PRISM

Net0Pathways through impRoved IAMs across Sectors, diMensions, and scAles

Deliverable 2.3
Report on distributional implications of mitigation pathways

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30 November 2025

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Executive Summary

The European Green Deal and the global commitment to Net Zero demand a rapid and deep transformation across energy, industrial, and societal systems. While this transition is vital for climate stability, it inherently carries significant social and economic consequences. This report, Deliverable 2.3 of the PRISMA project (Net0Pathways through improved IAMs across Sectors, diMensions, and scales), provides a crucial, multi-faceted assessment of the distributional implications of both climate change itself and the aggressive mitigation pathways required to limit global warming. Moving beyond conventional macro-level cost assessments, the analysis specifically examines how climate impacts and corresponding policies are disproportionately distributed across households, income groups, and regions, both within and across countries. The central objective is to significantly enhance the analytical capacity of Integrated Assessment Models (IAMs) to better represent household heterogeneity and resulting inequalities. By addressing this critical blind spot, the report aims to provide policymakers with a robust evidence base for designing Just Transition policies that ensure climate action is both highly effective and socially equitable. The findings are primarily derived from two pioneering published papers (Emmerling et al. 2024; Kulkarni et al. 2025) that integrate detailed inequality metrics into global climate modeling. The research identifies a crucial "double-inequality" dilemma: unmitigated climate change is inherently regressive, and without careful design, many standard mitigation policies are also regressive, disproportionately burdening lower-income groups. Climate change impacts—such as reduced agricultural productivity and extreme weather events—exacerbate global and national inequalities, with the most vulnerable populations suffering the greatest relative losses due to limited resources for adaptation and recovery. Quantification shows that unmitigated warming significantly widens the income gap globally and domestically. Mitigation pathways, in turn, introduce distinct distributional challenges, notably through carbon pricing: policies that increase the cost of fossil fuels, such as extending Emissions Trading Systems (ETS2) to transport and heating, tend to be regressive because lower-income households allocate a larger share of their budget to essential energy services. However, the analysis highlights that the recycling of carbon revenues is the single most critical factor in reversing this regressive effect. Furthermore, subsidies for low-carbon technologies (e.g., EVs, heat pumps) are often pro-rich in their current structure, failing to benefit low-income households due to initial capital requirements, which can lock vulnerable populations into high-emission, high-cost fossil fuel dependency. The transition will also necessitate a large-scale reconfiguration of labor markets, making targeted re-skilling and vocational training essential components of a Just Transition framework to sustain the labor input in economic activity and improve the progressivity of climate policies. This report strongly argues that achieving deep mitigation targets requires policy packages where distributional concerns are integrated ex-ante. The most progressive outcomes are achieved through policies that target the structural causes of inequality, such as aggressive, state-led programmes for deep energy retrofitting in social and low-income housing, which directly reduce energy demand and permanently lower household energy bills. Strategic revenue recycling is paramount if carbon pricing is utilized; instead of universal lump-sum payments, revenues should be recycled through targeted mechanisms like increasing welfare payments, reducing regressive taxes, or implementing a progressive carbon dividend. Crucially, a significant portion of revenue should be earmarked for structural investments in energy efficiency and clean infrastructure, ensuring a dual benefit of climate mitigation and inequality reduction. Deliverable D2.3 thus demonstrates that the twin goals of climate neutrality and social justice are deeply intertwined, and a well-designed, investment-led, and revenue-recycled mitigation strategy can be a powerful engine for achieving both climate targets and a more equitable society. The continued work in the PRISMA project will explore the policy mechanisms required to operationalize this integration across EU Member States.

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1 Introduction

This deliverable summarizes the work performed in PRISMA under Task 2.3 on distributional issues. A central finding emerging across multiple analytical approaches is that climate mitigation need not trade off environmental effectiveness for equity; rather, well-designed redistribution mechanisms can simultaneously strengthen climate policy credibility, advance equity objectives, and improve overall welfare. However, realising this potential requires deliberate policy design moving beyond idealistic assumptions about revenue recycling toward realistic implementation accounting for institutional constraints, political economy, and sectoral specifics. Our analysis demonstrates that differentiated but complementary policy approaches are necessary across different contexts: carbon pricing with targeted transfers in developing economies facing acute energy poverty; sub-national differentiation in developed economies with high regional inequality; and international mechanisms addressing global inequality driven by unequal climate impacts. This report provides evidence base and analytical frameworks supporting such comprehensive distributional approaches to climate policy design.

This report is structured as follows. We first present the micro-level dataset on household income and expenditure inequality disaggregated by income deciles and settlement type, documenting data sources, methodology, and key patterns of how inequality manifests across income and geographic dimensions. We then present results from a multi-model assessment examining how climate impacts and mitigation policies affect inequality at the global and regional scale, exploring mechanisms through which both climate damages and policy costs distribute across populations. Subsequent sections examine specific policy applications: the distributional implications of European Union climate targets including the Fit for 55 package and national energy and climate plans, analysed at the sub-regional level; the intersecting dimensions of inequality and gender disparities as demonstrated through India case analysis; and the potential for global redistribution mechanisms including carbon dividends to simultaneously advance climate and equity objectives.

Moreover, multiple large-scale IAMs representing diverse economic paradigms—including cost-benefit, computable general equilibrium, and dynamic process-based models—are harmonised to compare distributional outcomes under consistent climate policy scenarios. We analyse these outcomes under alternative revenue recycling schemes ranging from uniform per-capita redistribution through targeted transfer programs, quantifying how redistribution design shapes both equity and aggregate welfare. The analysis distinguishes carefully between short-term and long-term distributional effects, recognising that immediate policy costs may differ markedly from long-term benefits of avoided climate damages.

The economic rationale for distributional analysis rests on three pillars. First, climate impacts themselves are deeply unequal: lower-income populations, concentrated in climate-sensitive sectors like agriculture and informal services, face disproportionate risks from warming and have substantially lower adaptive capacity. Second, the immediate costs of decarbonisation—particularly carbon pricing and energy system transformation—fall unequally absent complementary policy design, with energy-intensive consumption and transport burdens concentrated among lower-income households. Third, long-term growth trajectories shaped by mitigation constraints may distribute opportunities for income growth unequally, potentially widening existing inequalities unless deliberately addressed through transition policies. Understanding these distributional dynamics is not merely a social concern; it is essential for designing climate policies that maintain public support, prevent maladaptation through forced behavioural changes, and enable productive rather than disruptive economic transitions.

This report addresses this critical gap by comprehensively examining the distributional implications of mitigation pathways across multiple scales and dimensions. Drawing on state-of-the-art integrated assessment modelling from eight major research institutions, we quantify how climate impacts and mitigation policies affect within-country and global inequality, identify vulnerable population groups facing disproportionate costs or missing mitigation benefits, and evaluate how different revenue recycling and redistribution mechanisms shape pathways toward equitable net-zero transitions. Our analysis spans the European Union at member state and sub-national levels, major developing economies including India and

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China, and global aggregate assessments, enabling identification of distributional patterns that are robust across geographic contexts and modelling frameworks.
Climate mitigation pathways essential for achieving the Paris Agreement goals carry significant distributional consequences that remain underexplored in mainstream policy analysis. While integrated assessment models (IAMs) increasingly serve as primary tools for informing climate policy, most mainstream implementations rely on representative agent assumptions that mask critical heterogeneity in how climate policies and their benefits distribute across populations. This disconnect between model simplicity and policy reality creates a substantial blind spot: without understanding how costs and benefits of decarbonisation are shared across different income groups, demographic categories, and geographic regions, policymakers risk designing climate strategies that are economically inefficient, socially inequitable, and politically unsustainable.

2 Distribution of climate policy incidence: including urban and rural and gender dimension with a novel micro-based data-set

We compiled a comprehensive dataset on income and expenditure inequality with urban-rural settlement disaggregation for 32 countries across four continents. The dataset was developed to enhance Integrated Assessment Models (IAMs) with distributional dimensions, enabling more nuanced analysis of climate policy impacts across different population groups and settlement types. The data covers key inequality indicators including decile-level income and expenditure distributions, household characteristics, energy expenditure patterns, and educational attainment - all disaggregated by urban and rural settlements.
Key findings:

- Dataset covers **32 countries** (22 EU member states plus 10 additional countries from Asia, Africa, and the Americas)
- **9,858 observations** spanning multiple inequality dimensions
- Systematic urban-rural disparities in income inequality, with urban areas showing higher inequality in most developed countries
- Energy expenditure patterns show significant settlement-based differences, with rural households spending relatively more on transportation energy
- Between-group inequality (urban vs. rural) accounts for 5-25% of total inequality depending on country and indicator

The dataset is open source accessible at https://github.com/witch-team/inequality-dataset-for-iams

2.1 Data Collection and Methodology

The dataset encompasses **32 countries** providing broad geographic representation:

European Union (22 countries): Belgium, Bulgaria, Croatia, Cyprus, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Latvia, Lithuania, Luxembourg, Netherlands, Poland, Portugal, Romania, Slovak Republic, Spain, Sweden

Asia (3 countries): China, India, Vietnam

Americas (4 countries): United States, Mexico, Guatemala, Peru

Africa (3 countries): South Africa, Côte d'Ivoire, Mali

This geographic distribution covers approximately 60% of global population and represents diverse economic development levels, from low-income countries (Mali, Guatemala) to high-income economies (Luxembourg, Germany, USA), enabling comparative analysis across development stages.

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The data collection follows a standardized template methodology ensuring consistency across countries:

1. **Primary sources:** National household budget surveys, labor force surveys, and harmonized international databases (EU-SILC, World Bank LSMS, national statistical offices)

2. **Reference period:** Latest available data (typically 2018-2022 depending on country survey cycles)

3. **Settlement classification:** Two-category classification (urban/rural) following national definitions, ensuring consistency with each country's official statistics

4. **Decile construction:** Population divided into 10 equal-sized groups (deciles) based on household expenditure per capita (equivalized using modified OECD scale)

5. **Data validation:** Automated quality checks ensuring:

    - Decile shares sum to approximately 100% (±5% tolerance)
    - Household size consistency across variables
    - Value ranges within expected bounds (shares between 0-100%)
    - No missing data for core variables (income/expenditure deciles)

The standardized template captures nine core variable categories:

Income distribution:

- **Income deciles** by urban/rural settlement (D1-D10): Share of total income held by each decile
- **Income composition:** Breakdown by labor income, capital income, transfers, and other sources
- **Inequality indices:** Gini coefficients for income distribution

Expenditure distribution:

- **Expenditure deciles** by settlement (D1-D10): Share of total expenditure by each decile
- **Expenditure composition:** Three energy-related categories plus food:
    - Energy expenditure for housing (electricity, heating, cooling)
    - Energy expenditure for transportation (fuel for private vehicles)
    - Food expenditure
- **Savings rates** by decile and settlement

Household characteristics:

- **Household size:** Average persons per household by decile
- **Equivalized household size:** Adjusted for economies of scale
- **Educational attainment:** Population shares by education level (no education, primary, secondary, tertiary) and age group (under 15)

Additional indicators:

- **Wealth distribution:** Share of total wealth held by each decile (where available)
- **Emissions per capita:** Carbon footprint by decile and settlement (preliminary data)

All variables are disaggregated by **urban** and **rural** settlements and by **decile** (D1-D10), enabling detailed analysis of both vertical inequality (across income distribution) and horizontal inequality (between settlement

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types).

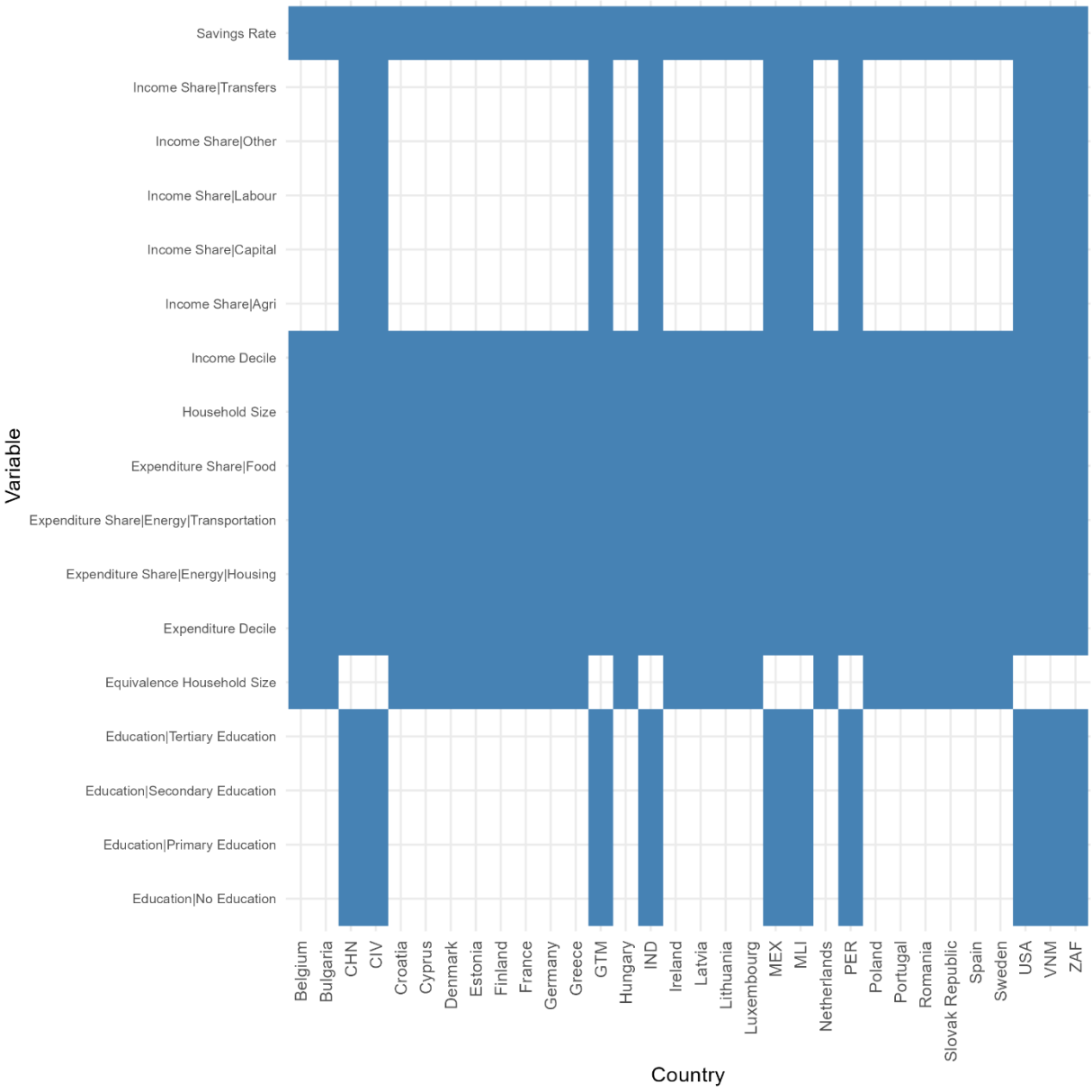


Figure 1: Data availability matrix showing which variables are available for each of the 32 countries. Blue tiles indicate available data, white tiles indicate missing data. The matrix demonstrates comprehensive coverage of core variables (income/expenditure deciles, energy expenditure, household characteristics) across all countries, with more limited coverage of wealth data and emerging variables like emissions per capita.

2.2 Key Findings on Urban-Rural Inequality Patterns

Analysis of the distributional data reveals systematic patterns in how inequality manifests across urban and rural areas:

Income concentration patterns: Across the dataset, urban areas consistently show higher income inequality than rural areas in developed countries, while the pattern is more mixed in developing economies. In EU countries, the top decile (D10) captures on average 25-30% of total urban income compared to 22-26% in rural areas. The bottom decile (D1) receives 2-3% of income in both settlements, but the middle class (D4-D7) is notably stronger in rural EU regions.

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In contrast, developing countries show more varied patterns:

- In China and India, rural inequality is extremely high, with D10 capturing over 35% of income in some rural regions
- In African countries (Mali, Côte d'Ivoire), urban inequality exceeds rural inequality by substantial margins, reflecting the concentration of formal employment and higher-wage jobs in cities

Expenditure inequality: Expenditure distributions are generally less unequal than income distributions (Gini coefficients 15-25% lower on average), reflecting consumption smoothing and the role of transfers. However, the urban-rural gap in expenditure inequality follows similar patterns to income inequality.

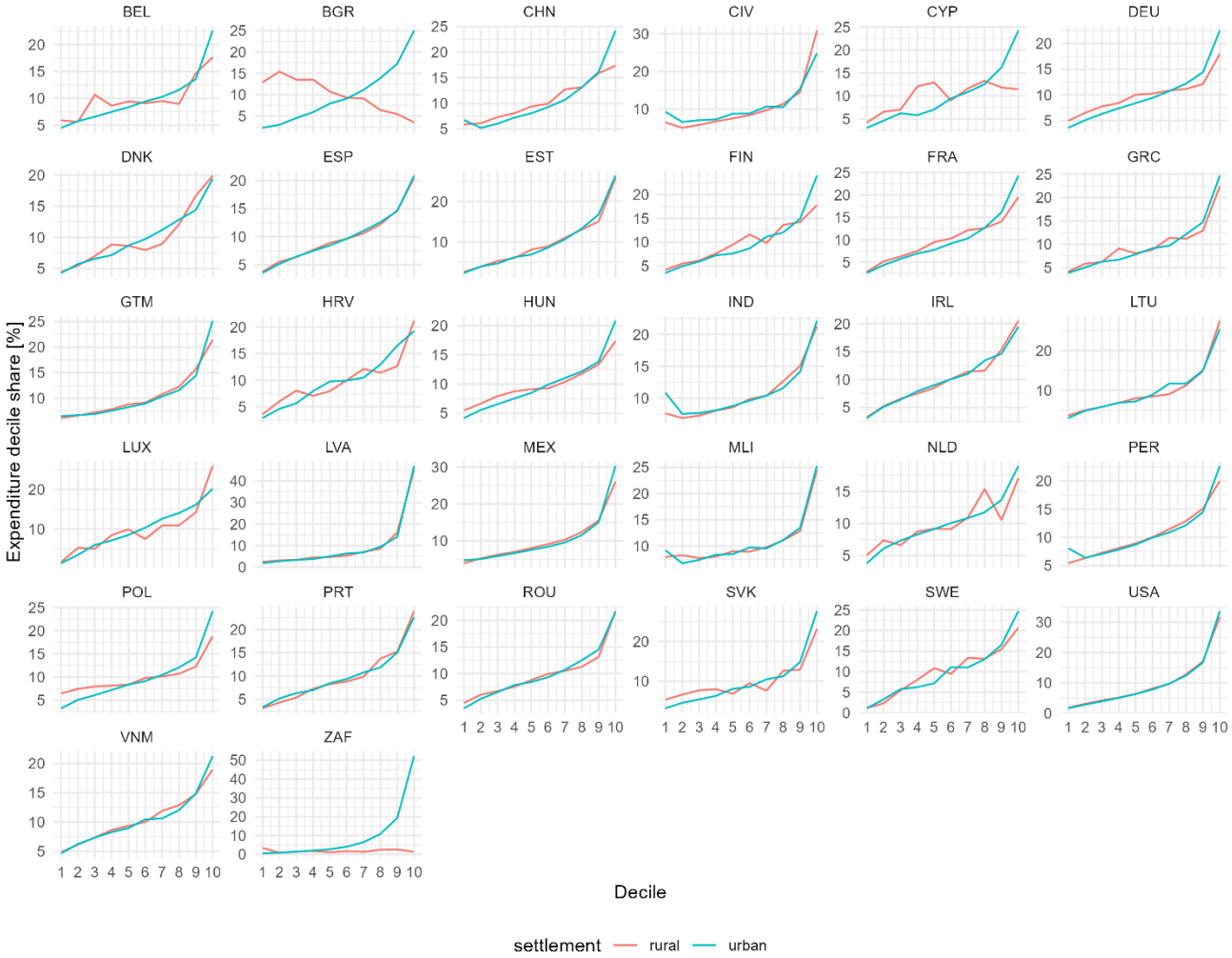


Figure 2: Expenditure share held by each decile in urban (red) and rural (blue) areas for all 32 countries. The vertical axis shows income share as percentage of total income, while the horizontal axis shows deciles from D1 (poorest) to D10 (richest). Countries are arranged in separate panels allowing comparison of distributional patterns.

Notable findings:

- Urban households in the top decile spend 20-25% of total urban expenditure in EU countries

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- Rural top decile accounts for 18-22% of rural expenditure
- In developing countries, expenditure inequality can exceed income inequality in rural areas, suggesting limited access to credit and insurance mechanisms

Energy expenditure patterns show some of the most pronounced settlement-based differences, with important implications for climate policy:

Housing energy (electricity, heating, cooling):

- Urban households in the bottom deciles (D1-D3) spend 8-14% of total expenditure on housing energy across EU countries
- Rural households in the same deciles spend 10-18% - a substantially higher burden
- This disparity reflects lower energy efficiency in rural housing stock and limited access to district heating networks
- The energy expenditure burden decreases with income in both settlements, but more steeply in urban areas (D10 spends 3-6% in cities vs. 5-9% in rural areas)

Transportation energy:

- Rural households face systematically higher transportation energy costs due to lower public transport availability and longer travel distances
- Across EU countries, middle-income rural households (D4-D7) spend 12-18% of expenditure on transportation energy vs. 10-14% for urban households
- In developing countries with limited public transport in cities, the urban-rural gap is smaller or reversed (e.g., in India, urban middle-class households spend more on transportation)

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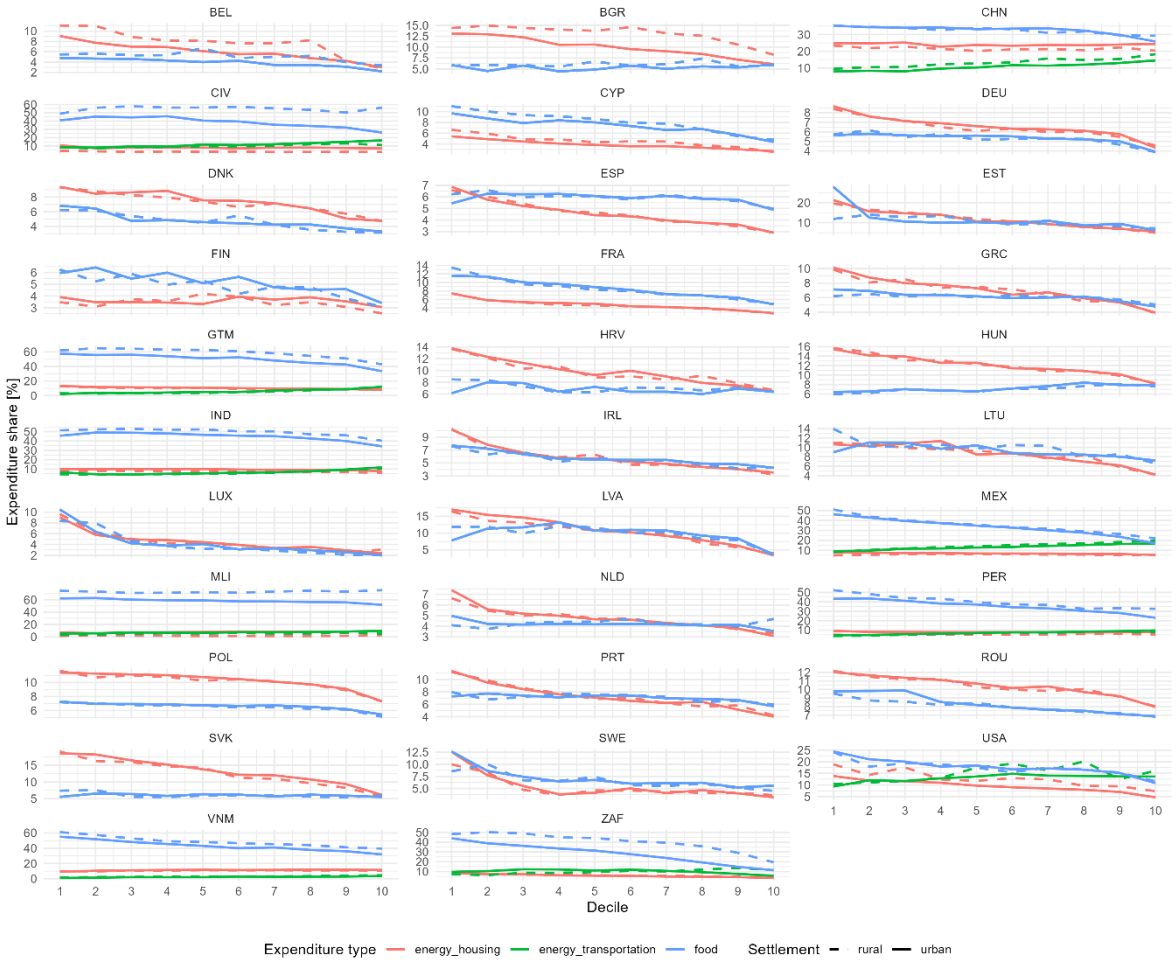


Figure 3: Energy expenditure shares (housing and transportation) and food expenditure across deciles for all 32 countries, with solid lines representing urban households and dashed lines representing rural households. The vertical axis shows expenditure share as percentage of total household expenditure, while the horizontal axis shows deciles from poorest (D1) to richest (D10). Different colors distinguish expenditure categories: food (red), housing energy (green), and transportation energy (blue).

Policy implications: These patterns suggest that carbon pricing or fuel taxation policies will have differentiated impacts:

- Rural low-income households face higher energy cost burdens and have fewer substitution options
- Carbon pricing without compensation mechanisms could disproportionately affect rural populations
- Energy efficiency programs targeting rural housing could substantially reduce inequality in energy burdens

Using Theil T index decomposition, we quantify how much total inequality stems from differences *between* urban and rural areas versus inequality *within* each settlement type.

Income inequality decomposition: Results show that the vast majority (75-95%) of income inequality exists *within* urban and rural areas, not between them:

- EU countries: Between-group component accounts for 5-15% of total inequality
- Asian countries: Between-group component reaches 15-25% in China and India, reflecting substantial urban-rural income gaps

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- African countries: Between-group component accounts for 15-20%, with urban areas having significantly higher mean incomes
- Americas: Between-group component is 8-18%, varying by level of urbanization

These findings indicate that while urban-rural income gaps are meaningful (especially in developing countries), within-group inequality is the dominant component. Climate policies that only consider settlement type without addressing within-group inequality will miss the majority of distributional impacts.

Expenditure inequality decomposition: Expenditure shows similar patterns but with slightly lower between-group components (5-20%), as rural-urban consumption gaps are smaller than income gaps due to price differences and home production in rural areas.

