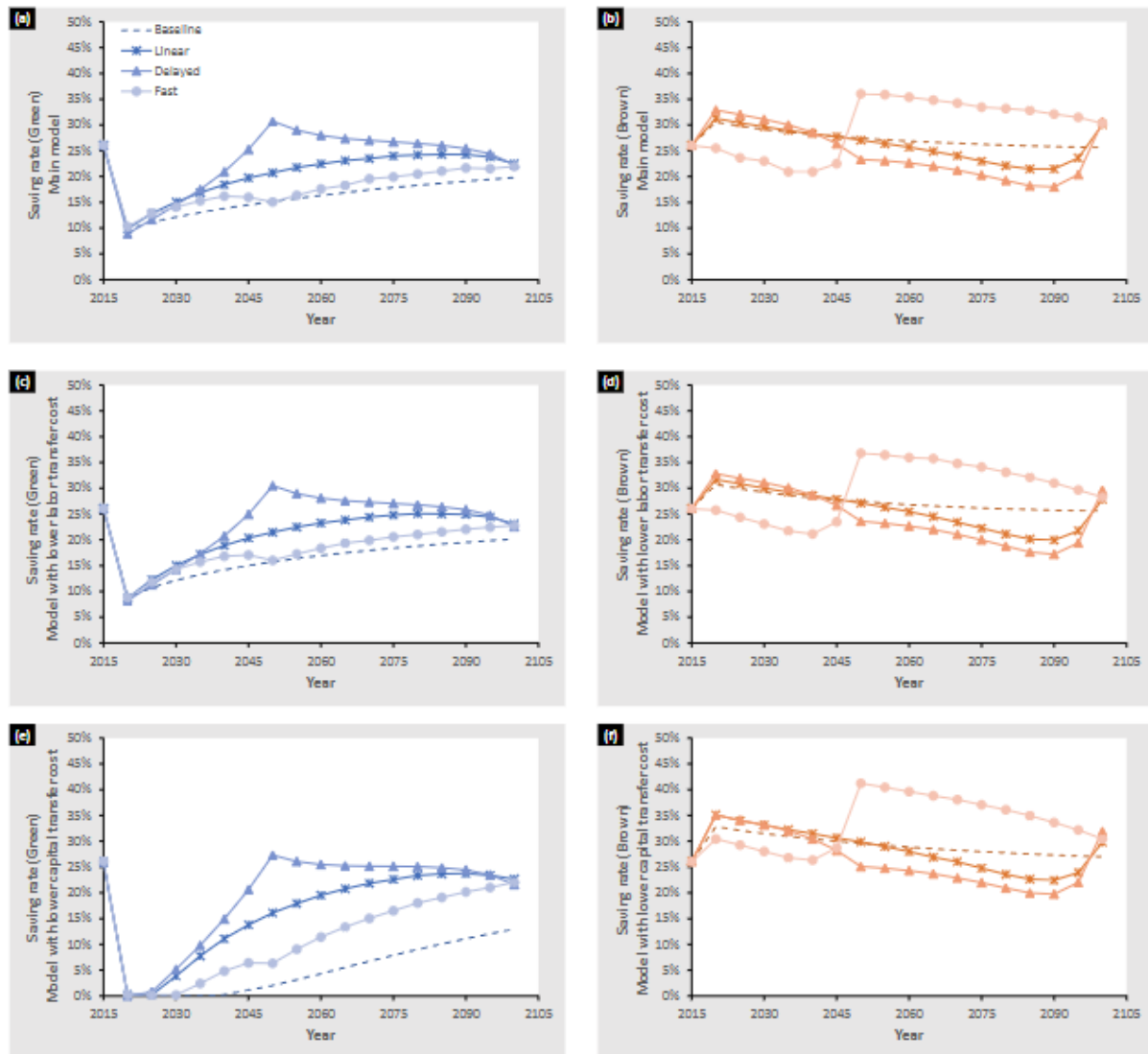


Figure 35. Optimal saving rates (a) in the green sector in the main model, (b) in the brown sector in the main model, (c) in the green sector in the scenario with lower labour transfer cost, (d) in the brown sector in the scenario with lower labour transfer cost, (e) in the green sector in the scenario with lower capital transfer cost, and (f) in the brown sector in the scenario with lower capital transfer cost.

7.6 References

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