Energy expenditure inequality: Interestingly, energy expenditure shows *higher* between-group components:

- Housing energy: Between-group inequality accounts for 15-30% of total inequality, reflecting systematic differences in housing types and energy infrastructure
- Transportation energy: Between-group component reaches 20-35%, the highest of any indicator, driven by fundamental differences in transportation modes and distances

This suggests that settlement-type-aware policies are particularly important for energy-related climate measures.

2.3 Data Quality Assessment and Applications for IAMs

The data collection achieved strong coverage across core variables, though completeness varies by country and variable type:

Coverage by variable category:

- Income/expenditure deciles: 100% (all 32 countries)
- Energy expenditure shares: 100% (all countries for housing and transportation)
- Household size: 100% (all countries)
- Educational attainment: 91% (29 countries)
- Savings rates: 88% (28 countries)
- Wealth distribution: 45% (14 countries - limited by data availability)
- Emissions per capita: 32% (10 countries - emerging variable)

Quality indicators: Data validation checks identified high quality across the dataset:

- 98.7% of observations pass the decile sum validation (total shares 95-105%)
- Household size data show realistic patterns (2-6 persons per household)
- Energy expenditure shares align with national account aggregates where comparable
- Urban-rural population distributions match official statistics

Known limitations:

1. **Temporal comparability:** Reference years vary by country (2018-2022), though most are 2020-2021
2. **Settlement definitions:** Urban/rural classifications follow national definitions, which vary across countries (population thresholds, administrative criteria)
3. **Wealth data gaps:** Many countries lack household wealth surveys, limiting wealth inequality analysis

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4. **Informal economy:** Developing countries may underestimate informal sector incomes, particularly in rural areas

2.4 Urban-Rural Population Dynamics

The dataset includes household size data that enables estimation of actual population distributions across deciles and settlements. This is critical for IAMs as it allows proper aggregation from household-level to population-level impacts.

Key findings on population-income relationships:

Household size variation:

- Rural households are generally larger (3.0-4.5 persons) than urban households (2.2-3.2 persons)
- Household size decreases with income in both settlements, but more steeply in urban areas
- Bottom decile rural households average 3.5-4.2 persons vs. 2.8-3.5 in top decile
- Bottom decile urban households average 2.5-3.2 persons vs. 1.8-2.5 in top decile

Implications for population weighting: When converting from household-based deciles (10% of households each) to population-based distributions, the poor have larger weight than a simple 10% per decile assumption would imply. This is particularly important for:

- Poverty impact assessments (more individuals affected than household counts suggest)
- Per capita vs. per household emission allocations
- Targeting efficiency of transfer programs

The dataset provides the necessary adjustments for proper population weighting in IAM applications.

2.5 Applications in Integrated Assessment Models

This dataset enables several enhancements to IAM frameworks:

1. Distributional incidence analysis of climate policies

IAMs can now model how carbon pricing, fuel taxation, or emission trading systems affect different population groups:

- **Direct impacts:** Energy price increases affect households differently based on their expenditure patterns
  - Rural households face higher transportation cost increases
  - Poor urban households face higher heating cost increases
- **Indirect impacts:** Through input-output linkages, carbon costs feed into all consumption goods
  - Food prices affected by agricultural energy use
  - Manufacturing goods affected by industrial energy costs

The settlement disaggregation allows identifying vulnerable groups (e.g., rural poor facing high transportation costs) for targeted compensation.

2. Revenue recycling and compensation mechanisms

Understanding baseline inequality patterns enables design of progressive revenue recycling:

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- **Lump-sum transfers:** Dataset provides household counts and sizes for calculating equal per capita transfers
- **Targeted transfers:** Identifies high-burden groups (e.g., rural bottom deciles) for additional compensation
- **Energy efficiency subsidies:** Prioritizes groups with high energy expenditure shares but low absolute expenditure (poor households)

3. Co-benefits analysis

Climate policies generate co-benefits through:

- **Air quality improvements:** Disproportionately benefit urban poor living near pollution sources
- **Energy access:** Rural electrification programs as part of renewable energy transitions
- **Employment effects:** Green job creation potentially reduces inequality if jobs are accessible to lower-income workers

The dataset enables quantifying which groups gain most from these co-benefits.

4. Just transition pathways

For fossil fuel-dependent regions, the data supports analysis of:

- **Worker transitions:** Income shares from labor inform impacts of fossil fuel job losses
- **Regional policies:** Settlement-level data guides place-based transition support
- **Consumption adjustments:** Expenditure patterns indicate adaptive capacity and transition challenges

5. Representation of heterogeneous households in IAMs

Rather than modeling a single "representative household," IAMs can now include:

- 20 household types (10 deciles × 2 settlements) per country
- Differentiated consumption bundles, energy use patterns, and behavioral responses
- Realistic aggregation from household impacts to national outcomes

This substantially improves policy realism by capturing distributional effects that aggregate approaches miss. The settlement disaggregation adds a new dimension not present in most existing IAM databases, while maintaining compatibility with established frameworks.

2.6 Conclusion and Future Directions

This dataset represents a significant advancement in providing IAMs with the distributional detail necessary for realistic climate policy analysis. By combining income/expenditure deciles with urban-rural settlement disaggregation, it enables modeling of both vertical inequality (across income levels) and horizontal inequality (across space and settlement types).

Key contributions:

1. **Comprehensive coverage:** 32 countries spanning diverse geographic and economic contexts
2. **Settlement disaggregation:** Systematic urban-rural breakdown enabling spatial distributional analysis
3. **Energy focus:** Detailed energy expenditure data critical for climate policy assessment

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4. **Quality assurance:** Standardized methodology with automated validation ensuring reliability
5. **IAM compatibility:** Integration-ready format compatible with leading IAM frameworks

Main findings:

- Urban-rural differences matter substantially for energy expenditure (15-35% of inequality) but less for overall income inequality (5-25%)
- Rural households face systematically higher energy cost burdens, particularly for transportation
- Within-settlement inequality dominates overall inequality, requiring policies that go beyond simple urban-rural distinctions
- Settlement-aware policy design is essential for energy-related climate measures

Future development priorities:

Data expansion:

- **Additional countries:** Priority on G20 countries not yet covered (Brazil, Indonesia, Saudi Arabia, Turkey)
- **Wealth data:** Improved wealth inequality measurement as national wealth surveys expand
- **Emissions data:** Complete carbon footprint calculations by decile and settlement
- **Time series:** Historical data enabling trend analysis and future projections

Methodological enhancements:

- **Finer geographic resolution:** Where data permits, sub-national regional disaggregation beyond urban-rural
- **Household types:** Incorporate additional demographic dimensions (age, family structure) for richer heterogeneity
- **Dynamic elements:** Link to demographic and economic projections for scenario analysis
- **Behavioral parameters:** Add price elasticities and substitution parameters by income group and settlement

IAM integration:

- **Soft-linking protocols:** Standardized data exchange formats for IAM-specific implementations
- **Validation exercises:** Compare IAM projections with observed distributional data
- **Scenario harmonization:** Align with SSP narratives and climate scenarios
- **Uncertainty quantification:** Provide confidence intervals and sensitivity analyses

This dataset and accompanying analysis framework provide a robust foundation for next-generation distributional IAM analysis, enabling evidence-based assessment of climate policy equity and the design of just transition pathways.

3 A multi-model comparison of distributional implications of climate policies

Based on this publication: Emmerling et al. (2024): A multi-model assessment of inequality and climate change, Nature Climate Change, https://doi.org/10.1038/s41558-024-02151-7

This project has received funding from the European Union's Horizon Europe programme under grant agreement No 101081604 - PRISMA, including the contribution of the Swiss State Secretariat for Education, Research, and Innovation. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting authority can be held responsible for them.

3.1 Background and Framework

Climate change and economic inequality are deeply interconnected yet persistently analyzed in isolation. While empirical evidence increasingly demonstrates that climate policies have significant distributional consequences, mainstream model-based climate assessments largely ignore these effects. This multi-model study addresses this critical gap by employing eight large-scale integrated assessment models (IAMs) representing diverse economic paradigms to quantify how climate impacts and mitigation policies affect inequality both within and across countries by 2100.

The research explicitly examines two complementary questions: first, how do climate impacts themselves affect the distribution of income within countries, and second, what role can redistribution schemes play in shaping more equitable mitigation pathways? The study implements a uniform carbon price framework consistent with Paris Agreement goals (1.5°C warming target and 650 $GtCO_2$ carbon budget), while exploring different revenue recycling methods including neutral recycling, equal per-capita (EPC) redistribution, and targeted transfer schemes. This ensemble approach enables quantification of uncertainty across models and allows identification of robust findings despite substantial country-level heterogeneity.

The eight models employed span different theoretical traditions including cost-benefit integrated assessment models (CB-IAM), computable general equilibrium models (CGE), and dynamic process-based integrated assessment models (DP-IAM), each incorporating income heterogeneity at the country level. Rather than relying on single-model results, the ensemble approach reveals which findings hold robustly across diverse modeling assumptions and which are sensitive to particular theoretical frameworks or parameterizations. Inequality is measured using the Gini coefficient as the primary metric, supplemented by assessment of equivalent distribution of expenditure (EDE) welfare measures that combine efficiency and equity considerations.

3.2 Climate Impacts and Inequality Dynamics

In the absence of climate mitigation policies, climate change is projected to increase global income inequality substantially. By 2100, climate impacts are estimated to increase the Gini index by approximately 1.4 points on average across models, representing a significant widening of income distribution. This global median effect masks important regional variation, with particularly severe inequality impacts in low- and middle-income countries. The mechanistic drivers include regressive impacts on agricultural production, heightened climate risks falling disproportionately on lower-income populations with limited adaptive capacity, and unequal geographic exposure to climate hazards.

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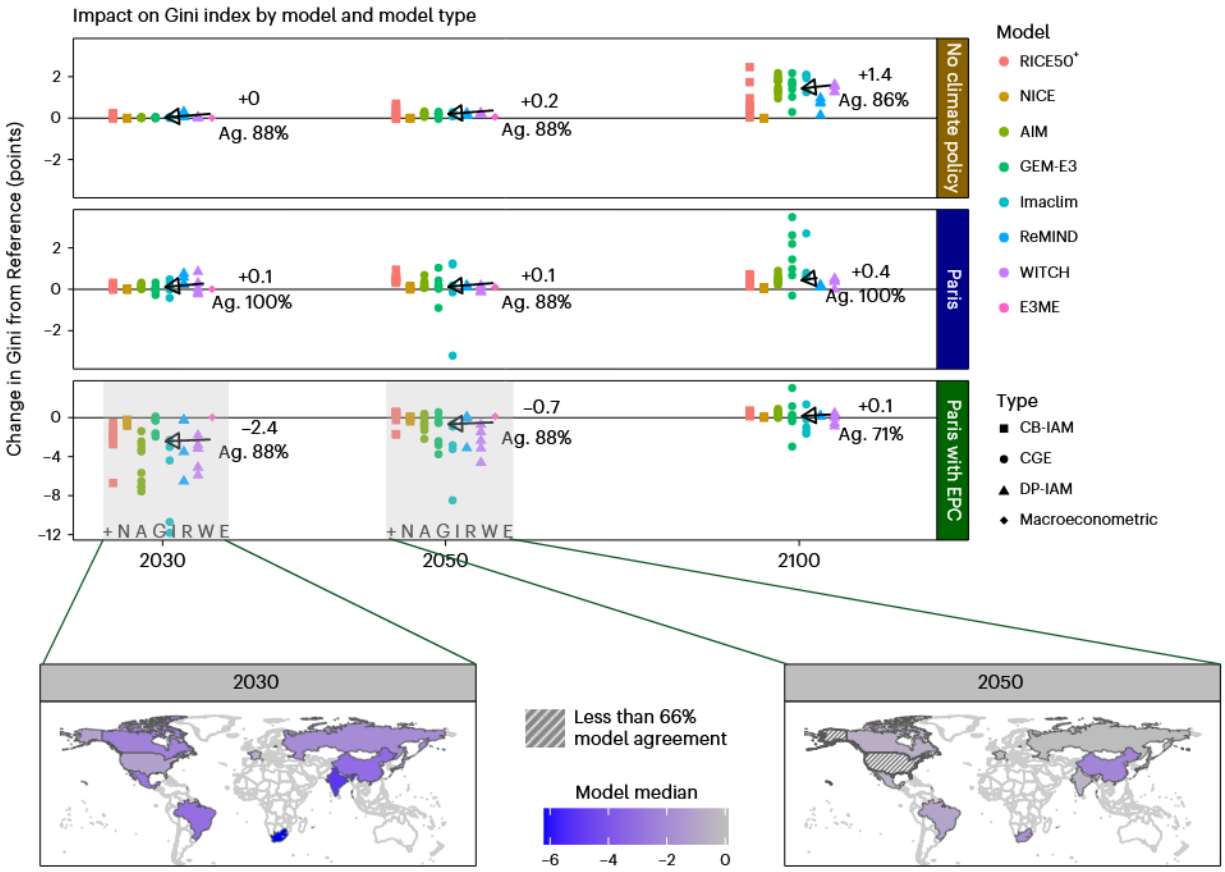


Figure 4: Change in Gini index from the Reference scenario without climate impacts.

Climate policy stringency provides some protection against inequality expansion, but the effects are time-varying and asymmetric. Maintaining global warming below 1.5°C reduces the long-term inequality increase by approximately two-thirds compared to no-climate-policy scenarios, yet paradoxically increases inequality slightly in the short term through increased policy stringency and related macroeconomic adjustments. This temporal inversion reflects the tension between immediate mitigation costs (which are regressive in the absence of redistribution) and long-term climate damage prevention (which protects vulnerable populations most). Model agreement is high in sign across scenarios, with 88% average model agreement that climate impacts increase inequality, though the magnitude varies substantially depending on model structure, sectoral detail, and treatment of adaptation dynamics.

The distributional consequences manifest through multiple channels. Direct climate damages impose disproportionate burdens on lower-income households dependent on climate-sensitive sectors like agriculture. Carbon pricing necessary for mitigation imposes immediate costs that are inherently regressive absent complementary redistribution, since lower-income households spend larger income shares on energy-intensive goods including transportation and heating. Economic adjustment costs from decarbonization fall heterogeneously, with carbon-intensive sectors and regions experiencing disproportionate shocks. Additionally, climate impacts themselves interact with economic development trajectories, potentially constraining growth pathways in vulnerable regions and exacerbating existing inequalities.

Welfare impacts, measured using equivalent distributed expenditure (EDE), reinforce these inequality findings. Compared with a reference scenario without climate impacts, climate damages reduce aggregate welfare by approximately 4.9% of GDP by century's end, but this aggregate effect obscures massive distributional heterogeneity. Notably, within-country inequality variations produce dramatic welfare losses

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exceeding GDP effects alone, highlighting that how damages and costs are distributed matters as much as their magnitude. Regional variation is substantial: South Africa, India and Brazil experience the largest welfare losses in EDE terms, while some higher-latitude regions show modest gains from climate stabilization through reduced cold-related mortality and enhanced agricultural productivity.

3.3 Policy Solutions and Distributional Effectiveness

Revenue recycling mechanisms demonstrate substantial potential to address inequality arising from both climate impacts and mitigation policy stringency. When carbon tax revenues from Paris-aligned climate policy scenarios are redistributed equally to all citizens on a per-capita basis, the Gini index falls by approximately 1.8-2.0 points in 2030, offsetting much of the short-term regressive policy effects. Critically, targeted transfer schemes outperform universal per-capita approaches by concentrating benefits among lower-income populations and existing social program beneficiaries, achieving inequality reductions exceeding two points. This reveals that design choices about how revenues are deployed—not simply whether they are recycled—fundamentally shape distributional outcomes and the potential for climate policies to advance both climate and equity goals simultaneously.

The policy costs of achieving Paris-compatible carbon reductions vary substantially by country. Carbon intensity of production, baseline energy system configuration, and existing welfare levels all influence relative policy stringency. Overall, models find policy costs in terms of GDP loss relatively modest in aggregate, though concentrated in particular sectors and regions. Importantly, the GDP elasticity of policy costs relative to carbon prices is estimated at approximately 1.04, indicating near-proportional economic impacts with respect to price levels. However, distributional analysis reveals that GDP-level costs mask heterogeneous incidence across income groups: lower-income households face significantly higher proportional costs absent redistribution, while higher-income households bear the burden when well-designed transfer schemes are implemented.

Temporal dynamics of redistribution reveal that inequality benefits front-load in time, then gradually diminish as carbon revenues decline with emissions reductions. By mid-century, continued welfare gains from redistribution stabilize at approximately 5% of baseline consumption through 2050, then decline toward 2100 as carbon revenues approach zero due to near-complete decarbonization. This points to a critical policy implication: early, decisive redistribution of carbon revenues from current climate policy implementation can generate substantial near-term equity gains, but long-term inequality management will require complementary policies beyond carbon pricing, including education investments, social protection systems, and structural economic transformation that broadens productivity and income growth opportunities across the distribution.

The robustness of findings across models and theoretical frameworks provides grounds for confidence in the core conclusions while acknowledging important remaining uncertainties. Stringent climate policies can simultaneously achieve environmental stabilization and promote economic inclusion when complemented by well-designed redistribution schemes. However, the analysis also reveals several dimensions of inequality still missing from standard model frameworks: gender dimensions of policy incidence remain largely unexplored, within-country regional disparities receive limited treatment, and dynamic behavioral responses to policy uncertainty and climate risks require further investigation. The ensemble modeling approach demonstrates that climate policy design cannot remain separate from equity considerations if international commitments to both climate and sustainable development goals are to be coherently pursued.

4 Distributional Impacts of Climate Mitigation Policies: Within-Country Equity Concerns

Based on this publication: Shridhar Kulkarni et al (2025): Towards improved representation of distributional impacts of climate change and mitigation policies in model scenarios, *Environ. Res. Commun.* in press https://doi.org/10.1088/2515-7620/ae1c04

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4.1 Introduction and Research Gap

Climate mitigation policies and climate change damages affect populations unequally. While the IPCC has established that climate risks are not evenly distributed—disproportionately harming the poor—the interaction between mitigation costs and avoided damages at the sub-national level remains understudied. This paper addresses a critical gap by examining how carbon pricing policies, a key mitigation tool, and their resulting avoided climate damages are distributed across income groups within countries.

The core tension is apparent: without complementary redistributive policies, carbon pricing can exacerbate existing inequalities through increased residential energy costs, disproportionately burdening poorer households. Simultaneously, successful climate mitigation delivers greater benefits to vulnerable populations most exposed to climate impacts. Understanding this trade-off is essential for designing socially acceptable climate policies that maintain public support and prevent increased hardship among low-income groups.

The authors use the IMAGE integrated assessment model to analyze scenarios limiting global warming to 1.5°C and 2°C, examining impacts across 26 world regions and five income quintiles. The analysis distinguishes between regressivity—whether costs fall more heavily on poor or rich—and overall inequality effects, a crucial distinction for policymakers designing just transitions. This methodological clarity helps explain why a policy might show small overall inequality changes yet still create severe burden concentration among specific income groups.

4.2 Methods and Analytical Framework

The study employs a comprehensive scenario analysis using the IMAGE 3.4 model, which simulates interactions between human activities and environmental systems. Two parallel streams of analysis run in tandem, allowing the researchers to isolate how carbon pricing affects different income groups relative to the damages they avoid by preventing unmitigated climate change.

The residential energy module (TIMER) simulates energy demand and costs for five income quintiles across urban and rural areas, accounting for six end-use functions including cooking, heating, cooling, water heating, and appliances. The model captures a critical dynamic: poorer households exhibit lower discount rates for clean technologies and have less access to modern energy sources, forcing them to remain dependent on cheaper but dirtier fossil fuels. When carbon prices rise, wealthier households can more readily invest in heat pumps, rooftop solar, and insulation, while poorer households face prohibitive upfront costs and either remain locked into expensive fossil fuels or revert to traditional biomass, which remains unpriced. This "energy ladder" mechanism drives much of the observed regressivity.

The climate damage analysis (MIMOSA model) operates differently than energy costs. Rather than assuming equal damage incidence across income groups, the authors apply an income elasticity of damages of 0.7, derived from recent research showing that lower-income groups have substantially lower adaptive capacity. This means lower-income households experience larger economic losses from the same climate shock. By distributing aggregate regional damages using this elasticity, the model captures how poorer populations are more vulnerable to agricultural losses, heat stress, health effects, and other climate impacts.

The analysis employs two complementary distributional indices. The Suits index measures regressivity or progressivity on a scale from -100 to +100, with negative values indicating regressive impacts (costs concentrated on the poor) and positive values indicating progressive impacts (costs concentrated on the rich). The Gini coefficient captures overall income inequality, ranging from 0 to 1, where higher values indicate greater inequality. This distinction matters considerably: a policy might show minimal Gini changes if the overall income distribution barely shifts, yet simultaneously show large negative Suits index values if costs are

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heavily concentrated on lower-income groups.

The analysis compares three scenarios: a baseline with no additional mitigation action and two mitigation pathways achieving 1.5°C (with greater than 50% probability) and 2°C (with 67% probability) targets, all driven by globally uniform carbon prices from 2025 onwards. The focus on uniform pricing, while acknowledged by the authors as neither realistic nor equitable across countries, allows clearer interpretation of underlying dynamics without confounding regional differentiation effects.

4.3 Energy Expenditure Impacts and Short-Term Regressivity

Carbon pricing creates substantial energy cost increases for poorer households through three interconnected mechanisms. First, the same absolute increase in fossil fuel prices represents a much larger share of lower incomes. Second, wealthy households already use cleaner energy sources and can afford to invest in efficiency measures, while poor households cannot access these options. Third, poor households remain locked into fossil fuels or must revert to traditional biomass despite having lower overall emissions, because they lack capital for transitions.

In the 1.5°C scenario's short term spanning 2025 to 2045, the increase in energy burden for the poorest quintile is an order of magnitude higher than for the richest. Regional variation is substantial: Russia, Western Africa, and South Africa show the strongest regressivity due to high fossil fuel dependency among poor households. Brazil presents an exception where poor households benefit because they already rely on modern biofuels and renewables, so carbon pricing increases costs primarily for wealthier households using fossil fuels. The Gini analysis reveals sharp inequality spikes immediately after carbon price introduction, averaging 2.4 points in the 1.5°C scenario and peaking within 2025-2045, before declining substantially by 2100 as renewable electricity expands and becomes affordable.

4.4 Climate Damage Distribution and Progressive Benefits

The avoided damages scenario reveals a starkly different picture from the energy cost story. Because lower-income groups suffer disproportionately from climate impacts through agricultural losses, heat stress, reduced labor productivity, and other mechanisms, they benefit most from mitigation that prevents these damages. Across world regions, the poorest quintile gains twice as much from avoided damages compared to the richest in 1.5°C scenarios. In vulnerable regions including Sub-Saharan Africa and South Asia, this advantage reaches six-fold, reflecting both the greater exposure and lower adaptive capacity of poor populations. The Suits index for avoided damages remains predominantly positive throughout the analysis, indicating the progressive nature of mitigation benefits and showing that damage reductions concentrate their gains among lower-income groups.

4.5 Combined Effects and the Temporal Transition Dynamic

When integrating energy costs and avoided damages, the analysis reveals a critical temporal dynamic that shapes policy implications. In the short term spanning 2025 to 2045, higher energy burdens dominate the combined picture, creating near-zero combined Suits index values that indicate roughly neutral distributional outcomes. However, by mid-to-long term covering 2046 to 2085, avoided damages increasingly outweigh energy burden costs. Most regions transition to modestly progressive combined outcomes with positive Suits values, and poorer regions show the strongest progressive effects. This temporal pattern suggests that climate mitigation ultimately benefits vulnerable populations most, but only if complementary redistributive policies protect them during the critical 2025-2065 transition period when energy costs peak before renewable alternatives become affordable and accessible to all income groups.

The paper emphasizes that without such redistributive policies, carbon pricing alone risks eroding public support for climate action by imposing visible short-term costs on vulnerable populations before long-term benefits materialize. Effective policy should combine carbon pricing with targeted compensation during

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transitions, including subsidies for clean technologies and energy efficiency investments, infrastructure development ensuring poor households access affordable clean energy alternatives, progressive revenue recycling through targeted transfers rather than equal-per-capita rebates, and sectoral combinations addressing transport and food sectors. The distinction between short-term regressivity and long-term progressivity is essential: policymakers must design transitional support systems that prevent energy poverty and maintain climate policy legitimacy while allowing long-term mitigation benefits to materialize.

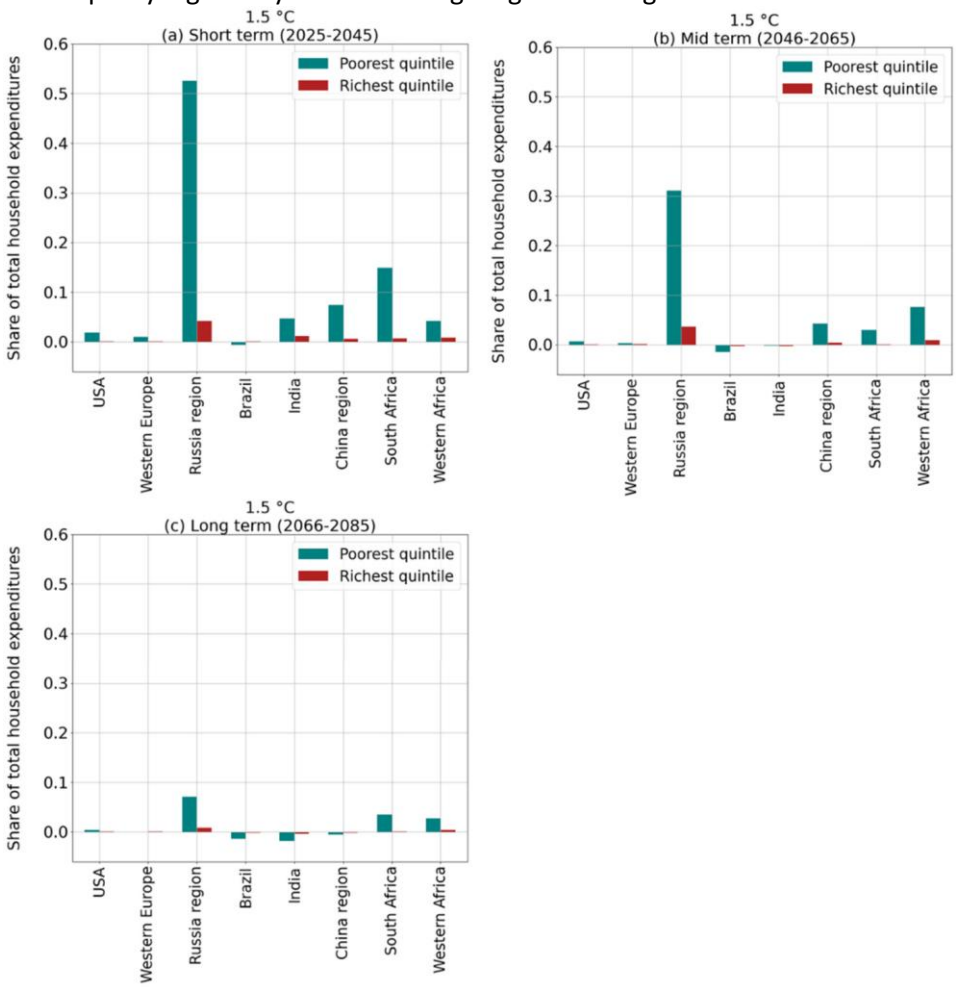


Figure 5: Additional energy burden (energy expenditure per capita as fraction of total household expenditures per capita) in the 1.5°C mitigation scenario relative to baseline for poorest and richest quintiles in selected model regions. This figure compares short-term (2025-2045), mid-term (2046-2065), and long-term (2066-2085) impacts across world regions including the USA, Western Europe, Russia, Brazil, India, China, South Africa, and Western Africa. The figure clearly demonstrates the regressivity of carbon pricing through residential energy channels, showing how the poorest quintile faces disproportionately higher burden increases compared to the richest, with substantial regional variation that reflects differences in baseline energy systems and access to clean alternatives.

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5 Within-country distributional impacts of climate change

Based on this manuscript: Zhong, J., Piontek, F., Collins-Sowah, P. A., Leimbach, M., Soergel, B., Bauer, N., & Kriegler, E. Beyond Averages: Uncover Historical Climate Change Impact on Between-and Within-Country Income Inequality Dynamics. Available at SSRN 5115559.

5.1 Introduction and Research Gap

Most quantitative assessments of climate damages focus on average country-level GDP, leaving open the question of how different income groups within countries have been affected. Existing work shows that warming has widened income gaps between countries and that hotter climates are associated with higher within-country inequality, but systematic global evidence on how historical climate change has shaped income trajectories across the whole national distribution remains limited, as does evidence on the regressivity of climate impacts that is needed to downscale national damages in modelling applications.

This study fills that gap by estimating how post-1980 warming has affected income growth for ten income deciles in 170 countries between 1980 and 2019. By constructing a counterfactual world without additional warming after 1980, we attribute gains and losses in decile-level incomes to climate change and assess how these impacts have altered both global income levels and inequality. We find that warming has reduced 2019 global income by about 2.7% under realistic persistence assumptions and that the poorest 10% have suffered roughly twice the relative loss of the richest 10%. Preliminary estimates of within-country income elasticities of climate impacts indicate that the elasticity of damages is below unity in 84% of cases (median 0.93), while the elasticity of benefits is likewise below unity (median 0.63), implying that both losses and gains tend to be proportionally larger for poorer groups.

5.2 Methods and Analytical Framework

The study combines econometric damage functions with a counterfactual simulation. Decile-specific income growth is regressed on annual mean temperature and precipitation, using non-linear specifications and interactions with World Bank income groups to capture heterogeneous vulnerability across low-, middle-, and high-income economies. Country fixed effects, year fixed effects, and country-specific time trends control for unobserved structural differences and long-run development patterns. The model is estimated separately for each decile across 170 countries and 1980–2021, with bootstrapping to characterize uncertainty.

$$g_{it} = \gamma_1 T_{it} + \gamma_2 T_{it}^2 + \beta_1 P_{it} + \beta_2 P_{it}^2 + Lo_{it}\left(\delta_1 T_{it} + \delta_2 T_{it}^2\right) + Lm_{it}\left(\delta_3 T_{it} + \delta_4 T_{it}^2\right) + Um_{it}\left(\delta_5 T_{it} + \delta_6 T_{it}^2\right) + Lo_{it}\left(\alpha_1 P_{it} + \alpha_2 P_{it}^2\right) + Lm_{it}\left(\alpha_3 P_{it} + \alpha_4 P_{it}^2\right) + Um_{it}\left(\alpha_5 P_{it} + \alpha_6 P_{it}^2\right) + \varphi_i + \upsilon_t + \theta_{1i} t + \theta_{2i} t^2 + \varepsilon_{it}$$

For attribution, we construct counterfactual temperature paths using a delta-method approach based on ISIMIP GSWP3-W5E5 data and compare these to observed temperatures to isolate climate-induced income changes. Differences between observed and counterfactual temperatures are fed through the estimated damage functions to obtain annual climate-induced changes in income growth for each decile, which are then accumulated into 1980–2019 income paths with and without warming. A flexible "half-life" structure governs the persistence of climate shocks, with results reported for both permanent effects and a 10-year half-life case.

Distributional impacts are quantified using standard inequality measures (Theil, Gini, Palma ratio) at country, regional, and global levels, including decomposition of Theil index into within- and between-country

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components. We also derive income elasticities of climate impacts to summarize how losses and gains scale across the income distribution and whether they are regressive or progressive.

5.3 Income and Inequality Effects of Historical Warming

The estimated damage functions show that warming boosts income growth at low baseline temperatures but becomes increasingly harmful above an optimal band around 12–16°C. Poorer deciles in low-income, already hot countries are the most adversely affected, reflecting high exposure and limited adaptive capacity, while richer deciles and high-income economies are less sensitive and sometimes experience mild gains.

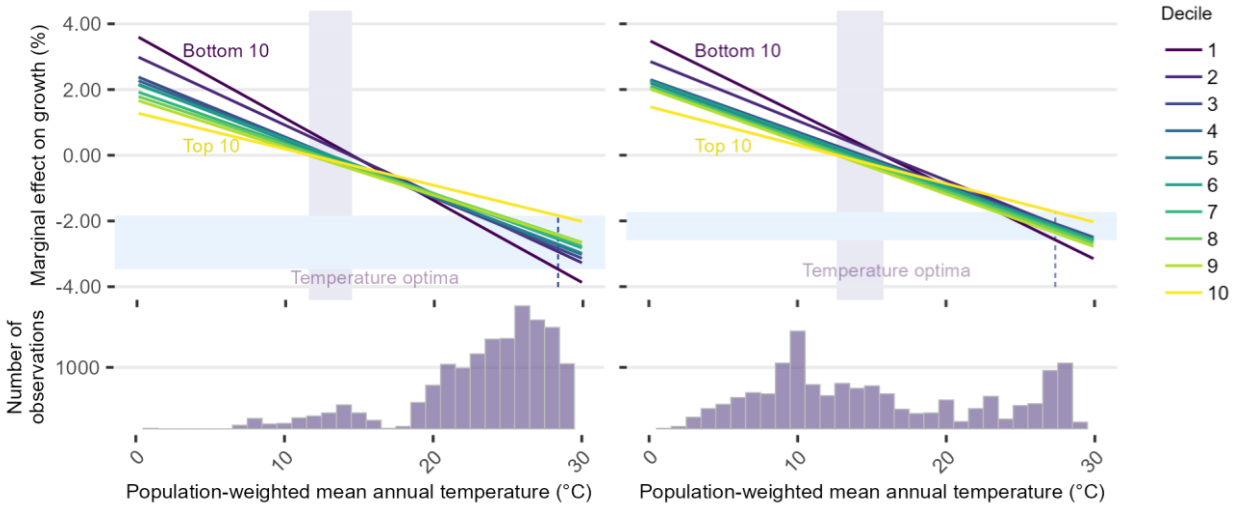


Figure 6. Observed temperature and marginal impacts of temperature change on income growth

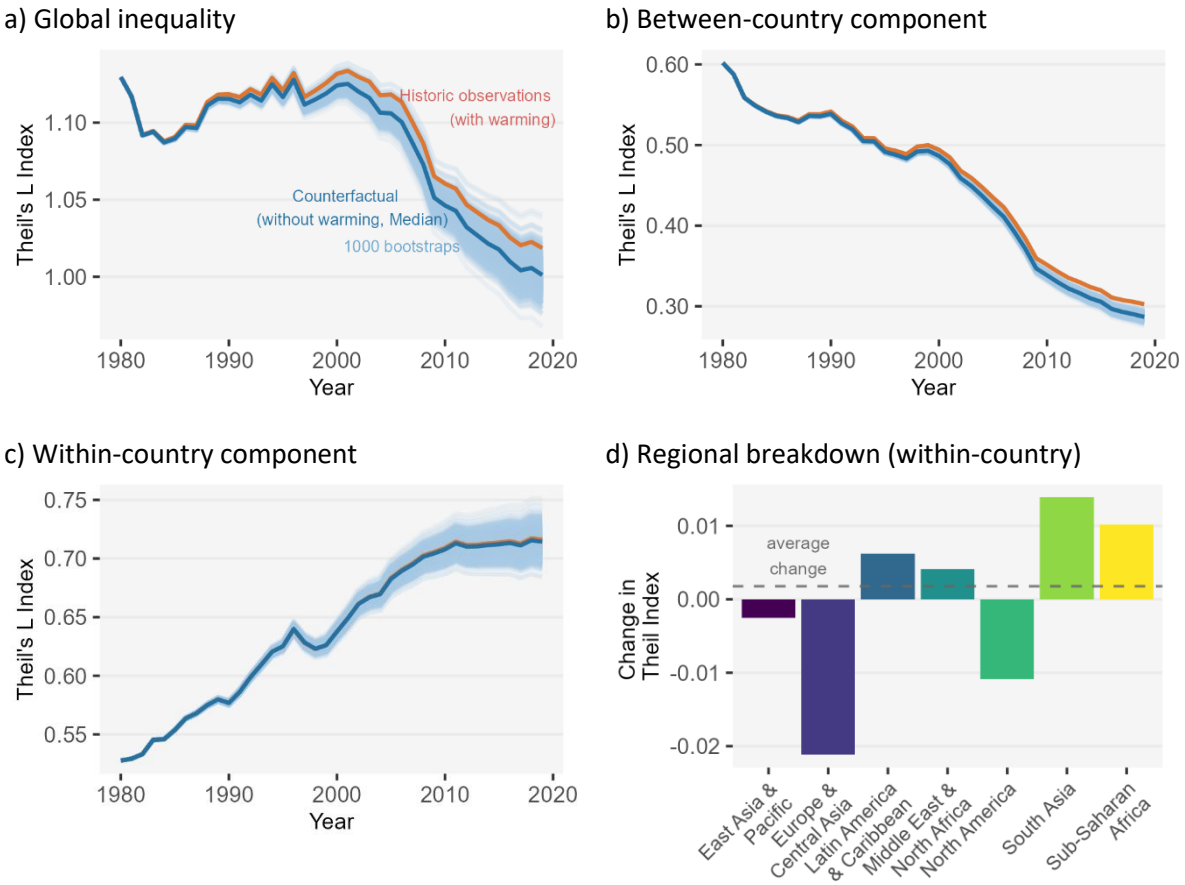
Note: The upper plots display the median marginal effects computed from 1,000 bootstrapped estimates of the coefficients. Decile 1 to 10 represent income groups ranging from the poorest to the richest. The light purple area illustrates the range of temperature optima across the 10 income deciles, and the light blue area shows the spread of marginal effects for these deciles at the 90th percentile of the temperature distribution. The lower histograms depict the temperature distribution for each country group, with each observation corresponding to the income decile of the country for a specific year.

Accumulated over four decades, these growth effects translate into substantial income losses in much of the global South and modest gains or near-neutral impacts in some colder, high-latitude economies. Under a 10-year half-life, global income in 2019 is about 2.7% lower than in the no-warming counterfactual. In low-income economies, losses for the bottom decile are markedly larger than for the top decile, while in high-income economies poorer deciles often fare slightly better than richer ones, implying mildly progressive impacts within that group.

The inequality analysis shows that historical warming has raised global inequality primarily by widening income gaps between countries. The global Theil L index increases relative to the counterfactual, with most simulated trajectories indicating higher observed inequality due to warming. Gini and Palma measures confirm that countries experiencing larger climate-related income losses tend to see greater national inequality increases, while those with mild gains often see reductions. Within-country inequality rises in many warm, low-income regions such as South Asia, Sub-Saharan Africa, and parts of Latin America, compounding their aggregate losses.

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Figure 7. Income inequality attributable to global warming (1980-2019, 10-year half-life)



Note: In Figures 3.a, 3.b, and 3.c, 1000 blue lines represent the estimated inequality for the counterfactual world from 1000 bootstrapping regressions, demonstrating the uncertainty range from the estimation of impact functions. The darker blue line represents the median estimates.

5.4 Income Elasticities and Policy Implications

Across country-years with climate-induced losses, preliminary estimates of within-country income elasticities of climate impacts indicate that the elasticity of damages is below unity in 84% of cases (median 0.93). For climate-related gains in cold area, the elasticity is likewise below unity (median 0.63), implying that both losses and benefits tend to be proportionally larger for poorer groups.

The results imply that historical warming has not only reduced global income but also shifted its distribution in ways that systematically disadvantage poorer populations in already warm countries. For policy and integrated assessment modelling, this underscores the need to account explicitly for heterogeneous, income-dependent climate damages when evaluating mitigation, adaptation, and compensation strategies.

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6 Distributional implications of mitigation policies in overshoot scenarios

Based on manuscript in preparation: Zhong, J., Piontek, F., Bordisky, B.L., Chen, D.M.C., Missbach, L., Hasse, R., Kriegler, E. Distributional Impacts of 1.5 °C Overshoot Pathways: Food, Energy, and the Limits of Carbon Revenue Recycling. In prep.

6.1 Introduction and Research Gap

Limiting warming to 1.5 °C is a central goal of Paris Agreement, yet with current pledges off track, many scenarios now rely on temperature overshoot and large-scale carbon dioxide removal (CDR). IPCC assessments warn that both the level and duration of overshoot increase climate risks and endanger the feasibility of climate targets, yet most analyses focus on biophysical or macroeconomic indicators and say little about who within countries bears the resulting burdens. Mitigation policies and large-scale CDR deployment also raise energy and food prices, which weigh disproportionately on low-income households and can undermine social acceptance of mitigation if they are perceived as unfair. High levels of CDR under high overshoot scenarios change the revenue structure allowing for redistributional policies which has been identified as a key way to alleviate distributional impacts in other scenarios.

We address this gap by examining how 1.5 °C overshoot pathways affect within-country inequality via food and energy prices, and to what extent carbon revenues can realistically compensate these distributional impacts over time. We compare low- and high-overshoot pathways and explicitly link the timing of mitigation, CDR deployment and fiscal flows to decile-level welfare outcomes.

6.2 Methods and Analytical Framework

We combine the REMIND-MAgPIE integrated assessment modelling framework with a post-processing distributional module that tracks real consumption for ten income deciles in 12 world regions. REMIND provides regional projections of food and energy prices, carbon prices, and carbon revenues for three core pathways: a baseline reflecting current policies, a low-overshoot 1.5 °C scenario with earlier and stronger mitigation and limited CDR, and a high-overshoot 1.5° scenario with delayed mitigation and extensive late-century CDR deployment.

Using empirically estimated Engel curves, we map changes in food and energy prices into decile-specific welfare effects, accounting for heterogeneous budget shares across the income distribution. We then compare two stylized carbon revenue recycling schemes: (i) a period-by-period inequality-neutral scheme, in which net carbon revenues in each year are returned to households in an inequality-neutral manner; and (ii) an Intertemporal Equal-Per-Capita Recycling (IEPR) scheme, in which a fixed share of early surplus revenues is pooled in a national “carbon bond” and later used to finance equal per-capita transfers if and when net carbon revenues turn negative during the CDR phase. IEPR is designed to capture the idea that high early carbon price revenues under overshoot can be earmarked to cover later negative fiscal flows, providing an upper bound on what intertemporal recycling of mitigation revenues could achieve for mitigating distributional consequences.

We measure household welfare as real consumption and quantify inequality using the Gini and Theil indices, decomposing the latter into within- and between-country components. We further break down welfare changes by region, sector (food vs energy), and income decile to identify the main drivers of distributional impacts under low- and high-overshoot pathways.

6.3 Key Findings: Overshoot, Prices and Inequality

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We find that both overshoot pathways raise inequality relative to baseline, but with distinct temporal and sectoral profiles (Figure 7). Low-overshoot front-loads mitigation: inequality rises earlier, driven mainly by higher energy prices for poorer deciles, but stabilizes or improves again after mid-century as energy systems decarbonize. High-overshoot spreads the increase over a longer period and reduces the medium-term peak, but leads to larger and more persistent inequality in the second half of the century, when extensive CDR deployment drives sustained food price increases.

Compared with the neutral scheme, IEPR helps to reduce global inequality. In the low-overshoot scenario, it can fully offset or even overcompensate the additional inequality generated by mitigation for most periods, effectively neutralising the distributional impact of higher prices. In the high-overshoot scenario, however, IEPR is not sufficient: saving into the climate bond reduces available fiscal space already in earlier decades, and the revenue available after these savings is too small to offset the additional inequality over the century.
Figure 1. Change in global inequality due to climate policy relative to the reference current policy scenario, under alternative overshoot and recycling schemes. Colors refer to the type of overshoot (orange: high overshoot, green: low overshoot), line styles to the recycling scheme (solid: neutral, dashed: IEPR).

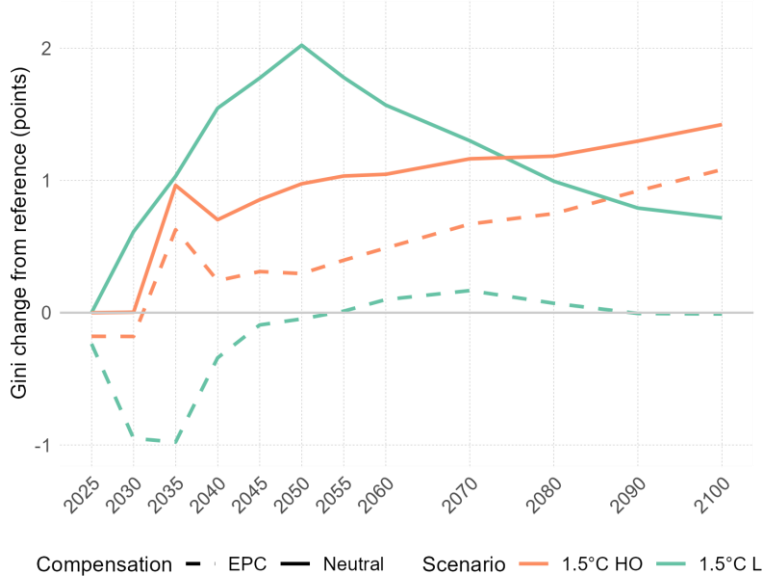


Figure 8: Impact on the Gini index

In terms of sectoral drivers (Figure 9), higher energy prices – particularly for transport fuels and residential fuels other than electricity, gas– are an important source of additional inequality in the early century, but their contribution gradually fades as energy systems decarbonize. Food expenditures, by contrast, already account for a comparable or larger share of inequality impacts in many regions early on and become the dominant driver over time: prices for staple crops and animal products rise persistently, especially under high-overshoot pathways, and disproportionately burden lower-income households. Despite regional heterogeneity, this shift from a mixed energy-and-food pattern to one where food, especially animal products and staples, drives distributional outcomes is a robust feature of our results.

6.4 Policy Implications

Our results indicate that overshoot is not only a feasibility risk for climate policy and a risk for higher climate change impacts, but also a distributional one. High-overshoot pathways create a situation in which the need for redistribution is greatest just as fiscal space is eroded by CDR-related negative revenues. In such cases, equal per-capita recycling is insufficient; more progressive compensation schemes that concentrate transfers on lower-income households would be required to prevent rising inequality. The sectoral profiles in our analysis point to where such targeting is most effective, suggesting that support should focus in particular on food expenditures – especially staples and animal products – and on vulnerable regions where these items

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account for a large share of poor households' budgets. Dietary changes might alleviate this pressure as well.

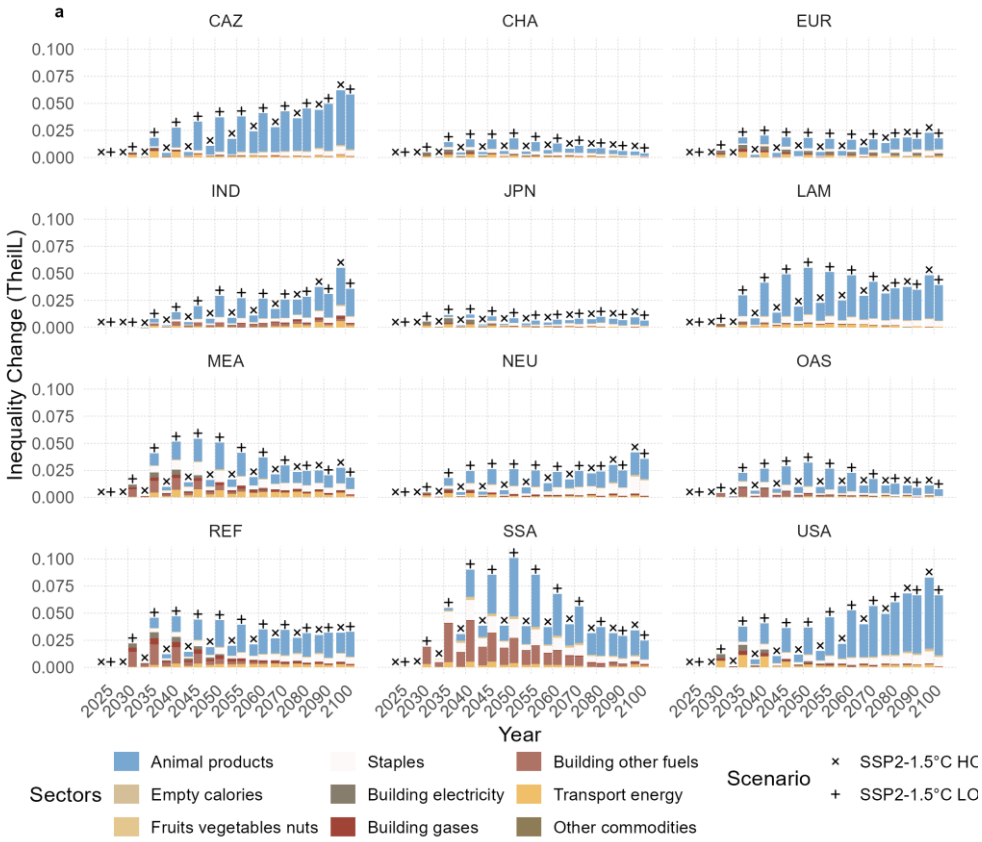


Figure 9. Sectoral contribution to within-country inequality change compared to the reference current policy scenario (in percentage points), for the 12 world regions in REMIND-MAgPIE. Crosses mark the high overshoot, plus signs the low overshoot scenario.

7 Inequality and Gender Disparities in India - Climate Policies, Revenue Recycling, and Just Mitigation Pathways

7.1 Background and Motivation

Climate mitigation policies create complex distributional outcomes across populations. While integrated assessment models (IAMs) increasingly incorporate within-country inequality metrics, critical gaps remain in how these models address gender dimensions. This research addresses two interconnected challenges: how to meaningfully integrate gender disparities into climate policy analysis, and how different revenue recycling schemes from carbon taxation affect inequality across both income and gender dimensions.

Recent advances in IAM development have incorporated income inequality through quantile/decile distributions. However, current approaches often rely on simplistic assumptions about redistribution mechanisms. This research moves beyond idealized per-capita redistribution schemes to examine targeted transfer programs that reflect actual implementation, including their exclusion errors and political constraints. The findings demonstrate that modeling redistribution choices substantially affects social cost of carbon estimates.

While most climate-inequality research focuses on vertical inequality between income groups, gender

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represents a critical horizontal dimension often neglected in mitigation analysis. Gender-disaggregated data remains scarce in climate-economy models, constraining the ability to understand how climate policies affect women and men differently. This gap is particularly pronounced in developing countries like India, where gender disparities intersect with poverty, labor participation constraints, and institutional design of social programs.

7.2 Methodology and India Case Study

The study employs a soft-linked inequality module integrated with an IAM framework (WITCH), using India as the focal case. The methodology combines macro climate-economy modeling with micro-level distributional analysis calibrated to household survey data disaggregated by gender of household head.

The approach endogenizes income and consumption distributions through a microfounded heterogeneous agent framework incorporating Pareto-distributed income at the country level. Key sources of heterogeneity include skill premia differences, capital and wealth distribution, endogenous savings behavior, and sector-specific energy consumption patterns. Data comes from Indian household surveys disaggregated by deciles and gender of household head, capturing variations in income shares, consumption patterns across energy, housing, food and transportation, savings rates, education attainment, and wealth distribution.

Gender differences are integrated through household-level disaggregation, recognizing that income, consumption, capital, and transfers are household phenomena. While individual-level wage data on gender gaps is collected for calibration, the distributional modeling primarily uses gender of household head as the classification variable. This approach acknowledges both the household-level nature of consumption and budget decisions, and the empirical reality that in many South Asian contexts, household businesses are the primary income source, making individual-level attribution difficult.

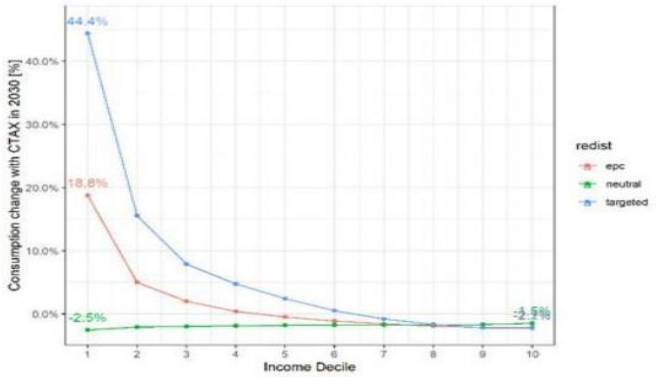
India presents a complex case combining ambitious climate commitments (net-zero by 2070 with current low per-capita emissions), persistent inequality despite growth-driven poverty reduction, and acute gender challenges including the lowest female labor participation (20%) among large economies and demographic imbalances. Cash transfer programs targeting poverty reduction through schemes like Below Poverty Line cards face substantial implementation challenges including leakage and weak targeting. These implementation realities inform the distributional assumptions in the model.

The analysis compares a reference scenario based on current policies with a mitigation pathway implementing a $\$30/tCO_2$ carbon tax in 2020, increasing at 5% annually. Results are examined across inequality metrics, revenue recycling schemes, and gender dimensions.

7.3 Inequality Dynamics and Revenue Recycling

Baseline inequality projections show the Gini coefficient increasing from 0.63 today to approximately 0.70 by 2100, driven by wealth accumulation and limited educational convergence. Carbon taxation alone has minimal impact on inequality. However, revenue recycling substantially alters distributional outcomes. Equal per-capita redistribution reduces inequality by approximately one point on the Gini scale. Targeted transfers to existing social assistance beneficiaries achieve even greater inequality reduction since carbon revenues concentrate among fewer, poorer households with higher pre-existing vulnerability.

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Decile	BPL_card	Antyoda card	other card
1	20.18%	4.42%	7.73%
2	20.56%	3.14%	12.46%
3	19.22%	3.02%	17.37%
4	19.90%	2.58%	18.56%
5	19.06%	2.27%	22.63%
6	16.83%	1.89%	24.72%
7	14.59%	1.23%	27.08%
8	12.26%	0.97%	28.80%
9	8.89%	0.78%	32.03%
10	4.19%	0.41%	32.15%

Figure 10: Consumption changes by income decile across three redistribution scenarios (redistributive, neutral, targeted) and implementation challenges. The chart reveals strong regressivity of carbon taxation on lower income deciles, but targeted schemes can reverse this and generate stronger distributional benefits. The table shows that Below Poverty Line (BPL) cards, while covering 20% of decile 1, miss substantial portions of the population, with exclusion errors increasing in lower deciles (only 4.19% of decile 10 are BPL cardholders), highlighting the tension between targeting efficiency and coverage breadth.

7.4 Gender Differentiation in Baseline Characteristics

Gender differences emerge primarily through education levels and income source diversity rather than consumption patterns or savings rates. Transportation consumption concentrates in higher deciles for both genders, while housing represents a larger share of expenditure for lower-income households regardless of gender. The critical gendered dimension lies in educational attainment, where stark differences appear across the income distribution. Female-headed households show significantly lower educational attainment in lower income deciles but converge and even surpass male-headed households at higher income levels, likely reflecting selective survival effects and compositional differences in household formation.

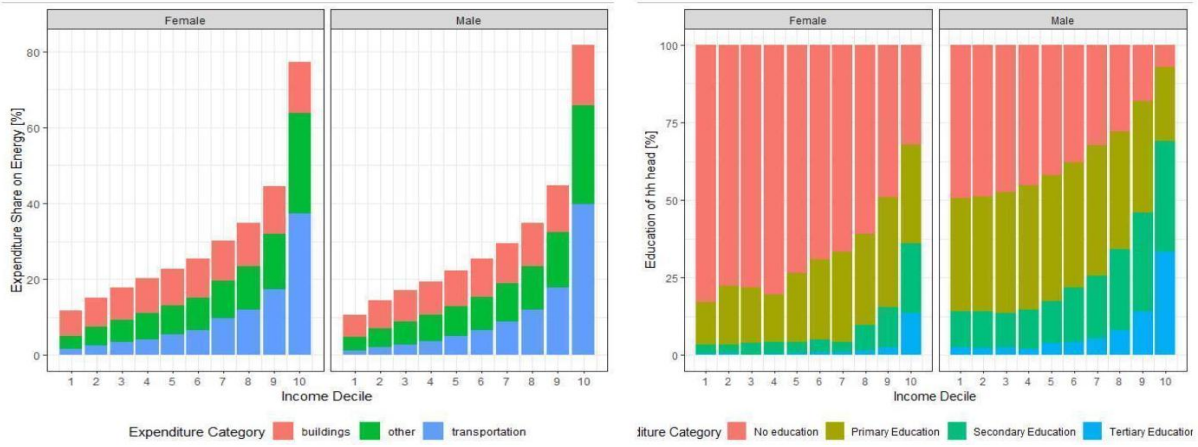


Figure 11: Gender differences in household expenditure patterns and educational attainment. Left panels show expenditure shares for buildings (red), other consumption (green), and transportation (blue) across income deciles for female- and male-headed households. Right panels display educational attainment composition across deciles. Transportation exhibits a strong concentration gradient in upper deciles for both genders, while housing shares decline with income. Critically, education reveals the sharpest gender gaps, with female-headed households in lower deciles showing much higher shares of no education, while tertiary education increases more steeply for female-headed households in higher income deciles, suggesting complex selection and achievement effects.

7.5 Policy Incidence and Gender-Differentiated Impacts

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Policy incidence is regressive for both genders, but redistribution mechanisms can convert this into progressive outcomes with especially pronounced gains for women. This reflects the combination of lower initial consumption levels and greater pre-existing vulnerability among female-headed households. Targeted redistribution substantially outperforms universal per-capita approaches, with the strongest effects for women in lower income deciles. The mechanisms operate through two channels: first, women spend less on carbon-intensive energy services, reducing their direct burden from the carbon tax; second, targeted transfers direct resources to households with lower baseline consumption, where marginal utility of income is highest.

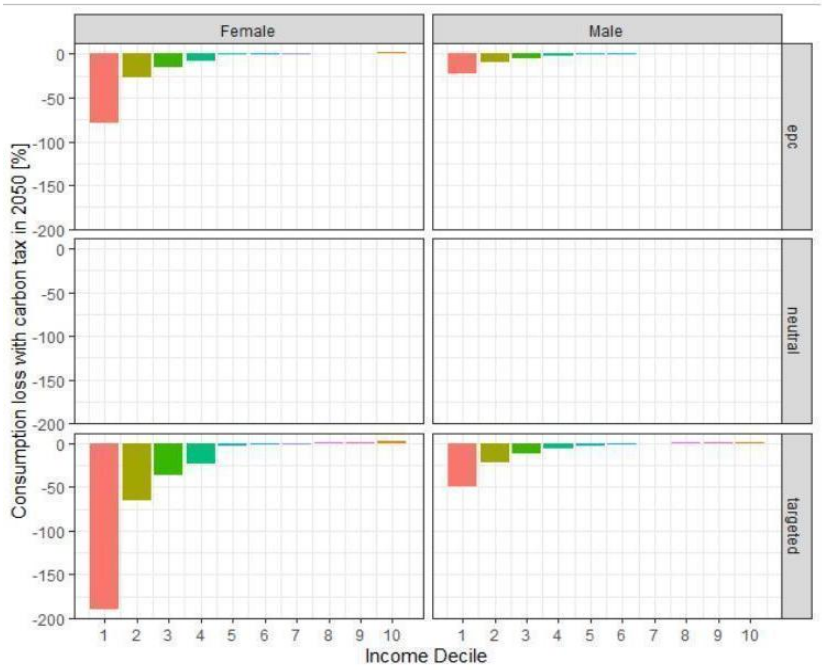


Figure 12: Consumption losses (top four panels) and their reversal through redistribution by gender and decile for three policy scenarios. Without redistribution (2050 baseline).

7.6 Policy Implications and Research Gaps

Results demonstrate that mitigation policy design choices fundamentally shape distributional outcomes. Targeted transfer schemes significantly outperform universal per-capita approaches in reducing inequality and protecting vulnerable populations, but implementation challenges including exclusion errors and political constraints mean actual outcomes depend critically on institutional capacity. Gender-disaggregated analysis reveals that horizontal inequalities substantially influence the "justness" of mitigation pathways, particularly through education's mediating role on labor opportunities and income generation.

This analysis reveals substantial data limitations constraining gender-aware climate policy modeling. Current household surveys lack detailed intra-household distribution information, necessitating simplifying assumptions about household-level aggregation. Individual-level labor supply data for women remains limited in most developing country contexts. Future research should: expand gender-disaggregated individual-level data collection; develop improved methodologies for modeling intra-household decision-making in climate-economy frameworks; incorporate social norms and behavioral constraints affecting gendered labor supply and consumption choices; and conduct comparative analysis across country contexts to identify how institutional contexts mediate gender-climate policy interactions. These extensions would substantially strengthen the evidence base for designing truly equitable climate mitigation pathways that advance sustainable development objectives.

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8 Climate Policy and Global Redistribution – The potential of a global climate fund

As one singular exercise, we were inspired by the proposal by Fabre et al. (2025), we simulated in the RICE50+ IAM (from above) what a global climate dividend could entail in terms of achieving climate neutrality while at the same time tackling global inequality and poverty.
We find that two-thirds of the global population would be economically better off already by 2030 due to a global dividend, that we estimate to start out at 360 US-$ per capita, peaking at 700 US-$ by 2060. This global climate dividend could successfully alleviate short-term purchasing power losses in developing countries and poorer households world-wide, while enabling stabilizing global warming by the end of the century.

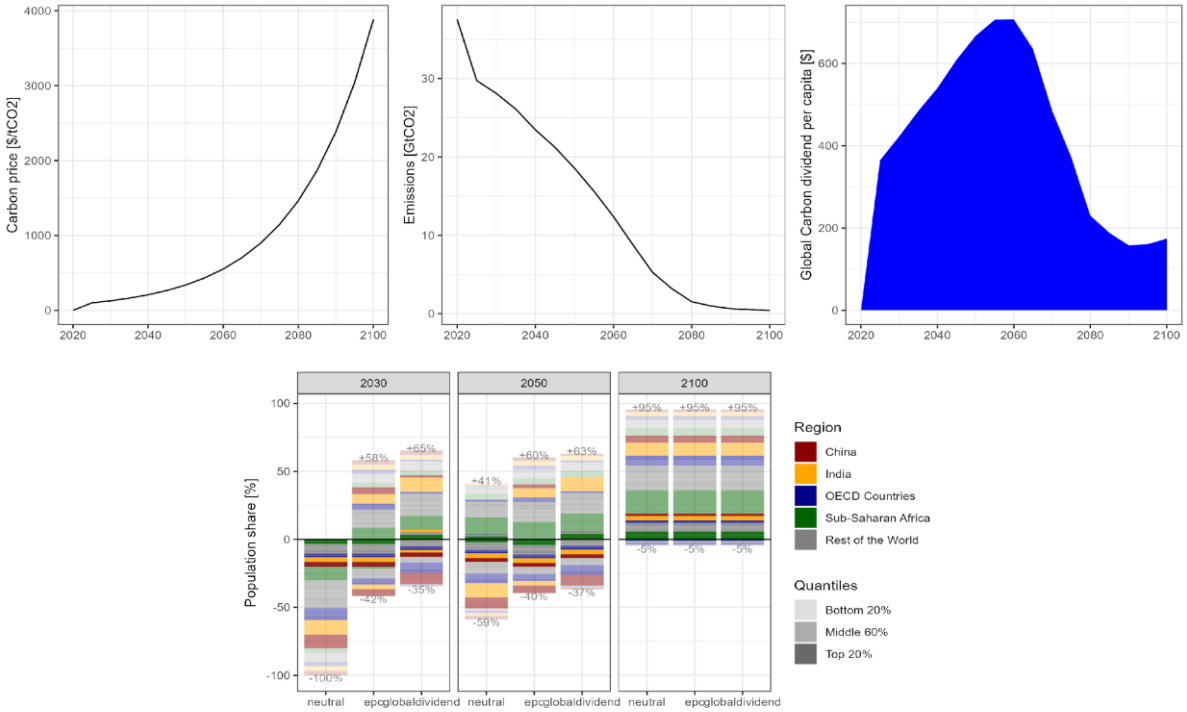


Figure 13: Implications of a global climate dividend

9 Sub-national implications on the electricity sector investments and marginal prices from the targets of Fit-for-55 and National Energy and Climate Plans

Based on the manuscript: Frilingou F., Van de Ven D.-J., Sampedro J., Torné A., Trutnevyte E., Horowitz R., Rodés-Bachs C., Koasidis K., Mittal S., XexakisG., Nikas A. Cost-optimal vs. policy-driven scenarios for a decarbonised European energy system. Environmental Research Letters 2025, submitted.

This study soft-linked the GCAM Europe integrated assessment model that has a disaggregation at the EU Member State level with the electricity sector model EXPANSE that has a disaggregation at NUTS-2 subnational level. The aim was to analyze the regional distributional implications throughout Europe of implementing EU-wide Fit-for-55 targets (FF55 abbreviation) and targets from National Energy and Climate Plans (NECP). Two

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pathways for reaching these targets were compared: a cost-optimal pathway through carbon caps (FREE) and a pathway that is in line with current policies (POLICY), such as emissions trading system, vehicle standards, country-specific phase-outs, and renewable energy and energy efficiency targets. The two models hence complemented each other because GCAM Europe provided the whole-system, big-picture context, and EXPANSE then evaluated the detailed implications for the electricity sector and the European NUTS-2 regions.

Solar PV and especially onshore and offshore wind power were found to be the main technologies to reach the decarbonization targets, together with enabling infrastructures, such as extension of transmission grid, battery storage, and power-to-hydrogen (Figure 14). Overall investment needs were up to 50% higher in the case of the scenarios with current policies (POLICY) that do not allow optimizing the choice and location of power plants at a continental level and hence require higher overall generation capacities to be built, while investments in storage and transmission overall remain similar. As a result, the scenarios with the current policies (POLICY) also led to higher and more regionally varied wholesale marginal electricity prices if accounting for the carbon price element in this price (Figure 15). Eastern, central, and western Europe had relatively higher prices as compared to the very northern and southern Europe. Cost-optimal pathways through carbon caps (FREE) to reach the EU-wide Fit-for-55and NECP targets kept the locational marginal prices lower and relatively even throughout Europe. The differences between the Fit-for-55 (FF55) and NECP (NECP) targets were minor as compared to the differences between the POLICY and FREE scenarios throughout the whole of Europe, except for several peripheral regions, such as parts of Ireland or Northern Sweden. For this reason, it is recommended that current policies are monitored and recalibrated to steer investment effectively and to keep the electricity prices low and as regionally even as possible.

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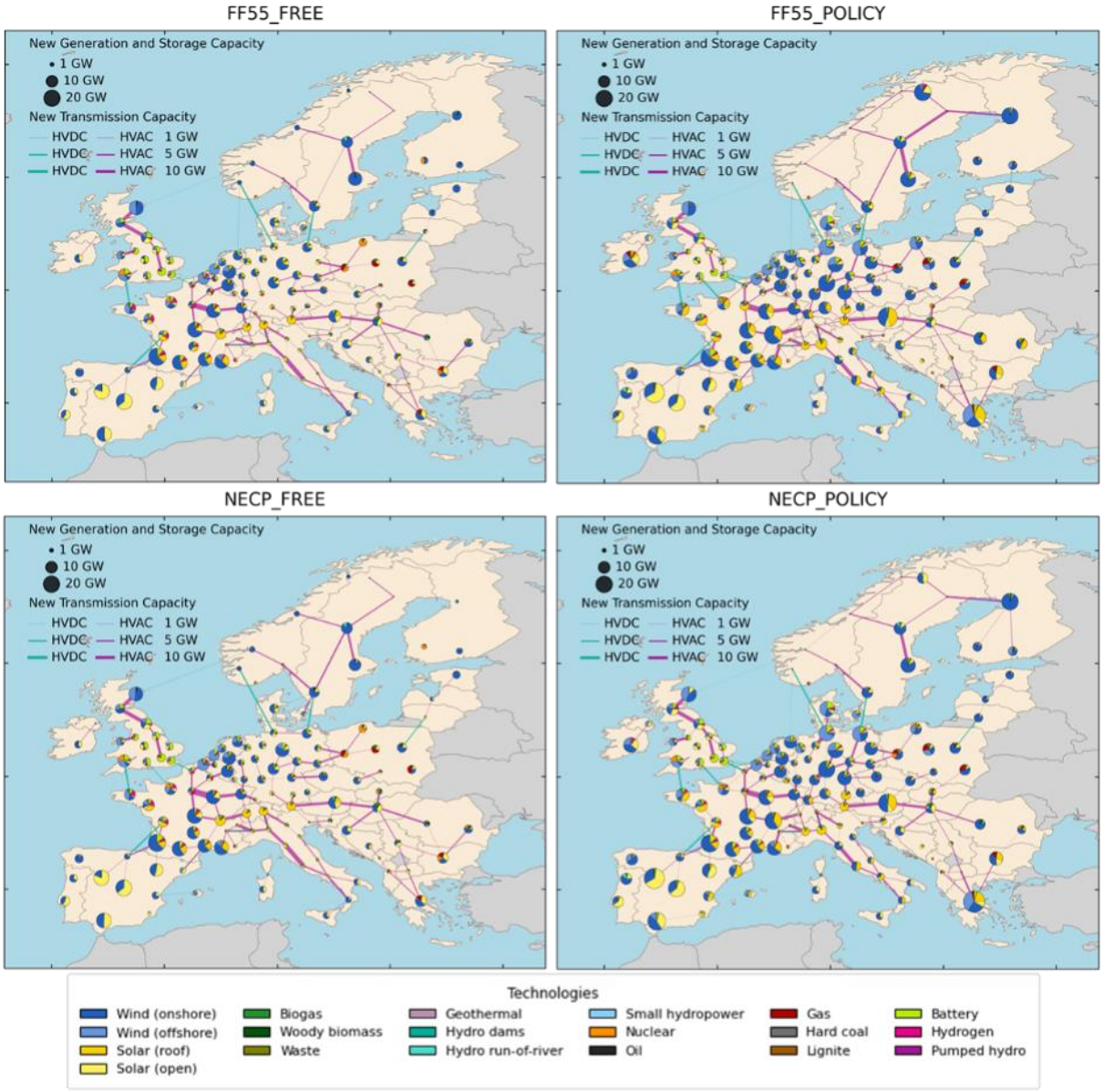


Figure 14: Europe-wide regional distribution of new installed electricity capacities in 2035 as compared to 2018 under the modelled scenarios: FF55 – Fit-fo-55 targets, NECP - targets from the National Energy and Climate Plans, FREE – cost-optimal implementation of the targets, POLICY – current policy-driven implementation of the targets

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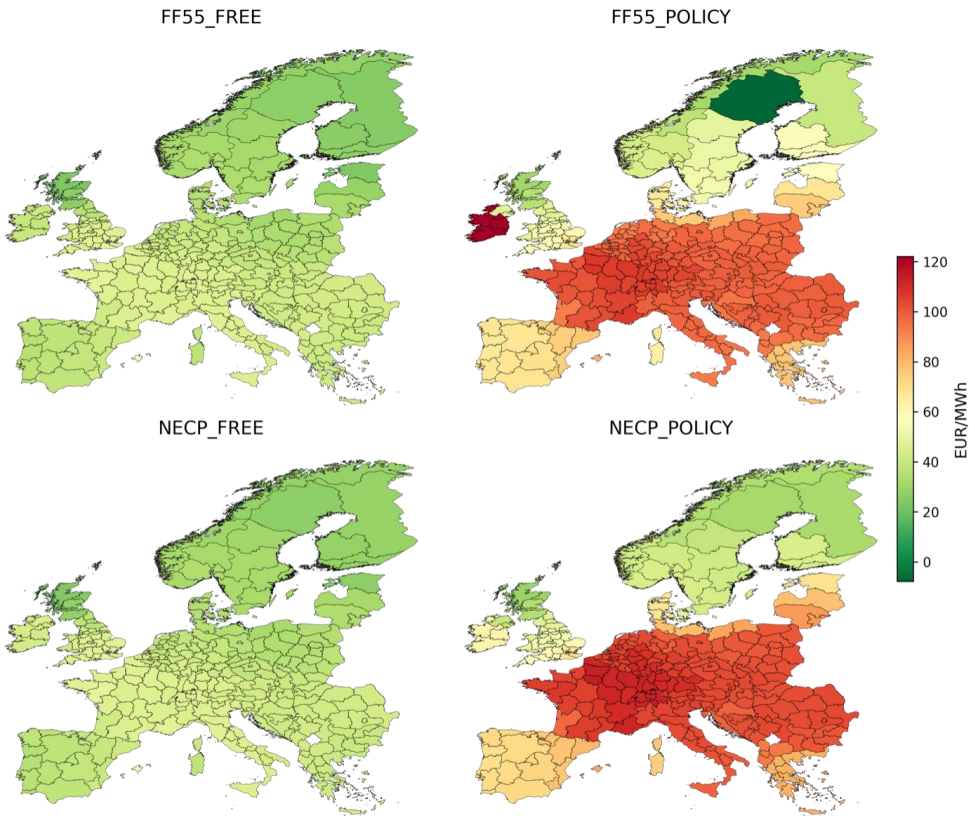


Figure 15: Europe-wide regional distribution of wholesale locational marginal prices, including the contribution of carbon price: FF55 – Fit-fo-55 targets, NECP - targets from the National Energy and Climate Plans, FREE – cost-optimal implementation of the targets, POLICY – current policy-driven implementation of the targets

8. The equity and efficiency of carbon taxation: a multi-model, multi-country analysis

Based on the manuscript: Méjean, A., Leblanc, F., Lefèvre, J., Fragkiadakis, D., Fragkos, P., Garaffa, R., Lynch., C., Vandyck, T., 2025. The equity and efficiency of carbon taxation: a multi-model, multi-country analysis, Working paper.

8.1 Background: the roles of the source and use of income in shaping inequalities

Climate change mitigation policies can have contrasted economic effects across socio-economic groups and countries. Depending on income levels, geographical locations and dependence on fossil fuels, mitigation policies can increase the costs for consumers, disproportionally affecting their purchasing power. The links between inequality, climate change, mitigation policies and redistribution systems have been extensively studied in the economic literature. This literature generally concludes that carbon pricing and higher energy prices are regressive. Indeed, because carbon taxation raises the price of carbon intensive goods, the burden is shared unequally among households, thus exacerbating existing economic inequalities as the poorest households tend to spend a larger share of their income on carbon intensive goods compared to the rich. This effect is known as the tax incidence via the use of income, and has been the main focus of the existing literature on the distributive impacts of carbon pricing. Carbon taxation can also influence economic inequality through

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its effect on the prices of factors of production (e.g., labor, capital, land). It alters the structure of the economy, and therefore the nature of household income. The share of capital and labor in total household income differs by income quantile, with poorer quantiles relying more on labor income than richer ones. A lower labor share is associated with higher income inequality. All else being equal, carbon taxation may further increase inequalities if low-carbon economies are more capital intensive than those based on the extensive use of fossil fuels. This second effect is the tax incidence via the source of income, and has received less attention in assessments of the costs of climate change mitigation.

In this study, we examine the combined and respective roles of the use of income and the source of income channels in shaping economic inequalities. More precisely, we highlight how the terms of the equity-efficiency trade-off of carbon pricing may be driven by these channels, and may vary across regions with contrasted levels of economic development and across time.

8.2 Four macroeconomic models, one ex-post inequality module

We develop an ex-post inequality module that includes both channels, with a distinction between capital and labor income, and plug it onto climate policy scenarios obtained from four multi-sectoral macroeconomic integrated assessment models: E3ME-FTT, GEM-E3-FIT, IMACLIM-R World, JRC-GEM-E3.

We consider a baseline scenario that only includes already implemented national climate policies. Baseline GDP and population trajectories are aligned with the SSP2 scenario quantification. Climate policy scenarios are compatible with the Paris Agreement objective of staying well below 2°C, with an imposed cumulative CO2 budget between 2020 and 2050 ranging from 552 to 639 GtCO2. The emission budget is reached using a uniform carbon price across regions and sectors, without any temperature overshoot. In climate policy scenarios, we consider two types of tax revenue recycling: Labor Tax Cuts (carbon revenues are used to reduce the labour taxes or the social security contributions) or Lump-Sum Transfers (carbon revenues are transferred back to households on an equal basis per household).

This exercise is carried out with four multi-sectoral integrated assessment models: E3ME-FTT, GEM-E3-FIT, IMACLIM-R World, and JRC-GEM-E3. It is interesting to consider these models together, as they incorporate contrasting macroeconomic paradigms and assumptions on the way capital and labor markets work. GEM-E3-FIT, IMACLIM-R World and JRC-GEM-E3 are general equilibrium (supply-driven) models based on crowding-out effects, i.e., any additional investment linked to climate change mitigation is assumed to crowd out investment in other productive sectors. By contrast, E3ME-FTT is a post-keynesian (demand-driven) model which assumes that labor and capital are under-utilised, with no constraint on investments. We use an ex-post inequality module to study the impact of different modes of recycling carbon tax revenues on inequality for selected regions in the four models.

The ex-post inequality module computes consumption and income Gini indices, and consumption and income quantiles using the following macroeconomic outputs from the 4 models: consumption, mitigation costs, emissions, carbon taxes, GDP per capita, and the ratio of labor income to total income. We assume that for each country, income is distributed across deciles according to a lognormal distribution. We can deduce standard deviations from country Gini indices, and then a Lorenz curve for each country and each time step. We then aggregate country Lorenz curves into regional Lorenz curves, following the regional definition of each model. The regional consumption deciles obtained from the calibration are then fed into the model. They are modified depending on the climate scenario considered. In the inequality module, the use of income channel refers to how revenue is used, whatever its origin. This is the effect of carbon pricing on inequality via consumption (carbon pricing increases the price of all goods, which may disproportionately impact low income households). The source of income channel refers to the effect of the origin of income on economic inequalities. Carbon pricing may shift the balance between labor and capital in the economy as a whole, which will affect inequalities across households, as poorer households tend to rely less on revenues from capital than

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richer ones. We account for the use of income channel by assuming that mitigation costs and carbon tax burdens are distributed across deciles using consumption elasticities. The initial burden of a carbon tax is the distribution of mitigation costs and carbon tax payments before tax revenues are recycled and redistributed. We follow the approach of (Budolfson et al. 2021). We account for the source of income channel by representing in a stylized way the impact of the labor share (labor income in total national income) on consumption Gini indices. We assume that the consumption Gini indices computed initially decrease with the labor share according to an elasticity calibrated on econometric estimates available in the literature.

8.3 The progressivity of carbon tax revenue recycling

First, we find economic losses but reduced domestic inequalities in most climate policy scenarios compared to the business-as-usual. Lump-sum transfers to households are found to be more progressive than labor tax cuts in most cases. The progressivity of climate policy decreases with the level of economic development of countries (Figure 16) and this is the reason for observing much higher progressivity in low-income countries like India. Further, the comparison between Europe and the US, two regions with relatively similar income per capita, shows that lump-sum transfers tend to be more progressive in carbon-intensive economies (the US in this case).

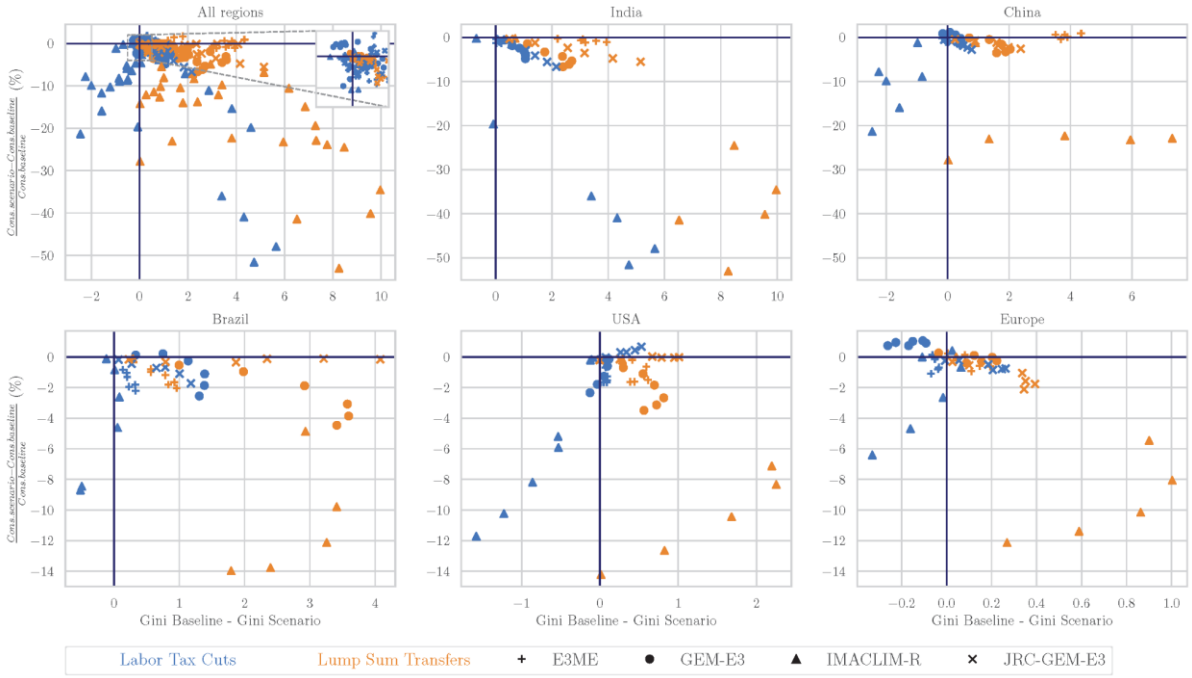


Figure 16: Difference in consumption between climate scenarios and the reference vs. difference between consumption Gini in the business-as-usual and climate scenarios for all regions combined, India, China, Brazil, the USA and Europe, for all years considered (2025-2050, in 5-year time steps). Scenarios account for both the source of income and the use of income channels.

Second, we examine the impact of climate policy on inequalities over time. A large majority of climate policy scenarios are progressive compared to the business-as-usual scenario over the time horizon considered (2025-2050), as they are characterized by a lower Gini coefficient than in the business-as-usual scenario. This is the case for all scenarios where carbon tax revenues are recycled through lump-sum transfers, and to a lower extent for scenarios where carbon tax revenues are recycled through labor tax cuts (Figure 17). Further, we find that the progressivity of carbon revenue recycling depends on the volume of carbon tax revenues, and decreases as the carbon tax base depletes.

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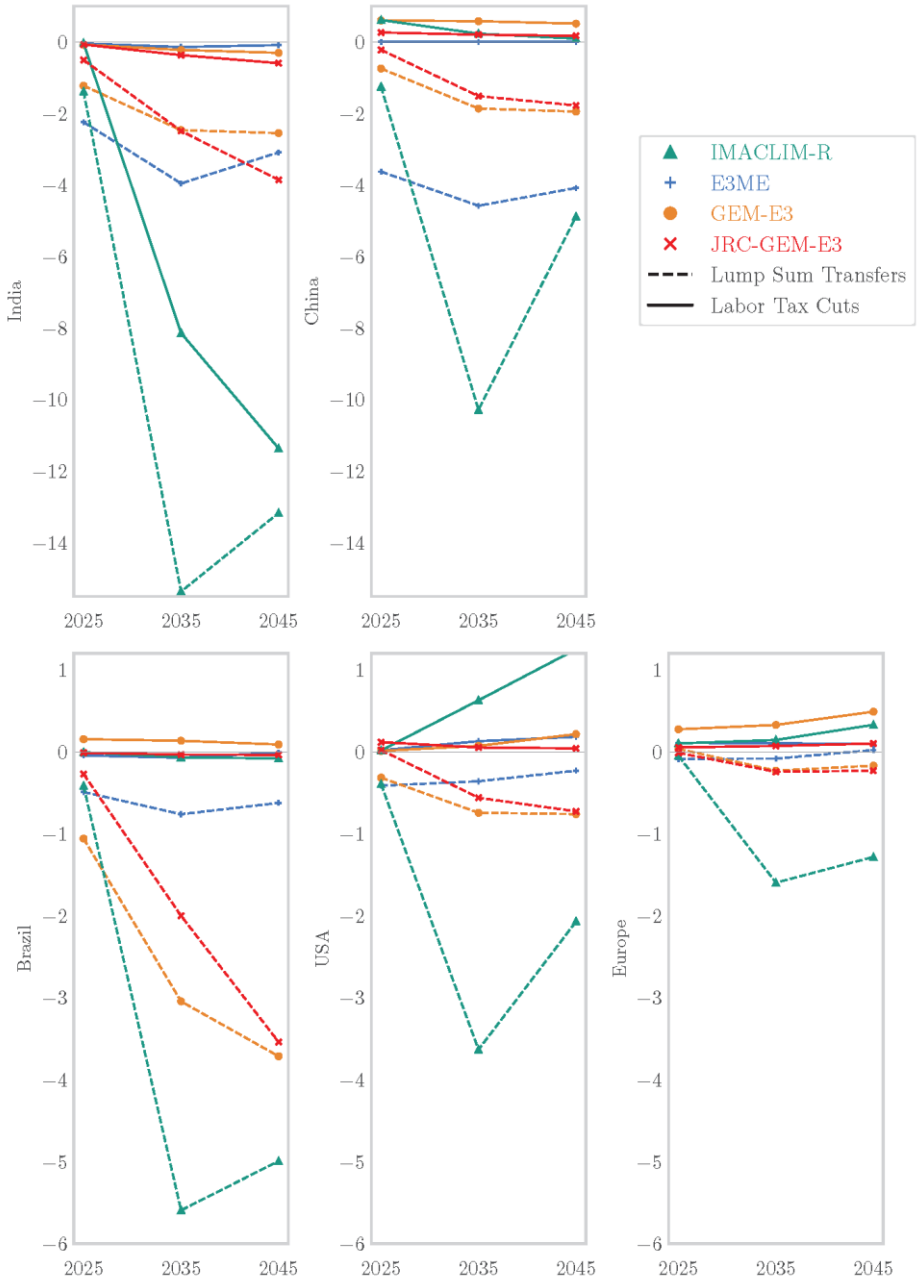


Figure 17: Difference in consumption Gini coefficients in climate policy scenarios wrt the business-as-usual scenario over time, for China, India, Brazil, Europe and the USA. Scenarios account for both the source of income and use of income channels (i.e., they include the effect of the evolution of the labor share on inequality). The results are presented for two types of carbon revenue recycling: lump-sum transfers (dotted lines) and labor tax cuts (solid lines), for the four models.

Third, we find that accounting for the impact of the source of income channel on inequalities reduces the gap between the impacts of the recycling schemes: it can mitigate the regressivity of labor tax cut revenue recycling depending on the model and region, while it reduces the progressivity of lump-sum recycling in most cases. The loss of progressivity of climate scenarios when accounting for the impact of the labor share on inequalities is driven by the capital-intensity of the transition to a low-carbon economy, and its effect on the level of real wages, which can be somewhat compensated by an increase in labor intensity in some cases (Figure 18).

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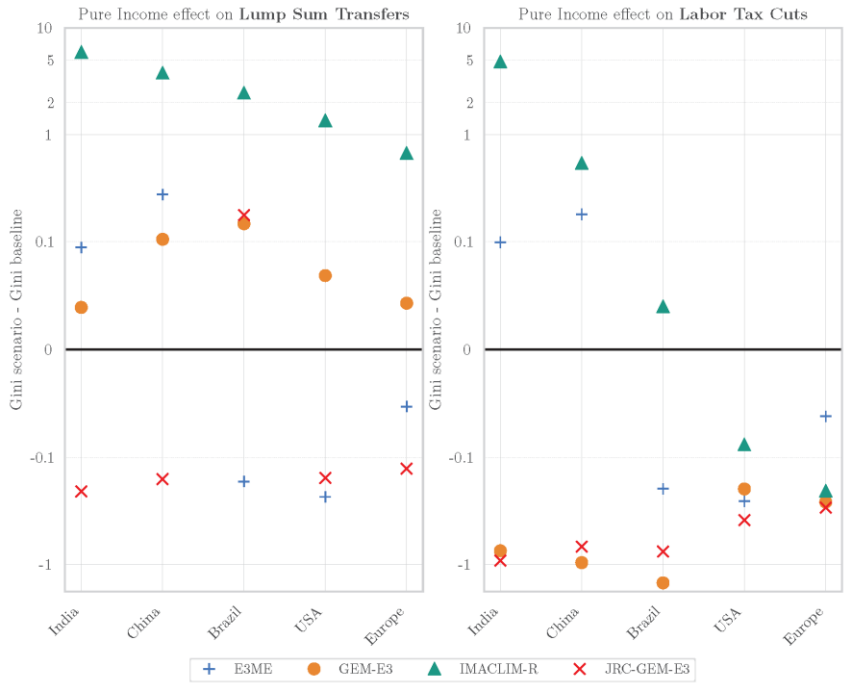


Figure 18: Variation in consumption Gini compared to the business-as-usual scenario due to the pure source of income channel in year 2040. Results are presented for recycling via lump-sum transfers and labor tax cuts, for the USA, Europe, China, Brazil and India, for all four models. We use a symlog scale: to deal with positive and negative values, the interval [-0.1, 0.01] is plotted on a linear scale. Data points above the zero line indicate that inequalities are higher in climate policy scenarios compared to the business-as-usual when one only accounts for the source of income channel.

Our message is twofold. First, while accounting for the labour share does not reverse the merit order of recycling schemes regarding inequality, it may still change the terms of the analysis. Indeed, accounting for the source of income channel hampers the progressivity of all revenue recycling options, and particularly so for lump-sum transfers. Second, policy-makers should be particularly attentive to the role of the labor factor in driving inequalities, as the transition may be accompanied by a large-scale reconfiguration of labor markets due to structural change and the emergence of green jobs and new skills requirements. This is crucial for future inequalities, as the progressivity of climate policies could be improved by sustaining the labor input in economic activity.

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Appendix

The appendix consists in the two published papers

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and

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A multi-model assessment of inequality and climate change

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Climate change and inequality are critical and interrelated issues. Despite growing empirical evidence on the distributional implications of climate policies and climate risks, mainstream model-based assessments are often silent on the interplay between climate change and economic inequality. Here we fill this gap through an ensemble of eight large-scale integrated assessment models that belong to different economic paradigms and feature income heterogeneity. We quantify the distributional implications of climate impacts and of the varying compensation schemes of climate policies compatible with the goals of the Paris Agreement. By 2100, climate impacts will increase inequality by 1.4 points of the Gini index on average. Maintaining global mean temperature below 1.5 °C reduces long-term inequality increase by two-thirds but increases it slightly in the short term. However, equal per-capita redistribution can offset the short-term effect, lowering the Gini index by almost two points. We quantify model uncertainty and find robust evidence that well-designed policies can help stabilize climate and promote economic inclusion.

Economic inequality between and within countries has become a major topic of debate. both in research and in society[1–3]. Inequality is interlinked with climate change mitigation and impacts, because of the regressive impacts of carbon taxes or higher energy prices[4,5] and of social repercussions and acceptability of climate policies. An increasing body of literature has explored the distributional effects of climate policies[6–8], poverty[9] and climate impacts between and within countries[10–12], suggesting that both climate policy and climate impacts affect more the lower end of income distribution. However, carbon revenues redistribution can address the adverse distributional implications of climate and energy policies[12–15].

Redistribution of carbon market revenues has been advocated to ensure that vulnerable households and businesses are sheltered from higher energy expenditures due to carbon pricing, in the hope of increasing support for climate policy (for example, the European Association of Environmental and Resource Economists' statement signed by more than 1,700 economists: www.eaere.org/statement). The European Union recently approved a climate policy package that establishes a Social Climate Fund to be financed with emission trading scheme revenues. Even if the impact on policy support might not be as strong as theoretically predicted[16], 'climate dividends' or lump sum transfers could have major impacts on inequality and poverty alleviation[17,18] and become even more relevant as a result of the pandemic, the energy crisis and the ongoing inflationary period[19]. The empirical evidence on public opinion support for redistribution is mixed: equal per-capita (EPC), or targeted (on poor households),

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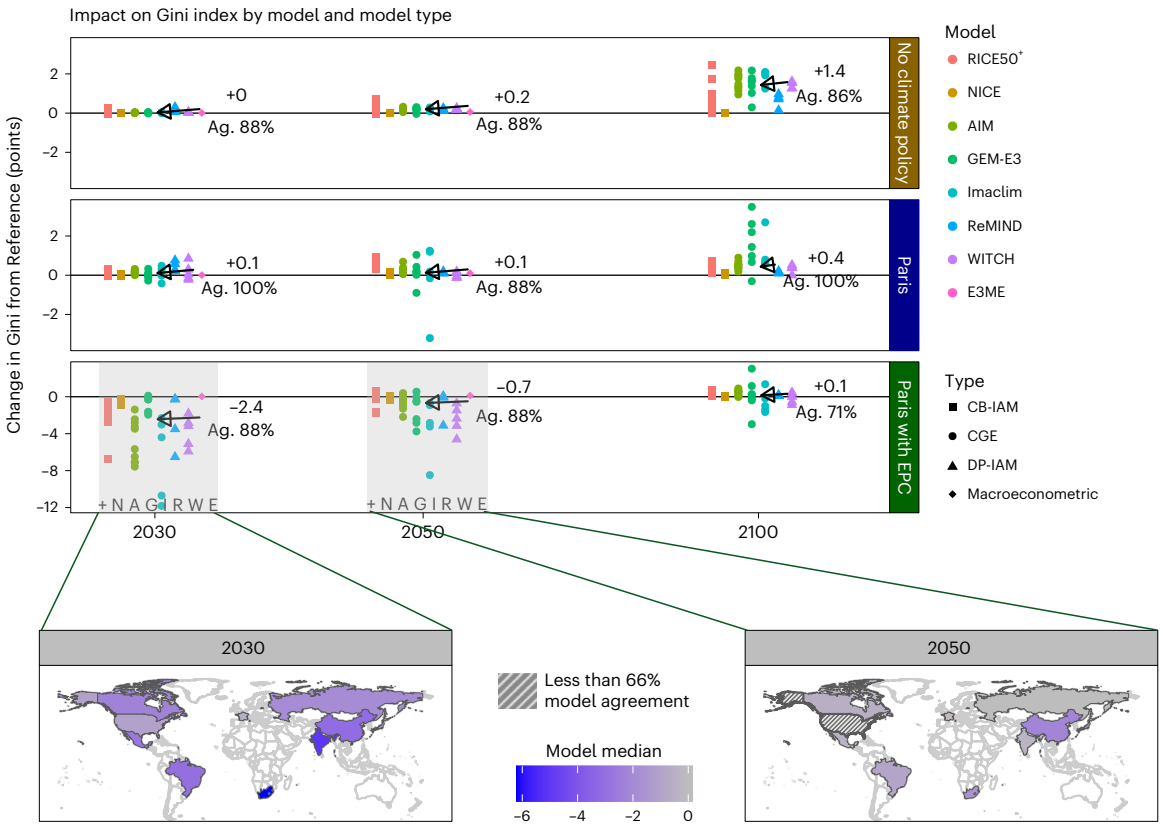


Fig. 1 | Change in Gini index from the Reference scenario without climate impacts. The top row shows the case of no climate policy, the middle row the Paris scenario and the bottom row shows the Paris scenario including EPC transfers. All individual countries are shown as points and all scenarios include climate impacts. Also included are the distributional consequences of climate damages. Models are categorized (colour and letter coded on the *x* axis using the first letter of each model ('+' for RICE50^{+})) and ordered and clustered by model type. Bottom, maps of the model median in 2030 and 2050. Numbers in black indicate median values pointing by the arrow to the median value. Note the different *y* axis scales across panels. Countries with less than two-thirds model agreement are shaded. Ag., agreement among models in terms of sign.

carbon tax redistribution has strong support in middle-income countries but lower support in high-income countries[20]. Redistribution of carbon revenues could also be combined with international between-country effort-sharing schemes[21], increasing the revenues available in developing countries.

Inequality is also affected by the uneven distribution of climate impacts and risks within and between countries. The advancements in estimation of impact functions of climate change with improved datasets and empirical methods[22–25], and highlight major regional discrepancies of climate risks, with potentially large implications of increasing inequalities across countries[26–28]. Recent empirical studies have found that climate impacts increase within-country inequality[11,29–33], in particular in low- or middle-income countries[34]. To date, however, assessments focus on the distributional effects of climate policies without considering the effect of climate impacts both within and between countries, with some exceptions[10,12,35].

Despite their relevance, climate–inequality interlinkages are not yet routinely included in mainstream climate–economy models, although individual modelling studies have explored policy incidence[36,37]: no scenario reported in the IPCC 6th assessment report database reports economic inequality indicators. One exception is a recent Energy Modelling Forum study[38], although this focused on international emission trading and is limited to computable general equilibrium models. Overall income deciles differ including in terms of in particular energy expenditures (Supplementary Fig. 1).

This Article provides a model comparison explicitly designed to investigate the link between climate change and inequality, quantifying the distributional implications of climate policies and climate change impacts. We do so through a model ensemble of eight integrated assessment models (IAMs) covering four main modelling paradigms. The multi-model analysis addresses the following research questions: (1) how climate impacts will affect inequality within countries; (2) how climate policies will affect the distribution of income and consumption within countries; (3) what role redistributive policies can play; (4) how these three channels compare quantitatively; and (5) the robustness of findings across a diverse set of models and countries.

This multi-model study employs eight models (Supplementary Fig. 2) representing four theoretical approaches (notably computable general equilibrium (CGE) models, detailed process-based (DP-IAM) and cost-benefit (CB-IAM) integrated assessment models and one macroeconometric-Keynesian model) for the analysis of six scenarios, focusing on a Reference case and a scenario compatible with the goals of the Paris Agreement with a 650 $GtCO_2$ carbon budget. All models show persistent inequalities in the Reference scenario (Supplementary Fig. 3). The study implements a uniform carbon price across sectors and countries without international transfers and explores two revenue-redistribution methods: neutral recycling and EPC distribution. Inequality in climate risks is incorporated using various impact specifications. The analysis concentrates on ten large countries, allowing for uncertainty quantification through model agreement assessment. This diverse modelling approach adds value by addressing the varying results in the decarbonization economics literature and provides insights into the effectiveness of compensatory policies in mitigation of the distributional impacts of climate change and related policies.

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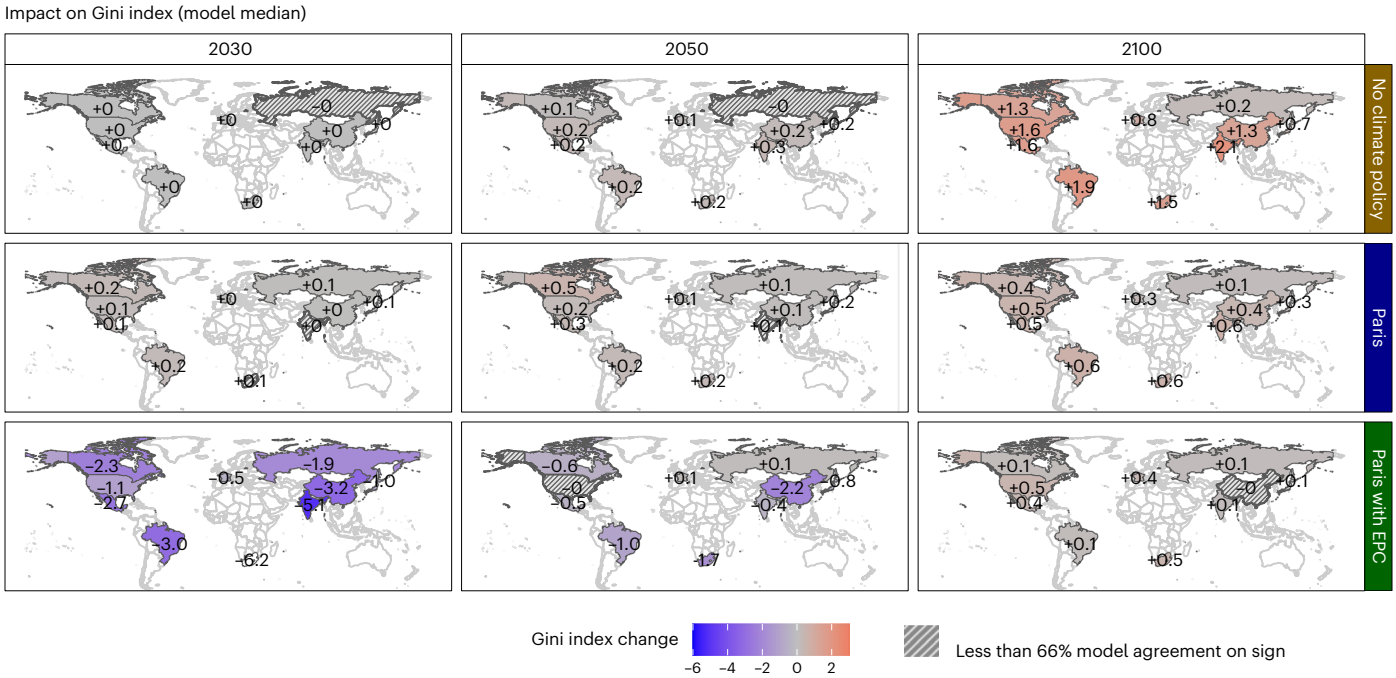


Fig. 2 | Map of the median across models showing change in Gini index with respect to the Reference scenario without climate impacts. Top, Reference scenario; middle row, Paris scenario without redistribution; bottom, the Paris scenario with impacts and EPC redistribution (all quantified by points). All scenarios include climate change impacts. Countries with less than two-thirds model agreement in terms of the sign of the effect are shaded.

Results

The Reference scenario (without climate impacts) projects a continuation of secular trends of persisting within-country inequality. Within-country inequality varies by country, in line with the current range of 0.3–0.7 for the Gini index (Supplementary Fig. 4). Most models use baseline Gini projections from ref. 39 that project—in particular, in their Shared Socioeconomic Pathways 2 or 'middle of the road' scenario variant—a slight increase in within-country inequality for most countries. Notable exceptions include an increase in inequality in India and a faster decrease in China and Mexico (Supplementary Fig. 4). This allows good harmonization of inequality dynamics across models, despite important country specificities, with the top income decile representing up to 70% of total consumption in South Africa, followed by Brazil, India, the United States and Mexico. Canada, France and Japan show the lowest consumption dispersion, while Russia and China are in the middle of the regions analysed.

Climate impacts

We begin by quantifying the inequality arising from climate impacts in a world without ambitious climate policies. The Reference scenario foresees increasing temperatures reaching 2.75 (2.5–3.1) °C by 2100. With this temperature increase, climate impacts are expected to increase the Gini index by about 1.4 points (median across models) by 2100 (Fig. 1, top). For some regions/models, the inequality increase is as high as 2.5 points of the Gini index (Fig. 2). While in the short term the effect is marginal, by the end of this century almost all models find important effects, the exceptions being NICE, which found no effect (based on its assumption of proportional damages), and ReMIND, which showed relatively low effects. The models also largely agree on the sign of the effect. Overall, we estimate an effect of about 0.4 Gini points increase per degree of country-level temperature increase (Supplementary Table 2).

Climate policies without redistribution

In the senarios compatible with the goals of the Paris Agreement, the global carbon price leads to a modest and temporary increase in income inequality (Fig. 1): Gini index increases by 0.1 points in 2030, but the inequality benefits of a lower global temperature have already materialized by mid-century. By 2100, Gini has increased by 0.4 points with respect to a world without either climate policies or climate impacts; this is one full Gini point below the scenario including climate damages, emphasizing the equality benefits of climate stabilization. Computable general equilibrium (CGE) models show a larger increase in inequality on average, because they capture the sectorial and structural costs of decarbonization to in greater detail but are also more rigid in terms of economic adjustments (for the 'Weak Paris' scenario based on a carbon budget of 1,150 $GtCO_2$ (Supplementary Fig. 5)). By 2100 the CGE models find the impact of the Paris agreement climate policy to be more than double the median value, and an increase in Gini index by up to 3.5 points in the case of the general equilibrium model for economy–energy–environment (GEM-E3). Detailed process-based IAMs on the other hand typically find a smaller impact with consistent increases of inequality due to climate policies. The macroeconometric model shows the smallest impact of all. In any case, model agreement is always above 70% (Fig. 1) for the sign of the effect.

These results partly confirm concerns about the regressivity of carbon taxes, notably due to changes in income and factor prices[36]. Countries with high carbon intensity (for example, South Africa) or high fossil extraction (for example, Canada and the United States) are most affected (see Fig. 2 and Supplementary Fig. 6 for country-level results). Only three cases of model–country combinations show a decrease in Gini index in the Paris scenario without redistribution, with Imaclim for India an improvement of about three points; this is because the much-reduced climate impacts obtained by stabilization of global temperature improve inequality more than the policy. Alternative inequality metrics, such as the share of the income of the richest 20% over the poorest 20% (D80:D20 ratio), lead to similar results (Supplementary Fig. 7).

To summarize the regressivity of climate policies we estimate the income elasticity of the policy cost, running an ordinary least-squares regression for each country and decile over both time and models (Supplementary Table 3), and estimate the income elasticity of climate policy costs by country. Overall, we find that policy costs are close to

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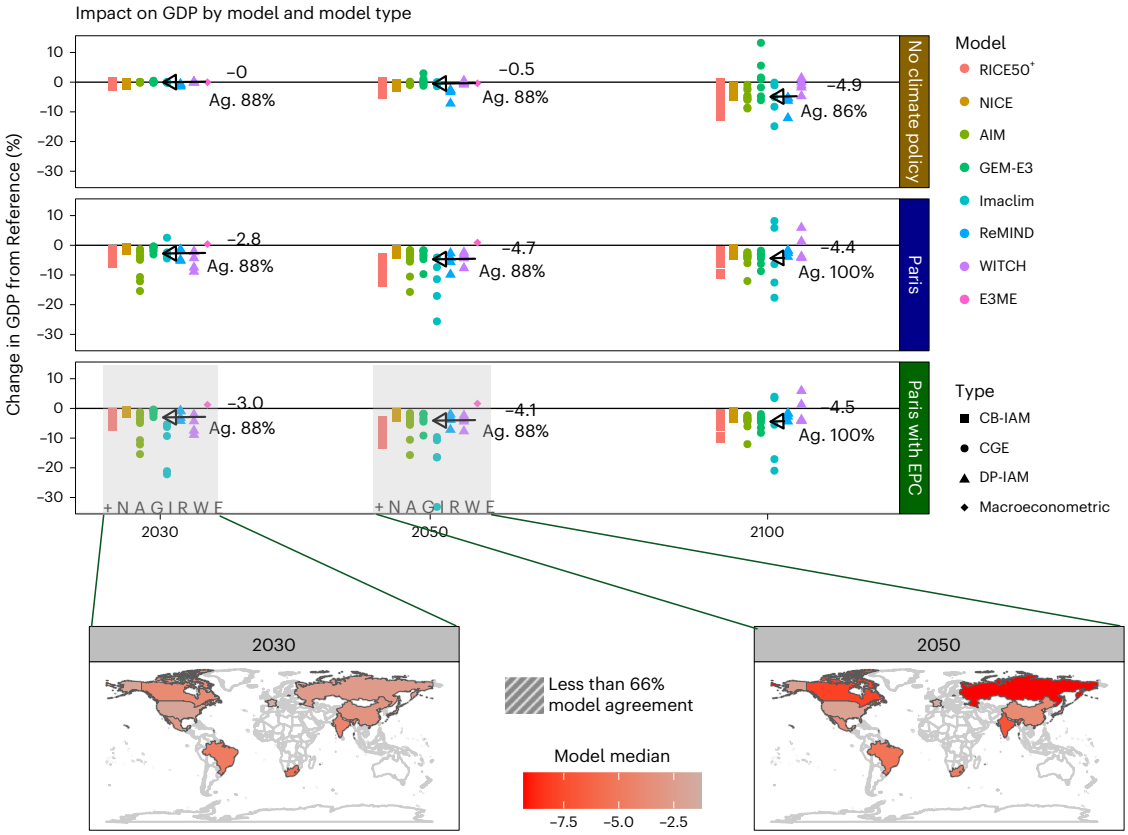


Fig. 3 | Policy cost in terms of GDP loss from the Reference scenario without climate impact. The top row shows the case of no climate policy, the middle row the Paris scenario and the bottom row shows the Paris scenario including EPC transfers. Individual countries are shown as points and all scenarios include climate impacts. Panels include the distributional consequences of climate damages. Models are categorized (colour and letter coded using the first letter or each model ('+' for RICE50+)), and ordered and clustered by model type. Bottom, maps of model median for 2030 and 2050. Numbers in black indicate median values pointing by the arrow to the median value. Countries with less than two-thirds model agreement are shaded.

proportional, with an estimated elasticity of 1.04 (note that a value of one would indicate equal relative policy costs and hence a neutral distribution). Across regions, the values in the ten countries lie between 0.75 and 1.05, with countries with higher gross domestic product (GDP) per capita typically exhibiting higher regressive policy costs (Supplementary Fig. 8). In contrast, poorer countries can even show progressive policy cost incidence, a finding in line with the meta-study of Budolfson et al.[12]. For assessment of model robustness, we also performed estimation for each model separately (Supplementary Table 4). Six of the eight models show this negative relationship with income (for three models it is statistically significant at the 10% level), and all models show on average a value of around one.

The role of carbon revenue recycling

The third building block of this analysis is carbon revenue recycling, which we implement across models with an EPC transfer within countries. Total carbon revenues by country are in most cases below US$1,000 per capita per year over the entire century (Supplementary Fig. 9), based on total emissions and carbon prices (Supplementary Fig. 10). When carbon revenues are redistributed equally as a climate dividend among citizens (Figs. 1 and 2), the combined effect of climate impacts, climate policy and redistribution becomes (with high agreement) inequality reducing, particularly in the short term. In 2030, on average across models, Gini decreases by 2.4 points compared with the Reference scenario (without climate impacts). The effect is higher in developing countries (Fig. 2 and Supplementary Fig. 6), and for model classes featuring higher economic resolution such as computable general equilibrium (Fig. 1). India and South Africa show the highest inequality reduction due to redistribution, given their lowest level of income among the poorer deciles. Over time, as carbon revenues dry up due to marked reduction in emissions, the inequality benefits of revenue-recycling diminish. By mid-century, Gini remains lower than in the Reference without climate impacts (by 0.7 points) and is roughly equal by 2100. Note, however, the major inequality benefits of combining climate stabilization and redistribution compared with a Reference scenario with climate damages (gains of 2.4, 0.9 and 1.3 Gini points in 2030, 2050 and 2100, respectively).

In regard to the amount of carbon dividend, overall we find a significant and robust reduction of around 0.6 points decrease in Gini index for each US$1,000 per capita of revenue redistribution (Supplementary Table 5). The highest reduction in Gini index is found for South Africa, India and Brazil (all with a reduction of about three points of Gini index ceteris paribus, while inequality in the Reference case is also highest in these countries). In contrast, the impact in Organisation for Economic Co-operation and Development countries is lower, with a reduction of 1.0–1.5 points. However, we also find some model differences, including some due to variation in the carbon prices required to implement the Paris scenario: notably, the CGE model Imaclim shows greater reduction due to higher carbon prices. The overall positive impact of revenue recycling with an EPC climate dividend is in line with single-model studies[8,12,40].

Macroeconomic and welfare impacts

In addition to income and consumption distribution within countries, the models also provide insight into macroeconomic dynamics (here measured as GDP loss compared with the Reference scenario without climate impacts, measured using purchasing power parities). When considering climate impacts, GDP losses reach on average 4.9%

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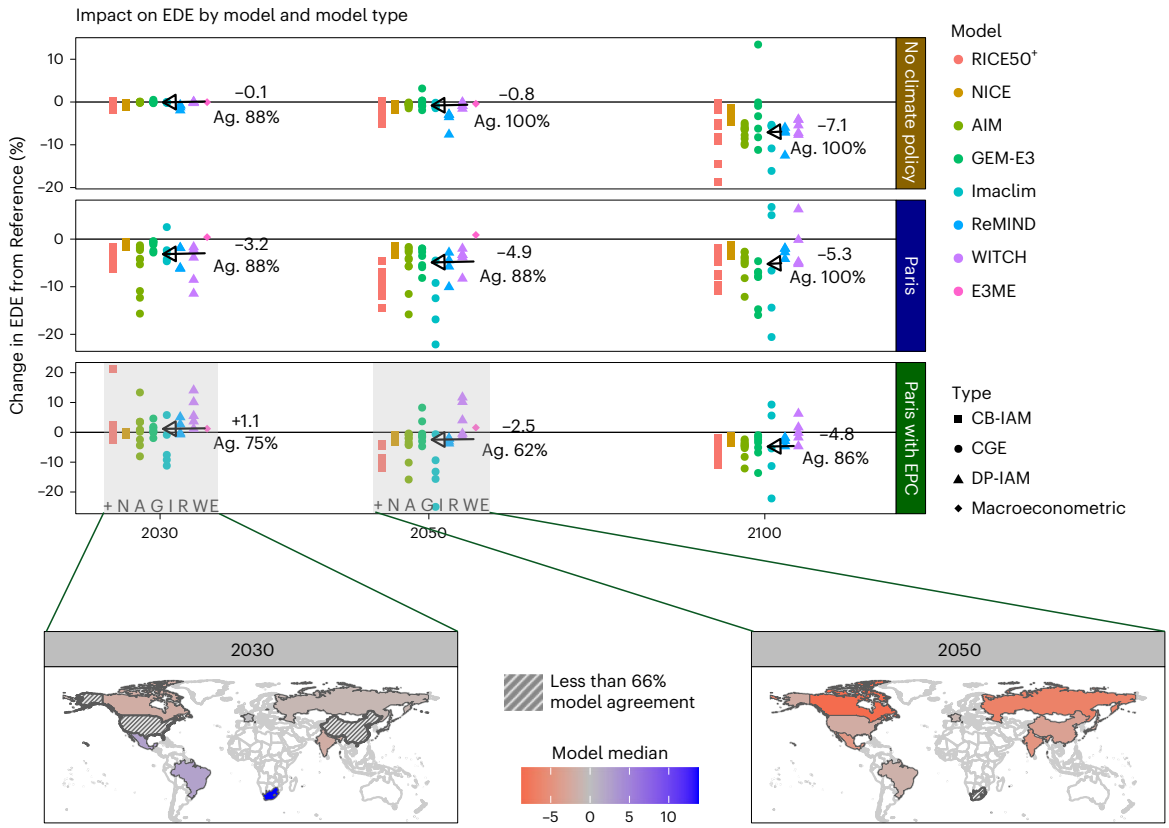


Fig. 4 | Welfare impact based on the EDE welfare measure. The top row shows the case of no climate policy, the middle row the Paris scenario and the bottom row shows the Paris scenario including EPC transfers. All individual countries are shown as points and all scenarios include climate impacts. Panels include the distributional consequences of climate damages. Models are categorized (colour and letter coded using the first letter or each model ('+' for RICE50^{+})) and ordered and clustered by model type. Bottom, map of the model median in 2030 and 2050. Numbers in black indicate median values pointing by the arrow to the median value. Countries with less than two-thirds model agreement are shaded.

of GDP by the end of the century, albeit with regional variation and some higher-latitude countries even showing gains (Supplementary Fig. 11). Under the Paris scenario, policy costs are added while impacts are reduced. The second row in Fig. 3 shows the policy costs in terms of GDP loss. Meeting the Paris agreement reduces global GDP by 2–5% of GDP on average per year until 2050. By 2100, the total GDP impact is lower than in the Reference scenario, reducing overall GDP losses by around one-third. Nevertheless, there is substantial model and regional variation (higher values in poorer and more carbon-intensive (and fossil fuel-exporting) countries). Some models find costs of up to 20%—in particular CGEs—and, in some cases, also indicate GDP gains (macroeconometric or CGE models in some cases). These results are coherent with those of the sixth assessment report of the IPCC. Redistribution of carbon revenues to households has almost no macroeconomic impact in almost all countries and models, except for the CGE model Imaclim. Here, in the standard Paris scenario by default, tax revenues are recycled by reduction of pre-existing labour taxes affecting GDP. Moreover, there is feedback on emissions, with increased economic activity from redistribution tending to increase emissions, resulting in slightly higher carbon tax trajectories needed to reach the same carbon budget. Regarding model uncertainty, the GDP impact has an even higher model agreement rate of no less than 86%, and only the Keynesian model E3ME shows potential positive GDP impacts of the Paris scenario.

Ultimately, what matters from a societal viewpoint is welfare. We compute a welfare measure that accounts for both aggregate GDP impacts and inequality. Specifically, we compute the equally distributed equivalent level of consumption (EDE)[41], which is the amount of consumption per capita that, if perfectly equally distributed, would yield the same welfare as the actual distribution[41]. It is based on an isoelastic welfare function (where we use a parameter of inequality aversion of one, or that utility is logarithmic. With inequality, EDE is lowered and a higher aggregate GDP level would be required to achieve the same level of welfare. It is, therefore, a broader measure than GDP alone and combines the equity and efficiency implications of a policy. Figure 4 shows the welfare impact (in percentages) compared with the Reference scenario.

In Fig. 4, the top row shows the impact of climate damages on welfare in the Reference scenario. Welfare losses accrue over time unanimously across models, reaching 7.1% by the end of century as climate risks reduce economic growth and increase inequality. In the Paris scenario without transfers (second row), welfare decreases early on due to higher policy costs and a small increase in inequality, stabilizing around 5% by mid- and end-century. Although significant, this welfare loss is about one-quarter lower than in the Reference scenario without climate policy.

With compensatory transfers on an EPC basis (third row), welfare increases by 1.1% on average in the short term (2030). That is, the redistribution effect overcompensates for GDP loss from a welfare perspective; this shows the crucial welfare benefits of compensatory policies. As shown above, the benefits of compensatory measures vanish in the longer term, notably after 2050, when carbon revenues dry up due to emissions reaching net zero, while mitigation costs remain substantial. Nonetheless, welfare loss due to the climate policy is approximately halved by 2050, at about 2.5% loss, while in the long term the welfare gains from maintaining global warming <2 °C are still dominant. The results also vary by country (Supplementary Figs. 11–13). Model agreement is high, although somewhat less than in the previous scenarios because additional policy provisions compound uncertainties.

Discussion

The intergenerational implications of climate change have received great attention and, more recently, the distributional consequences of climate policies within countries have gained traction while long-term climate impacts are also becoming better understood. As the ambition and implementation gap in climate policies persists, their public acceptability and feasibility have become more important. We use a large and diverse ensemble of coupled climate–economy models to analyse the short- and long-term economic and distributional effects of climate impacts (Supplementary Fig. 14), climate policies and redistribution options. Among the eight models employed, we also find some model differences; overall, however, the model agreement on the sign of the effects is, in most country, scenario and year combinations, above 70%.

We find that stringent climate policies can generate important welfare benefits, because climate benefits pay off in terms of higher GDP and lower inequality. Moreover, we find substantial inequality reductions and welfare gains in the short term due to carbon revenue redistribution. These results and methods highlight the potential of coupled climate–energy–economy models to complement the standard assessment of transition pathways by adding the equity dimension within countries towards welfare-enhancing policy design. The relative robustness of the direction and order of magnitude of results across modelling paradigms provides a sound basis for policy recommendations towards effective, just and acceptable climate policies.

However, we identify mid-century as a potentially critical period: carbon revenues dry up, negative emissions technologies need to be financed and the climate benefits do not yet overcompensate for policy costs in most countries and models. This points to the need for the implementation of new welfare-enhancing policies that are designed for net-zero times and societally disruptive technologies such as negative emissions—beyond traditional instruments such as carbon pricing with transfers[42]. The need for adaptation and related investments would also increase this challenge, in particular for lower-income households, even though a precise quantification is still missing.

Several additional dimensions of equity are still missing in the modelling analysis and will play a potentially important role in future policy design and research. Notably, the distribution of wealth alongside income appears to be becoming ever more relevant[1]. The interaction of economic growth and income disparities could also lead to mutual aggravation of economic development and inequalities[43]. Global redistribution schemes, as well as wealth and capital taxation proposals. could help to alleviate these dynamics[44].

Online content

Any methods, additional references, Nature Portfolio reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41558-024-02151-7.

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Methods

This study consists of a six-scenario protocol, run by eight models that represent four different theoretical paradigms (Methods): detailed process-based IAMs (two models), cost–benefit IAMs (CB-IAMS; two models), CGE models (two models) and one macroeconometric model. The diversity in representing economic processes, in the solution concept and in technological, sectoral and regional resolution, is a primary added value of this modelling exercise, given the widely differing results available in the literature on the economics of decarbonization[45–47]. The representation of economic inequality varies across model type and characteristics: from parametric assumptions such as log-normal consumption in ReMIND, through income and consumption deciles and disaggregated consumption patterns in CGE models, to elasticity-based approaches based on deciles in CB-IAMs (see Supplementary Information A for a detailed description of participating models). A dataset collected for this study, which includes energy expenditures for housing and transportation by household deciles, is used by several participating models (Supplementary Information B).

Participating IAM

A total of eight state-of-the-art IAMs have been used in this study, with the notable focus of adding the distributional consideration of mitigation costs, potential redistribution of carbon revenues and climate impacts. This section shows the main characteristics of the models used and their key features in terms of the modelling of within-country inequalities.

While most of the models considered have a global focus, regional disaggregation varies. Moreover, when aggregating several countries to macroregions, income distribution becomes a mixture of distribution across and within countries. Because wage distributions, net consumer prices, income taxes and transfer schemes are designed at the country level, aggregation of income distributions is challenging. Notably, within-country distributional impacts could be dwarfed by between-country variations through economic growth, convergence or potential transfers between countries. Because here we wanted to isolate the within-country dimension of climate change and policy, we chose to focus on single countries that have been modelled in at least three IAMs, which resulted in a set of ten large countries (Brazil, Canada, China, France, India, Japan, Mexico, Russia, South Africa and the United States). All models have a time horizon of at least 2100, except for E3ME, which runs until 2050.

Scenario protocol

The scenario protocol includes a reference scenario (Reference) without new climate policies and a scenario compatible with the goals of the Paris Agreement (Paris), modelled through a constraint on cumulative CO_2 emissions (from 2020 to 2100) of 650 $GtCO_2$, consistent with the Paris goal of staying well below 2 °C (1.5 °C with one-third probability, or 1.7 °C with more than two-thirds probability, according to IPCC Sixth Assessment Group Working Group 1 (AR6 WG1). For robustness, we also explore a carbon budget of 1,150 $GtCO_2$ consistent with 2 °C of warming.

The carbon budget is reached using a uniform carbon price across sectors and countries, with no overshoot. The carbon price is also applied to non-CO_2 greenhouse gases when represented in the models. As a consequence, we consider neither regionally differentiated carbon pricing nor transfers (implicit or explicit) and trade of carbon permits[48]. Therefore, these scenarios serve as a benchmark in the absence of international transfers that could, however, greatly increase the redistributive power in developing countries. While politically unrealistic, this allows for the separation of within-country distribution from the discussion of between-country transfers, which might interact with within-country redistribution[15].

Orthogonal to the climate policy dimension, the models implemented two redistributive policies to the revenues generated by carbon price: climate dividends are recycled within each country neutrally or distributed back to households on an EPC basis. The resulting scenario matrix allows quantification of both the within-country distributional implications of carbon pricing and the effectiveness of compensatory policies. To isolate the within-country dimension of climate change and policy, we focus on the ten large countries mentioned above that are represented in at least three models in the ensemble. Finally, we exploit the large-model ensemble for uncertainty quantification: we quantify an index of model agreement as the share of models that concurs regarding the sign of the policy response.

Main scenario details. *Reference*. This is a counterfactual scenario with lenient or absent climate policies. Each model is left free to choose a business-as-usual policy or to implement current policies until the year 2030[49]. Your model's default Reference scenario (after 2020, no (further) climate policies: this can be a business-as-usual scenario if you don't implement current policies, or current policies until 2020 without further strengthening (preferred).

Paris. Until 2020, fixed to Reference. After 2020, implement a global uniform carbon price, with time profile at the discretion of models (for example, Hotelling rule growing at social discount rate or, if not available, fixed at 5% per annum). Target: peak carbon budget (2020–2100) of 650 $GtCO_2$ for CO_2 emissions, including both fossil fuel and industry and land use. The carbon budgets cannot be overshot—that is, no net-negative emissions are allowed. This design is consistent with the most recent practices in the modelling community[49,50]. Non-CO_2 gases are prices at the same CO_2 price using the global warming potential from AR6 WG1 (www.ercevolution.energy/ipcc-sixth-assessment-report/) or, alternatively, model default global warming potential if not available.

Paris with EPC. Same as Paris. Now, all domestic carbon revenues are redistributed to households on an EPC basis. Note that, in some cases, (small) negative emissions might imply negative transfers with resulting increases in inequality. We preclude this and set transfers in these years to zero.

Moreover, for robustness, we also implemented two scenarios based on a 1,150 $GtCO_2$ carbon budget (Weak Paris). That is, we have a total of five different policy scenarios. Moreover, we have a set of these five runs without climate impacts, and (where models do implement climate impacts) also with climate impacts, for a total of ten scenarios (Supplementary Fig. 2).

One important distinction of inequality measurement is income versus consumption or expenditure inequality. All teams were asked to focus on consumption inequality, where available, because inequality data in expenditures or overall consumption are more reliable than income inequality, notably in surveys from developing countries. This seems justifiable in the assessment of climate policy incidence because carbon pricing in particular affects energy and food expenditures. Nevertheless, impacts on factor prices, including wages, can lead to additional impacts across income distribution[36,51], which are considered in particular in the Macroeconometric/post-Keynesian and CGE models (E3ME, GEM-E3 and Imaclim).

Climate impact post-processing for models without climate impacts

In addition to the distributional effects of climate policies, the models feature inequality in climate risks. While three of the models in this study have their own distributional impact implementations (NICE, RICE50$^+$ and ReMIND), for the other models we apply the impact function at the income decile level estimated in recent empirical work[32]. The damage function is based on the country-level degree of warming, taking into account heterogeneity across countries, and implies an income elasticity of damages of 0.6 on average. This damage function

suggests that damages are less than proportional to income, indicating modestly regressive impacts within countries.

We focus on the impacts of future temperature changes, controlling for precipitation, on decile income growth by estimating the following equations via ordinary least squares:

$$\begin{aligned}\Delta y_{iqt} = \Delta y_{iqt-1} + \beta_1^q \mathrm{Temp}_{it} + \beta_2^q \mathrm{Temp}_{it}^2 \\ + \gamma_1^q \mathrm{Temp}_{it} y_{it-1} + \gamma_2^q \mathrm{Temp}_{it}^2 y_{it-1} \\ + \pi \mathbf{P}'_{it} + \alpha_i + \lambda_t + \vartheta_i t + \varepsilon_{iqt}\end{aligned}$$

where y_{iqt} is the logarithm of income of decile $q = 1, \ldots, 10$ in country i in year t; Temp is average annual temperature; y_{it-1} is the log of per-capita GDP of country i over the sample period; $\mathbf{P}'_{it}$ is a vector of cumulative annual precipitation variables (linear and quadratic, and respective interactions with y_{it-1}, as for temperature); α_i are country fixed effects; λ_t are common time fixed effects; ϑ_i is a linear time–trends by country; and ε_{iqt} is an error term assumed to be orthogonal to temperature conditional on the controls. We thus estimate separate sets of coefficients for each income decile. The damage function is then defined by a change in decile-level income, specified as

$$\delta_{iqt} = f_q\left(\mathrm{Temp}_{it}, y_{it-1}^{impacts}\right) - f_q\left(\mathrm{Temp}_0, y_{it-1}^{Reference}\right)$$

where f_q is the estimated function defined above, and y_{it-1}^s is GDP per capita in country i either under the Reference scenario without climate impacts (Reference) or under Reference with impacts ($s = impacts$). This specification follows from the equation above, with climate impacts depending on the country's GDP which is, in turn, also impacted over time by the realized temperature changes.

The income of decile q in year t thus evolves according to

$$y_{iqt} = (1 + g_{iqt} + \delta_{iqt}) y_{iqt-1}$$

where g_{iqt} is the counterfactual growth rate under no climate impacts, which is taken from the submitted GDP and deciles computed by the different IAMs. To obtain country-level projections of future temperatures given an emission path, we first compute the global average surface temperature anomaly as a function of cumulative emissions.

We convert cumulative emissions to global temperature increase using the estimated transient climate response to cumulative emissions of carbon dioxide of 0.44 °C per 1,000 $GtCO_2$. We then downscale global average surface temperature to the country level according to the linear downscaling procedure based on the CMIP6 database[32] (Supplementary Fig. 14).

Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

Data availability

All scenario data and figure data are available via GitHub at https://github.com/JohannesEmm/navigate_inequality_mip.

Code availability

All code is available via GitHub at https://github.com/JohannesEmm/navigate_inequality_mip.

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Author contributions

J.E. and M.T. designed the research with all coauthors. J.E. carried out analysis of the modelling results, created figures and wrote the draft of the paper. S.D., S. Feindt, C. Grottera and D.M. compiled the national decile-based detailed datasets based on household surveys. M.G. implemented the climate impact post-processing tool. S.Z. and S. Fujimori provided AIM data. P.A. provided RICE50$^+$ data. I.C., D.F. and P.F. provided GEM-E3 data. A.M. and C. Guivarch provided Imaclim data. F.P., N.T. and B.S. provided ReMIND data. Y.S. and F.N. provided E3ME data. G.M., Y.Z. and J.E. provided WITCH data. F.D., S. Feindt, U.K., A.M. and M.Y.-B. provided NICE data. S. Feindt, C. Grottera, E.K., A.M., D.M., F.P., B.S., M.T., T.V., M.Y.-B. and S.Z. provided extensive contributions to the development of the narrative. All authors contributed to the discussion and interpretation of results.

Competing interests

The authors declare no competing interests.

Additional information

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Towards improved representation of distributional impacts of climate change and mitigation policies in model scenarios

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Abstract

Climate mitigation policies and climate change damages can have unequal incidences both between and within countries. This paper examines the under-explored dynamics of within-country distributional impacts, focusing on residential energy expenditures and avoided climate change damages resulting from climate policies, using the Integrated Model to Assess the Global Environment (IMAGE). By looking at energy expenditures for different income groups for residential energy consumption, we find that - without redistributive policies - climate mitigation action achieved via carbon prices alone could disproportionately affect poorer population groups. This is the result of both changes in relative energy costs and high up-front investment needs for low-carbon solutions. At the same time, poorer population groups would likely benefit the most from the same mitigation action through avoided damages. Overall, this might lead to a net-progressive outcome. The presented scenario analysis indicates the need for equitable policies to protect low-income groups, particularly in low-income regions vulnerable to the largest impacts of climate change.

Keywords

Climate change, mitigation, carbon pricing, climate damages, Gini index, Suits index, climate policy, distributional effects

1. Introduction

In its Sixth Assessment Report, the IPCC WGII has concluded that not all people are equally exposed to climate risks(IPCC, 2022b). More recent research confirmed this finding, both in terms of climate impacts and mitigation(Bistline et al., 2024; Cortés Arbués, I. & Chatzivasileiadis, T., Ivanova, 2024; Hsiang et al., 2019; Malpede & Percoco, 2021; Méjean et al., 2024; Spinoni et al., 2024). Climate impacts are found to disproportionately affect the poor, given higher levels of exposure and a lower ability to adapt. Climate mitigation could exacerbate existing inequalities as well, as it could lead to increasing energy costs for lower income groups.

Without additional measures to alleviate such potential regressive impacts, other societal goals, such as poverty alleviation, will become more difficult to achieve. Furthermore, injustice (real or perceived) can seriously undermine support for climate policy(Ewald et al., 2022; Feindt et al., 2021; Lamb et al., 2020). Reduced public support can influence the stringency or ambition level of national climate policies(Konc et al., 2022), risking increased climate impacts or the need for even more stringent mitigation action in the long run(Guivarch & Rogelj, 2017). Societal acceptance of climate policies is thus critical and this depends on improved understanding of who bears the costs of mitigation and benefits of avoided damages, and how mitigation policies can be designed to ensure fairer outcomes(van den Berg et al., 2020; Wang et al., 2016; World Bank, 2024).

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Existing literature on within-country distributional impacts of climate change policy mostly focus on case studies scoped to a single country or group of countries using relatively low carbon taxes(World Bank, 2024) or with short time scales (see (Wang et al., 2016) for a comprehensive overview). Integrated assessment models (IAMs) studies have mainly focused on fair distributions of mitigation action between countries(Du Pont et al., 2016; Holz et al., 2018; Leimbach, M. & Giannousakis, 2019; Okereke & Coventry, 2016; Pan et al., 2023; Robiou Du Pont et al., 2017; van den Berg et al., 2020), sometimes also accounting that climate change impacts are distributed unequally(de Cian et al., 2016; Hof et al., 2010; Taconet et al., 2020). An exception is a recent article in which the Global Change Analysis Model (GCAM) IAM is used to analyse the residential energy demand and expenditures across income deciles of different socio-economic and climate futures(Sampedro et al., 2024), but this article does not explicitly report on the regressivity or progressivity of mitigation policy and avoided climate impacts.

The present paper fills this gap by analysing the impact of mitigation on residential energy expenditures of different income groups in large world regions, and compares these with estimated (avoided) damages, using the Integrated Model to Assess the Global Environment (IMAGE). The key aim is to improve our understanding of these impacts to better inform just climate policies. Towards this end, distributional impacts are indexed along two dimensions: regressivity i.e., how the policy impacts are distributed across income groups, and inequality i.e., how the unequal distribution across income groups affect disposable incomes inequality. All further references to regressivity and impacts to income inequality in this article use this terminology for consistency (further elaborated in *Section 2.3*).

2. Methods

2.1 Overall framework

We apply a scenario analysis method using the IMAGE 3.4 integrated assessment modelling framework(Stehfest et al., 2014) that simulates interactions between human activities and the environment. The framework consists of a detailed representation of energy, land-use and climate systems through several sub-models and has been widely used to explore alternative climate change mitigation scenarios and implications of climate policy. The model has full global coverage divided into 26 world regions and typically runs scenarios to project outcomes until 2100.

The TIMER energy systems sub-model – particularly the residential energy module(Daioglou et al., 2012), and the MIMOSA cost-benefit assessment module(van der Wijst et al., 2021) – are the most relevant sub-models of the IMAGE framework for this study (*Fig. 1*). While the former covers the energy demand and costs for different income groups, the latter describes the climate impacts. Below, we describe the aspects of the model that are most relevant to this study, while further detail is provided in the Appendix (*Section A1*). A detailed account of the IMAGE modelling framework is available on the IMAGE wiki website(Netherlands Environmental Agency (PBL), n.d.).

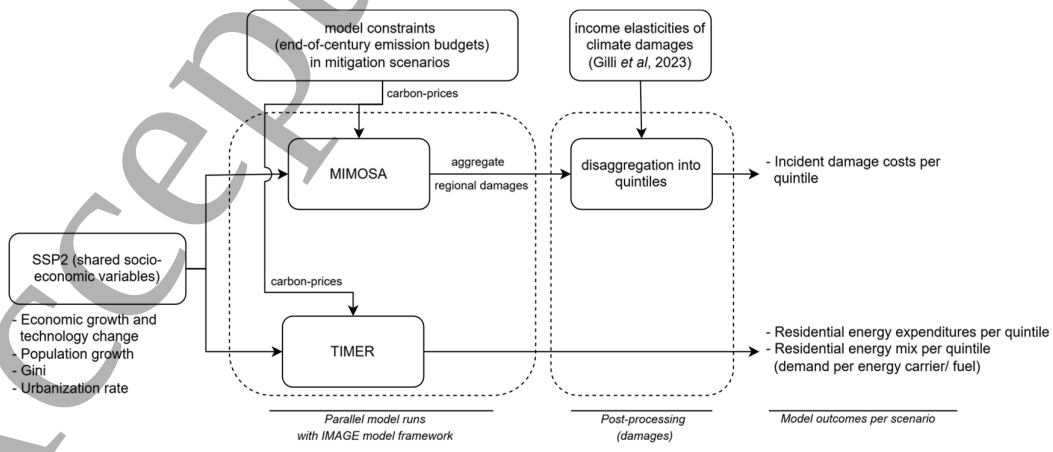


***Figure 1*:** Schematic modelling and outcomes in each scenario

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The calculations for each scenario are as follows. We derive residential energy costs across income quintiles using the TIMER model. In parallel, we use MIMOSA to derive first-order estimates of aggregate regional damages which we distribute across income quintiles. These two parallel runs are done for baseline and climate change mitigation scenarios (See *Section 2.5*). The scenario outcomes of TIMER and MIMOSA are compared to explore the impacts on energy expenditures and climate damages respectively, and as well as their combined impacts using distributional indices (see *Section 2.4*).

2.2 Modelling residential energy demand

The residential energy model of IMAGE simulates energy supply and demand. Demand is determined for five income quintiles for urban as well as rural households for 26 world regions across six energy functions: cooking, space heating, space cooling, water heating, and appliances[31,34].

The energy demand for each end-use function is driven by exogenous projections of socio-economic characteristics, including total household expenditures and population growth, and endogenously determined intermediate drivers such as electrification rates, household size, floor space, and climate conditions (see *Fig. A1* in the Appendix). Total household expenditures are used as a proxy for incomes, a common practice in economics literature given the inconsistent nature of income data (see for example *Tables 2.1 – 3.11* in (Kojima et al., 2010)). We estimate the distribution of total household expenditures with a log-normal functional form, with the shape parameter defined using the Gini index and the scale parameter by the total household expenditures share of GDP per capita (see *Section A1* in the Appendix). On the supply side, eight fuels (energy carriers) are represented in the model: solid fuels, liquid fuels, gaseous fuels, traditional biofuels, modern biofuels, hydrogen, secondary heat, and electricity.

The model allocates fuel shares to meet energy demand for each end-use function, using a multinominal logit function accounting for the availability and relative costs of the fuels, but also taking into account capital costs for the relevant end-use technologies. Furthermore, households can also adopt efficiency measures, such as insulation, to reduce their energy demand – dictated by the relative costs of insulation vs. heating (see Appendix, *Section A1.1*). As households get richer, consumer discount rates (i.e., how they perceive the costs of advanced technologies over their lifetime) reduce – and thus their incentive to buy expensive technologies increases. This affects investments in energy efficiency or cleaner fuels, which may have significant upfront costs for certain demographics. The model thus represents the concept of energy and efficiency ladders, i.e., households tend to switch to cleaner, more efficient, and more convenient fuels with higher upfront investments with increasing income(van Ruijven et al., 2015). The energy demand module has been calibrated for the 1971-2022 period in order to reproduce historical trends in fuel and electricity use as presented by the IEA energy balances. Historic data on population, private consumption, energy prices, household sizes, residential building types, floorspace, appliance ownership, and fuel use are used wherever available to aid with the calibration.

The costs of primary energy carriers in TIMER are based on supply curves of energy carriers, which may change over time due to technological learning or depletion. In mitigation scenarios, the application of carbon pricing and associated increase in energy prices has two effects in the residential sector: a shift towards the adoption of non-fossil energy carriers, including electricity and modern bio-energy, and a reduction in total energy demand due to adoption of efficiency measures. The model determines the expenditures paid for residential energy services through incident fuel prices and demand levels for each end-use.

In the mitigation scenarios, the socio-economic characteristics and activity levels driving total energy demand remain the same as in the baseline scenario. However, the presence of a carbon price affects fuel choices through the multinomial logit function. Moreover, the same demand for energy service (e.g. space or water heating, appliance use) is met by a smaller (larger) final energy demand as the representative agents make choices towards more (less) energy efficient options available to them. Furthermore, as climate policy affects the price of electricity, the expenditures for electricity-based energy services (appliances, lighting, space cooling) are also affected.

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TIMER is not an economic equilibrium model, but a recursive dynamic simulation model with a focus on the energy system and associated energy flows. Thus, the model ensures that physical flows (energy resources, carbon, etc.) balance out, but not necessarily monetary flows. This means that the determined residential energy expenditures are not constrained in the model by other expenditures towards taxes, food, housing, savings, or consumption of other goods and services. Non-energy expenditures are also not affected by introducing a carbon price. Although capital expenditures at the household level (such as for insulation, increased floor space, appliance ownership), as well as capital costs of associated public infrastructure (e.g., piped gas networks) influence the modelled household energy choices, the present analysis focuses on energy expenditures associated with fuel prices. Since demanded energy services in mitigation scenarios are maintained at the same level as in the baseline, additional energy expenditures and climate impacts may amount to very high shares of total household expenditures, especially for the lowest income groups. Such results are an indication that households cannot afford the same energy service demand levels anymore, highlighting the need to implement additional policies to protect them.

2.3 Estimating distribution of (avoided) climate impacts

Unlike energy expenditures that are first modelled bottom up and then aggregated to the regional levels, damage estimates are calculated first at the regional level before disaggregation across income groups for each scenario. Mean per-capita damage costs for the 26 world regions are calculated using the MIMOSA model(van der Wijst et al., 2021). Climate impacts, and especially their economic valuation, are very uncertain(Cortés Arbués, I. & Chatzivasileiadis, T., Ivanova, 2024; Howard & Sterner, 2017; Hsiang et al., 2019). Cost-benefit integrated assessment models such as MIMOSA typically use reduced-form damage functions that relate global temperature change to economic losses. We use the COACCH damage function(Bosello et al., 2012) which estimates economic losses corresponding to physical climate impacts using a computable general equilibrium approach. This damage function represents a step forward in this area of study by covering a broad range of sectors in climate impact models, viz agriculture, forestry, fishery, energy demand, energy supply, labour supply, riverine floods, transportation, and sea-level rise (van der Wijst et al., 2023). Furthermore, the approach allows an internally consistent treatment of sectoral uncertainties into the overall damage estimation that can be parametrised in integrated scenario analyses. In the present analysis we mainly use estimates with the median (50th percentile) specification. Further detail on the coverage of climate impacts quantified by the COACCH function, and how they compare with other commonly used damage functions are given in the Appendix (*Section A1.3*).

The distribution of the aggregate damages across income quintiles is done by using an income elasticity to damages, as estimated in a recent study which uses a novel method involving the downscaling of global and country-level damage functions to quantify distributional impacts within countries(Gilli et al., 2023). The study empirically supports the hypothesis that lower income groups have a lesser adaptive capacity to insulate themselves from the economic impacts of increased temperatures, and thus disproportionately bear the consequences of unmitigated climate impacts. The income elasticity of climate impacts is then calculated per country, relating the relative incidence of damages to changes in income levels within countries as follows:

$$\left(\frac{Damage\ costs\ ^{q}_{rt}}{Damage\ costs\ _{rt}}\right) = a_{rt}\left(\frac{Income\ ^{q}_{rt}}{Income\ _{rt}}\right)^{\xi_r} \quad (1)$$

where damage shares of the q^{th} quintile in region r relate to their respective income shares by elasticity ξ and scaling factor a. The study reports a global average income elasticity robust to the choice of damage functions at 0.7. Elasticity values below 1 indicate the overall regressivity of climate change impacts.

For each scenario, we implement the population weighted country level elasticities to estimate damages incident across income quintiles following *Equation 1*. The distribution of damages is modelled across regional income quintiles without an urban-rural disaggregation, since we do not have information on the distribution of damages to urban and rural areas. In a similar vein to the treatment of quintile-level energy expenditures (*Section 2.2* above), we do not endogenously adjust income levels for damage costs.

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2.4 Estimating distributional impacts of carbon pricing

For each scenario, we implement the population weighted country level elasticities to estimate damages incident across income quintiles following *Equation* The distribution of damages is modelled across regional income quintiles without an urban-rural disaggregation, since we do not have information on the distribution of damages to urban and rural areas. We calculate the change in energy expenditures between a mitigation and baseline scenario for all income groups. The (change in) energy burden is defined as the (change in the) ratio of energy expenditures to total household expenditures (*Eq. 2*). Equivalently, we calculate the difference between the incident damages in a mitigation and baseline scenario (avoided damages) for each quintile and determine the respective changes in damage burdens (*Eq. 3*). Two summary statistic measures, the Suits index and Gini coefficient, are then derived to analyse the distributional consequences of these unequal impacts.

$$\Delta\, Energy\ Burden\ {}^{q}_{1.5oC} = \left(\frac{Energy\ Expenditure\ {}^{q}_{1.5oC} - \ Energy\ Expenditure\ {}^{q}_{BL}}{Total\ household\ expenditures\ {}^{q}_{BL}}\right) \quad (2)$$

$$\Delta\, Damage\ Burden\ {}^{q}_{1.5oC} = \left(\frac{Damage\ costs\ {}^{q}_{1.5oC} - \ Damage\ costs\ {}^{q}_{BL}}{Total\ household\ expenditures\ {}^{q}_{BL}}\right) \quad (3)$$

The Gini index and Suits index are statistical summary indicators, both summarizing inequality but capturing different aspects.

The Gini index is derived from Lorenz curves and measures the degree of inequality in the distribution of income (or expenditure) across a population. It quantifies the deviation of income distribution from a perfectly equal distribution, with values ranging from 0 (perfect equality) to 1 (maximum inequality), or equivalently over the range (0, 100). The consequences of modelled carbon pricing and climate damages on disposable income inequality are captured by comparing the Gini coefficients after energy expenditures and incident damage costs between the mitigation and baseline scenarios. A positive (negative) change indicates increasing (decreasing) income inequalities attributed to the respective mitigation scenario.

The Suits Index uses the concept of Relative Concentration Curves (such as Lorenz curves used for the Gini index) to determine the ratio of the cumulative share of tax incident on the p^{th} percentile of the population to its cumulative share of income. Values are bound by the interval (-1, 1) or equivalently by (-100, 100), with -100 implying that the tax is entirely incident on the lowest group (most regressive) and +100 implying that the tax is entirely incident on the highest (most progressive). We calculate the progressivity or regressivity of mitigation scenarios through changing energy expenditure and damage burdens, and their combined impact. An overview of the index and its formulation is given in the Appendix (*Section A3*).

The Gini index measures overall income inequality across the population, while the Suits index(Feindt et al., 2021; Fragkos et al., 2021; Jiang & Shao, 2014; Köppl & Schratzenstaller, 2023; Suits, 1977) focuses specifically on whether the increases of the energy expenditures is distributed progressively (falling more on the rich) or regressively (falling more on the poor). This distinction between the distributional aspects captured by the two indices helps explain why small increases in income inequality, as reflected in small increases in the Gini index, can be seen alongside different movements in the Suits index.

For example, if increased carbon prices cause a relatively small additional cost for the poorest households, it may be small enough that it does not substantially affect overall income inequality. In this case the Gini index may show little change. However, if this small cost is a larger share of the poor households' incomes compared to the richer ones, the Suits index would show a regressive outcome (decreasing Suits values). Conversely, if higher-income households face higher absolute energy cost increases, roughly proportional to their income levels, and poorer households face smaller relative increases, the Gini index may still show little overall change, but the Suits index could indicate a slight shift toward progressive distributional outcomes (increasing Suits

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values). Thus, differences in the movements of the two indices reflect whether the energy cost burden is relatively heavier on the poor or rich, even if the overall change in income inequality remains small.

2.5 Scenarios

In the analysis, we focus on a baseline and two mitigation scenarios. All three scenarios are driven by the same socioeconomic variables (e.g., GDP growth, population growth, Gini coefficients, and urbanisation levels) of the "middle-of-the road" SSP2 Shared Socioeconomic Pathway(Riahi et al., 2017). The baseline scenario is defined by no additional mitigation action, whereas in the mitigation scenarios the end-of-century global average temperature increase is limited to 1.5°C with a greater than 50% probability, and 2°C with a 67% probability.

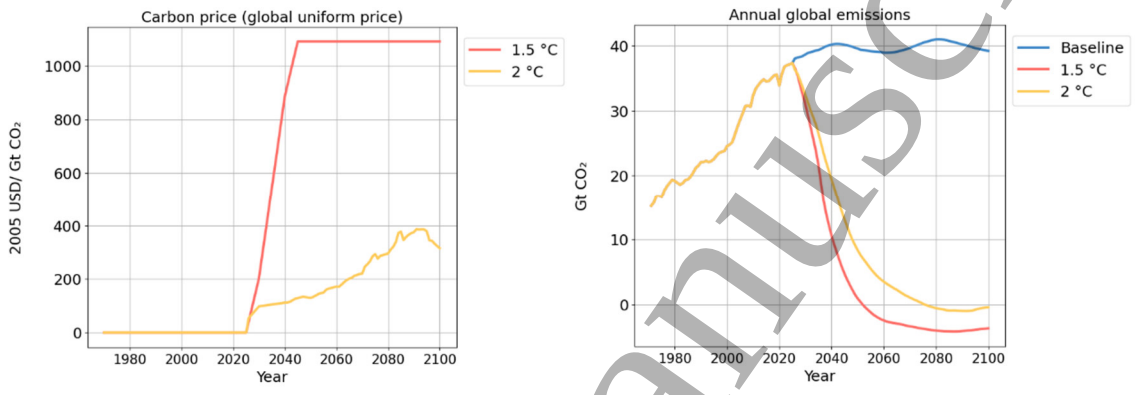


***Figure 2**: (a) Carbon price trajectories in the 1.5°C and 2°C mitigation scenarios and (b) corresponding emission profiles relative to baseline SSP2*

The additional energy expenditures in the 1.5°C and 2°C mitigation scenarios result from a globally uniform carbon price from 2025 onwards. We focus on a global uniform carbon price not because we assume that this is the most realistic or just form of climate policy (in fact, earlier studies have found that a universal carbon price in fact leads to unfair outcomes between countries (Du Pont et al., 2016; Okereke & Coventry, 2016; Pan et al., 2023; Taconet et al., 2020)), but because this allows better interpretation of the underlying dynamics and results. Recent efforts aim to incorporate more plausible regional differentiation in mitigation scenarios(Bertram et al., 2024); however, there is currently no consensus in academic literature or among policymakers on the topic.

The carbon prices are determined endogenously in the IMAGE model framework to meet specific climate targets (carbon price and corresponding global emission profiles shown in *Fig. 2*) based on the lowest global costs. A more detailed explanation of how they are derived and the assumptions that underpin their trajectories can be found in (van Vuuren et al., 2007).

All monetary data is converted into constant 2005 USD prices in IMAGE model. Unless otherwise specified, all further monetary values presented in this article are also expressed in 2005 USD terms.

3. Results

3.1 Distribution of additional energy expenditures

In both mitigation scenarios, implementation of carbon prices leads to increased energy expenditures relative to baseline. Globally, the strongest increase in expenditures is observed in the short term after the carbon prices are implemented. Differences in absolute energy expenditures between regions already present in the baseline are exacerbated in the mitigation scenarios (*Fig. A5*). For most regions, mean per-capita energy expenditures initially increase upon the introduction of carbon prices and decrease after this initial peak. The extent to which energy expenditures increase in mitigation scenarios, as well as how close to baseline levels

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they return to by the end of the century, varies across regions. These variations are due to differences in current energy mixes and how different income groups in different regions respond to carbon pricing, as explained in more detail below.

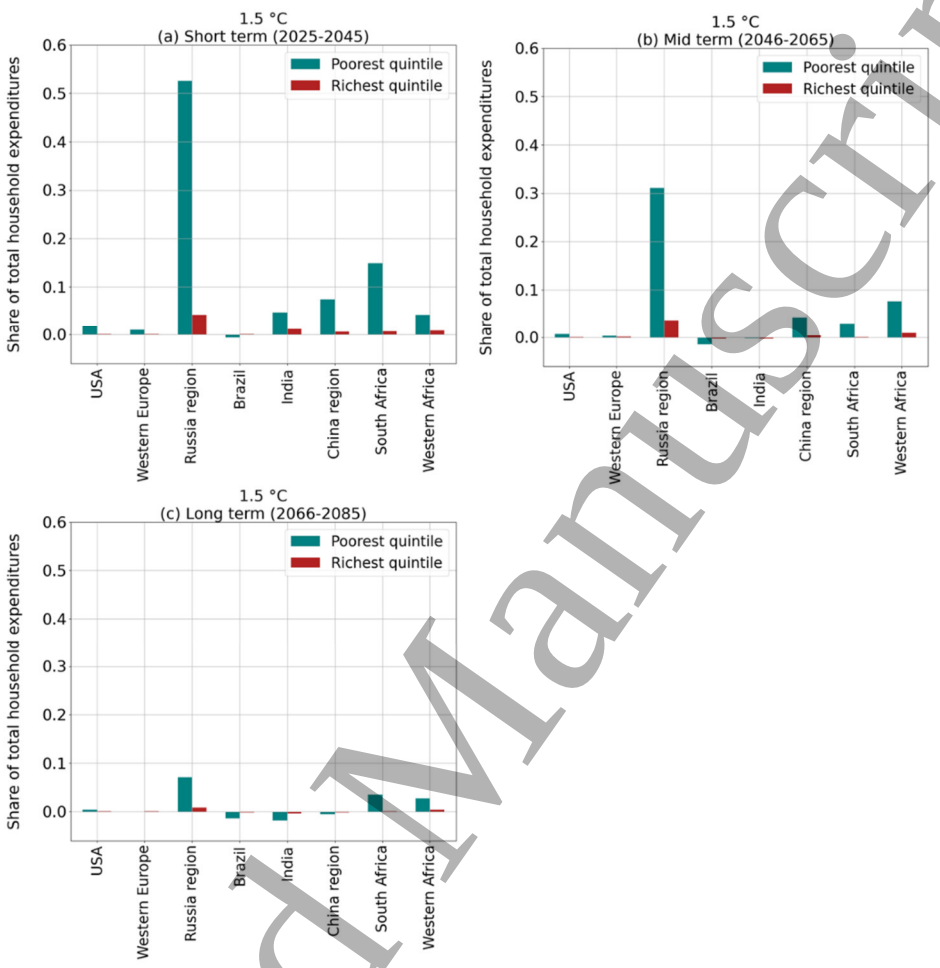


Figure 3: Additional energy burden (energy expenditure per capita as fraction of total household expenditures per capita) in the 1.5°C mitigation scenario relative to baseline for poorest and richest quintiles in selected model regions, (a) Short term, (b) Mid-term, (c) Long term.

Figure 3 shows the change in energy burden (i.e., additional energy costs as share of total household expenditures) for the poorest and richest quintiles in the 1.5 °C scenario in selected world regions, grouped by time periods. The increase in energy burden for the poorest quintile is an order of magnitude higher than for the richest quintile. As the demanded energy services as well as the total household expenditures for each quintile are unchanged between the baseline and mitigation scenarios, the differences are solely attributed to changes in fuel prices.

There are three main reasons why the change in energy burden is larger for poorer households. The first reason is simply that the same absolute increase in fossil fuel prices leads to greater changes in energy burdens among lower income quintiles, as their overall expenditures are lower. Secondly, high income quintiles are better positioned to make choices towards decarbonising their energy demand. They already exhibit high electrification rates (and electricity access) across residential end-uses and tend to use lower-emitting fuels in the baseline (*Fig. 4*). Richer households are also more likely to invest in efficiency measures and cleaner energy technologies (including heat pumps, rooftop PV, insulation, etc.(Daioglou et al., 2022; Gernaat et al., 2020)) due to lower discount rates. These features can help explain why many high-income households may incur only marginal additional costs in the mitigation scenario compared to their already favourable baseline. Coupled

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with expected energy efficiency gains over the century, this also explains why higher income quintiles are likelier to incur lower energy expenditure relative to baseline projections in the long term.

Conversely, poorer quintiles that do not have the means to invest in cleaner options or do not have access to electricity and so-called modern energy sources stick longer to fossil-based fuels (with disproportionate carbon price effects making them more expensive). They are also likelier to revert to traditional biomass which is not subject to carbon pricing (*Fig. 4*). This represents shifts down the so-called energy ladder, despite increasing income levels over time for all quintiles. These results highlight that poorer households may face important barriers to moving towards cleaner fuels, while also suffering disproportionately from the carbon prices, while their overall emissions are typically lower compared to richer households' (*Figs. A12-15*).

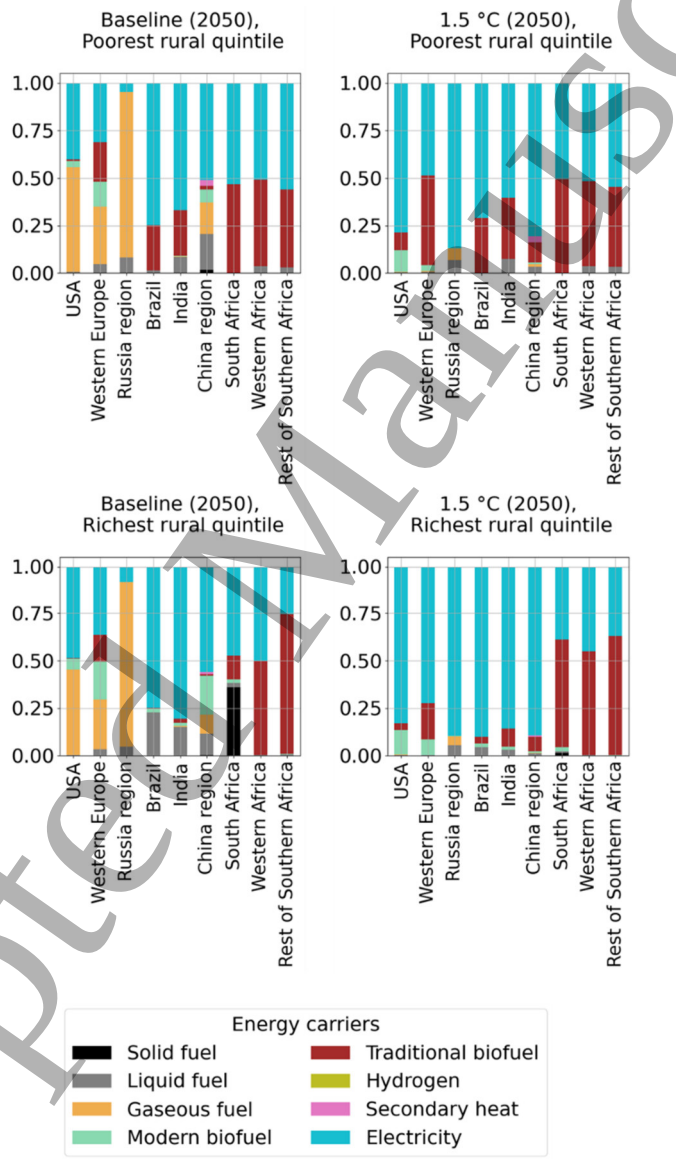


Figure 4: Residential energy mix (shares of total energy demand) in 2050 in the Baseline and 1.5 °C scenarios for the poorest rural quintiles (top panels), and richest (bottom panels)

While these described model dynamics explain a majority of the presented results, regional differences in the share of renewables in electricity generation also play a role in the availability and affordability of the choices available to all households within as reflected in *Fig. 4* for rural quintiles (also see *Fig. A11* for urban quintiles). For example, initial high impacts in Russia, Western Africa and South Africa regions (*Fig. 3*) also correspond

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with low renewable shares in electricity generation before the carbon prices are introduced. Even as households transition to electricity to meet their demanded residential energy services, they are exposed to more expensive electricity prices until the electricity production gets decarbonised under the same carbon price signal (*Fig. A.20*).

Not all regions and modelled income groups show an increase in energy burdens relative to baseline. In Brazil, for instance, changes in energy burden are negative, with the poorest income quintile benefitting more than the richest (*Fig. 3*). This is explained in part by the low dependence of the poorest quintiles on fossils fuels for residential energy needs in the baseline, since they predominantly use either traditional biofuels or electricity. In mitigation scenarios, they respond to high carbon prices by increased use of traditional biofuels, and are thus relatively less affected in expenditure terms compared to rich quintiles who reduce (but not completely eliminate) their fossil-based energy demand. Aided by already high shares of renewables in their electricity mix, the net result is the observed negative values for their energy burden change relative to baseline.

The global average annual additional energy costs for households resulting from the carbon price amounts to about USD(2005) 450 per capita between 2025 and 2100 in the 1.5°C scenario and USD(2005) 78 in the 2°C scenario.

3.2 Distribution of avoided damages

Damage estimates in all three scenarios increase over time in all regions, but there are strong regional differences in damage levels. In the baseline SSP2, mean per-capita damages are projected to be the highest in Sub-Saharan African regions, India, Southeast Asian regions, and the lowest in Europe, Central Asia, the Middle East and Russia. Meeting the emission targets represented by the mitigation scenarios greatly reduce damages in all regions at the aggregate level, as well as for all population groups within. Differences in the distributional impacts from avoided damages (*Eq. 3*) are nearly indiscernible between the two mitigation scenarios modelled. Estimated damages in the baseline scenario are up to an order of magnitude higher, compared to both the 1.5°C and the 2°C mitigation scenarios (*Fig. A21*), reflecting the universal benefits from climate mitigation in the long term.

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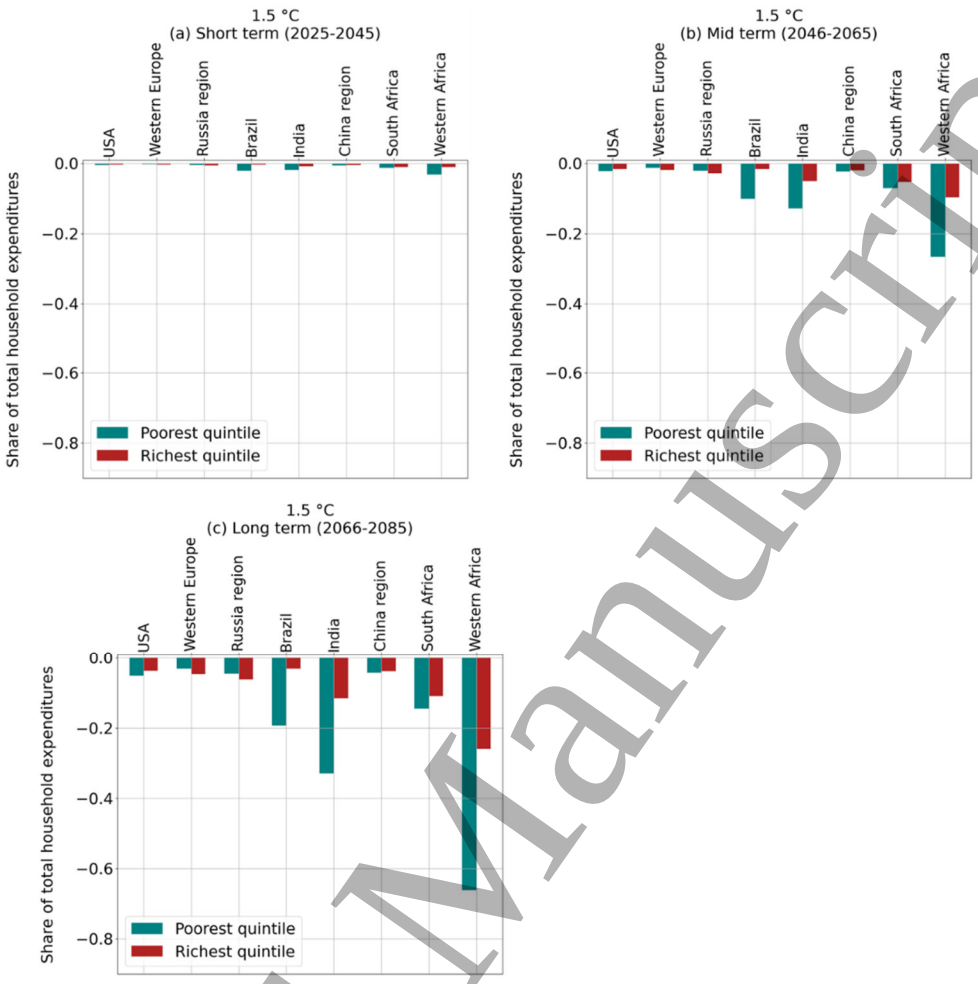


***Figure 5*:** Avoided per capita climate damages per capita (as fraction of total household expenditures per capita in 1.5°C mitigation scenario relative to baseline for poorest and richest quintiles in selected model regions, (a) Short term, (b) Mid term, (c) Long term.

Implementation of income elasticities of damages from (Gilli et al., 2023) lead to unequal distribution of damage costs for population groups within regions, with poorer households experiencing higher damages in a given scenario than richer ones. Subsequently, when analysing the impact differences between baseline and mitigation scenarios, poorer households stand to benefit more than richer ones from avoided damages (*Figs. 5* and *A21*). On average across world regions, the bottom income quintile benefits twice as much from avoided damages in a 1.5°C mitigation scenario than the top quintile in the same region. In poorer and warmer world regions, which are already known to be more vulnerable to climate change impacts, the relative benefit of the poorest quintiles is up to 6 times as large as the richest quintiles in the stringent mitigation scenario.

3.3 Impacts on distributional indicators

Energy expenditures.

The unequal distribution of additional energy expenditures and avoided damages are reflected in the regressivity indicators. *Figure 6* shows the regional variation in the Suits index in the two mitigation scenarios for selected regions. The negative values indicate that carbon prices have a regressive impact across income groups (i.e., the policies disproportionately impact poorer incomes). The Suits index reveals large differences in the regressivity of the carbon price between regions. The regressivity is the highest in Russia, Western Africa, and South Africa, especially in the medium and long term, reflecting the high additional energy burden for the poorest quintiles in these regions. This is due to the differences in fossil fuel phase out among the constituent

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quintiles seen in *Section 3.1* above, and the share of total expenditures represented by any remaining fossil fuel use among the poorer quintiles. In all other selected regions, there is no regressivity in the long term.

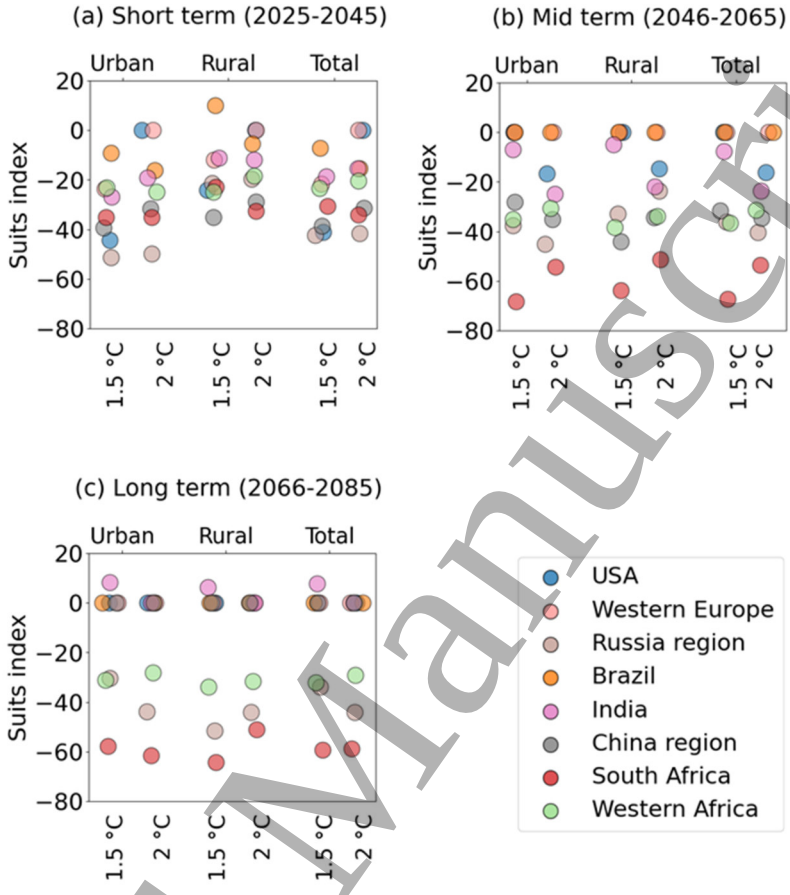


***Figure 6*:** Suits index for unequal energy expenditure impacts in mitigation scenarios relative to Baseline (selected world regions)

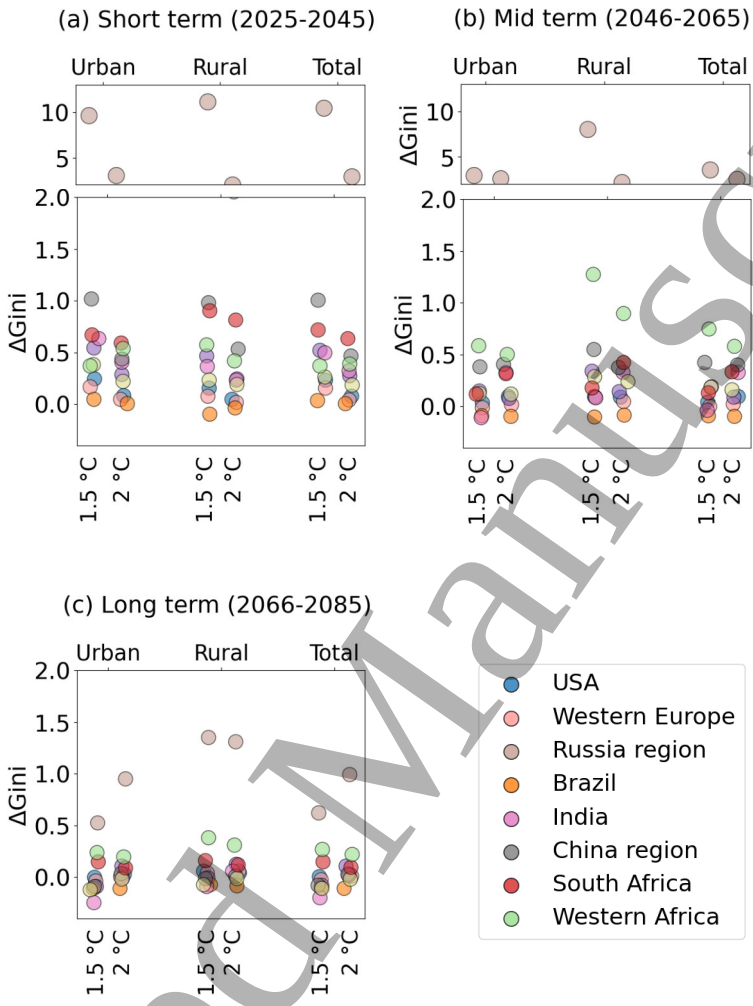
While there are some differences in the degree of regressivity between urban and rural areas, the variation across regions and mitigation scenarios is too large for a consistent picture. Outcomes are also not significantly more regressive in the 1.5°C scenario than in the 2°C scenario, only the magnitude of changes are higher due to the higher carbon prices.

Both mitigation scenarios result in more unequal outcomes relative to baseline as measured by Gini impacts (*Fig. 7*). Inequality increases sharply in almost all world regions shortly after the introduction of a carbon price, reducing significantly after the initial peak to baseline levels by the end of the century. Increase in inequalities are greater in the 1.5°C scenario (regional average peak +2.4 points) than in the 2°C scenario (regional average peak +0.7 points). Some middle-income regions in Asia and the Americas are even projected to be less unequal in the long term in the 1.5°C scenario compared to the baseline, albeit to a very small degree (< -0.2 points Gini change). Impacts in rural areas are slightly higher than in urban areas.

The difference in the initial peak in increased inequality reflects current differences in fossil-fuel dependency between regions. In this initial period, all households in regions with high fossil-fuel dependency face high energy burdens, with poorer households being affected more than richer ones. Later in the century as carbon price ramp up, the availability and affordability of alternative carbon-free fuels strongly determine inequality outcomes. Regions like Russia where decarbonised electricity remains expensive into the long term (due to low renewable shares in electricity production in the absence of carbon pricing) show the longest enduring inequality impacts. Other regions where households face obstacles in moving up the ladder from high initial shares of natural gas to electricity also show strong inequality impacts into the longer term. High increases in

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income inequalities are for instance seen in Sub-Saharan African regions, where poorer households remain partially dependent on fossil fuels for some energy services (e.g., kerosene for lighting and cooking). On the other hand, developed regions such as Western Europe, Canada, USA, Japan, Korea, and Oceania show low



increases in inequality, since the increased energy costs represent lower shares of household's expenditures.

***Figure 7*:** Gini change due to due to unequal energy expenditure impacts in mitigation scenarios relative to Baseline (selected world regions)

The universally observed dynamics of decreasing Gini changes after the peak in all regions and in both scenarios reflect the degree to which all income groups transition to energy sources that are not carbon priced. However, an important caveat to this behaviour is the increased – or at least not reduced – dependence of many poorer quintiles on traditional biofuels such as firewood or dung cakes (also see *Fig. 4*). This marks an energy transition opposite to the desired direction of increased uptake of cleaner energy sources.

Damages

Both the statistical summary indicators reflect the income elasticities of damages used to calculate them, and highlight the distributional benefits of achieving mitigation targets.

Predominantly positive values of the Suits index in *Figure 8* (top panel) indicate the progressive nature of avoided damages when respective emission targets are met in the mitigation scenarios. The benefits of avoided damages are more progressive for low- and middle-income regions in Central and South Americas, Asia and Africa that are characterised by low-income elasticity values determined in work by Gilli and colleagues

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(Gilli et al., 2023). The Suits indices for the distribution of damages only vary slightly over time for all regions, with the variation attributable to increasing total damages.

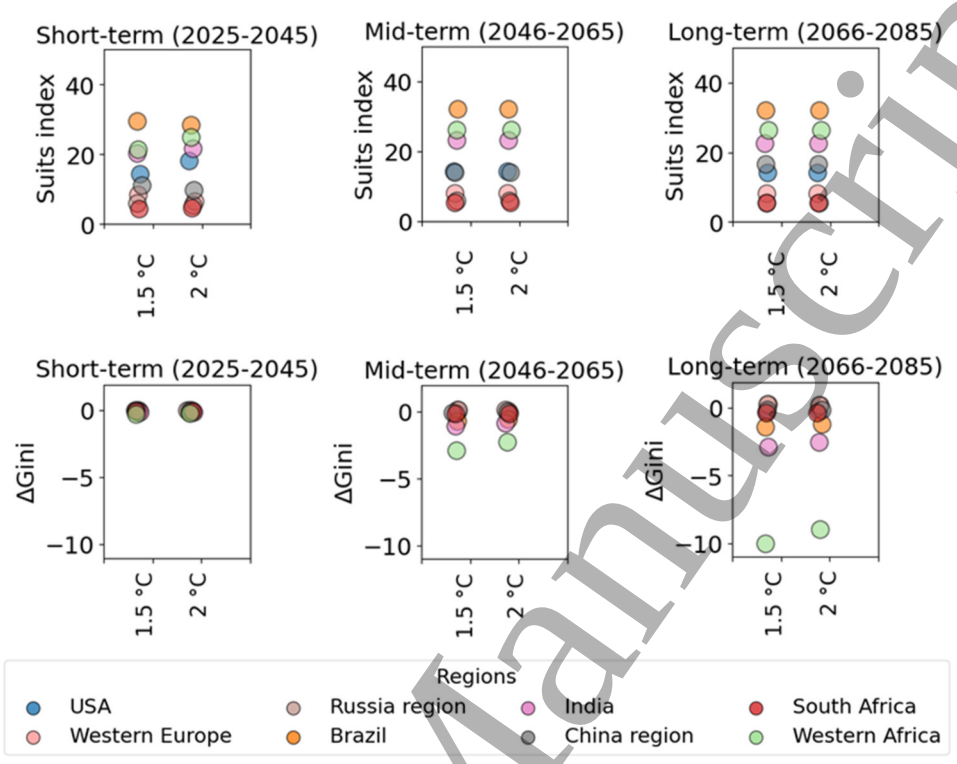


Figure 8: Distributional impacts from avoided damages for selected model regions, (top) Suits index, (bottom) Gini change

Unequal benefits of avoided climate damages in both mitigation scenarios are reflected by corresponding changes to the Gini coefficient (defined here with total household expenditures reduced by incident damage costs, see methods). Both mitigation scenarios lead to decreased Gini values on average across regions from about 0.09 points in the short term to 1.73 in the long term. However, the regions with low income elasticities to damages and high aggregate regional damages see a much more pronounced impact over time with Gini coefficients decreasing by up to 10 points in the long term (*Fig. 8, bottom panel*). One must be careful in interpreting the decrease in the Gini coefficient not as an active reduction of income inequalities, but rather as their avoided Increase in the absence of a mitigation policy.

Combined impacts – energy expenditures and damages.

Following the temporal trends of the Suits index calculated for energy expenditures and damages, their combined impacts indicate mostly neutral distributional impacts among regions (near-zero Suits index values), with modestly progressive impacts in the long term (predominantly positive Suits index values) in both mitigation scenarios (*Fig. 9*).

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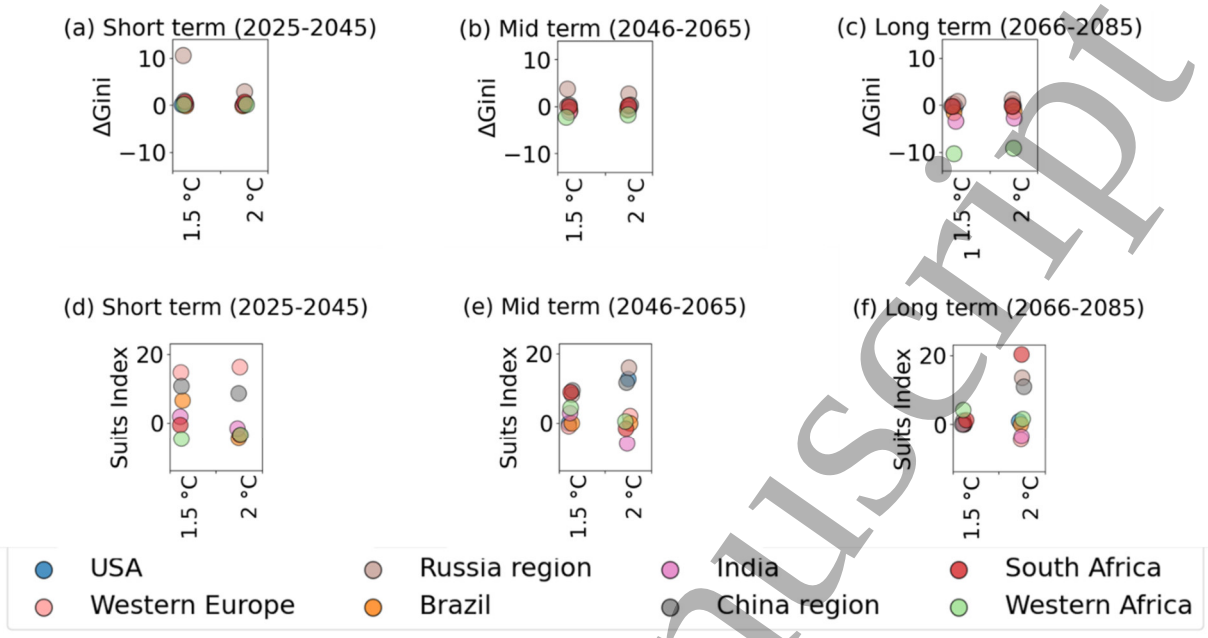


***Figure 9**:* Combined distributional impacts for selected model regions, (top) Suits index, (bottom) Gini change

Similarly, the combined impact to income inequalities (Gini change) follows from the opposing time trends seen for additional energy expenditures and avoided damages. Higher energy expenditures in mitigation scenarios dominate the combined impacts in the short term, resulting in small net increase in income inequalities (near-zero Gini change relative to baseline). However, in the mid to long term, achieving mitigation targets avoids a greater degree of increased income inequalities from avoided damages in vulnerable regions.

4. Discussion

In this study, we present the distributional impact of introducing carbon pricing to limit global temperature change to 1.5°C and well below 2 °C at a sub-national level. Using the IMAGE model framework, we capture the impacts through two key channels represented in the model: changing residential energy expenditures and avoided climate damage costs. We distinguish between regressivity of impacts (proportionality of impacts borne across increasing incomes) using the Suits index, and the impact on income inequality using the Gini index. While the terms regressivity and income inequality are sometimes used interchangeably in literature to refer to the Gini impact alone, the distinction can help policymakers develop fairer, socially acceptable climate policies. This is a first effort of capturing within-country/region distributional effects of climate policy on both energy expenditures and climate change damages, with some caveats that are important to take into account.

The residential sector representation in the IMAGE model focuses particularly on the expenditures on energy sources to capture the modelled distribution of mitigation impacts. These expenditures are directly influenced by mitigation policies modelled through carbon prices, and we show how they result in regressive distributional outcomes. However, capital investments and operational costs of devices and infrastructure at the household level are not included, nor public infrastructure expenditures to ensure access to appropriate energy sources as households move up the energy ladder. While some of these additional capital expenditures are not explicitly captured, they should be taken into account while designing a just redistribution policy. Increasing carbon prices may also have distributional consequences through other channels than those considered in this model. For example, in addition to residential energy expenditures, they also affect households unequally via changes in expenditures on personal transport or food. Currently, the transport and food sectors are modelled at the regional level of aggregation in IMAGE(Netherlands Environmental Agency (PBL), n.d.). Future model

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development can integrate a broader set of distributional channels of mitigation policy impacts and inform a more holistic multisectoral redistributive policies using combined revenues.

Although our model results show that the impact of carbon prices on residential energy expenditure is likely to be regressive in most regions in the short term, a comprehensive review of the case-study literature by Wang and colleagues(Wang et al., 2016), and a recent meta-analysis by Ohlendorf and colleagues(Ohlendorf et al., 2021) indicate a likelihood of some progressive outcomes in developing regions. This is typically explained by lower ownership levels of energy-consuming devices (appliances, private vehicles etc.) by poorer households than richer ones in these regions. Poorer households are thus expected to spend a lower share of their total expenditures on energy. Any increase in fuel prices would therefore disproportionately affect richer households. However, limited empirical evidence from developing countries in Asia and Africa indicate that expenditure shares on residential energy services addressed in the present study decrease along increasing income quintiles (in contrast to household expenditures on transport-related energy costs – which do indeed increase with income)(Kojima et al., 2010). Additionally, the reviewed studies in literature indicating progressive outcomes in developing regions differ from our approach in two significant ways. First, they involve carbon taxes much lower than needed to meet Paris Agreement targets. Second, they do not model households' dynamic responses of switching to a more affordable fuel type. Still, Ohlendorf *et al* find that studies that account for dynamic demand-side responses to increased fossil-fuel prices and cross-sectoral interaction effects typical of general equilibrium and microsimulation models are more likely to show progressive distributional impacts from introducing carbon taxes. However, the apparently progressive outcomes come at the cost of lowered demand for energy services, which might have particularly dire consequences concerning energy access for the poorest households.

While it is clear that mitigation scenarios lead to economically beneficial outcomes in the long term, assessing their distributional consequences is challenging. Estimates of climate damages, i.e., economic losses from increasing climate impacts, as well as their incidence across income groups within regions, are uncertain. We implement the most recent approach to modelling within-country distribution of incident damages that may be applied top-down to global scale models combined with a median estimation of aggregate damages. The COACCH damage function used here does not yet include economic evaluations of climate change impacts through biodiversity loss, or through changes in health and mortality indices (although through impacts to labour productivity are included) – which would increase the aggregate damage estimates(Bosello et al., 2012; Rising et al., 2022). In a similar vein to climate policy impacts, physical climate change impacts and their economic damage estimates may have distributional impact through other channels than those estimated using the chosen damage function. With higher damage estimates, poorer households in poorer countries would consequently likely stand to gain more from successfully achieved mitigation targets than our findings show, with the progressive distribution of benefits contrasting even more with the regressivity of carbon-pricing in the residential energy sector sans equitable redistributions.

Climate damages and increased carbon prices can also have unequal impacts on the baseline income distribution itself, such as through changes in sectoral employment, reduced aggregate consumption, inter-sectoral and inter-channel interactions, or through hitherto unmodelled impacts on population size and migration, health and mortality, and peace and conflict(Hallegatte et al., 2016; McLeman & Smit, 2006). These interactions and feedbacks are better captured by other modelling paradigms such as microsimulation and general equilibrium models(Kuiper & Zeist, 2023; Skoufias et al., 2011; van Ruijven et al., 2015), or health and demographic models. However, these models add much greater uncertainty, especially over long time scales. Our approach ensures that the unequal distribution of the costs and benefits of climate mitigation as well as the need to protect the most vulnerable recipients are identified along long-term scenario pathways.

Distributional effects are highly sensitive to assumptions on the logarithmic functional form of income distribution(van Ruijven et al., 2015). Due to data limitations, we estimate impacts at the mean income level per quintile, obscuring horizontal intra-quintile variations of incident impacts. While the relationship between climate impact incidence and income is significant enough for the scope of this study, capturing heterogeneity of climate impacts across other dimensions such as spatial location, age, gender, and employment sectors, could help develop policies aiding the most vulnerable further within each income quintile.

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The mitigation scenarios are represented by globally uniform carbon prices based on lowest global costs, without fairness considerations such as the capacity to reduce emissions or responsibility in order to be consistent with most scenarios in the literature(IPCC, 2022a; World Bank, 2024). This approach is criticized because efficiency is valued more than equity. Moreover, the feasibility of implementing such a policy instrument has been questioned, and alternatives have been proposed(Abrell et al., 2018; D'Autume et al., 2016; Verbruggen & Brauers, 2020). Others propose alternative regional differentiation in carbon prices with a focus on effectiveness in achieved emission reduction(Boeters, 2014), equitable outcomes(Boroumand et al., 2022; Chateau et al., 2024), or even sectoral differentiation within regions(Landis et al., 2018). An existing branch of literature actively delves into articulating fair burden-sharing alternatives through regionally differentiated carbon prices(Dennig et al., 2015; Leimbach, M. & Giannousakis, 2019). However, there is scant political or academic consensus on what may be considered as a realistic or feasible allocation of differentiated carbon prices. With our approach of using global uniform carbon prices, results can be interpreted more easily. However, future work evaluating the within-region distributional consequences of burden-sharing regimes could further aid in developing just transition policies.

As carbon pricing as a standalone policy instrument can lead to disproportionate burden on poor and exacerbated income inequalities, redistributive policies are imperative in ensuring broad societal support. Most literature addressing distributional concerns assume a recycling of the generated revenues as a lump-sum transfers(Emmerling & Tavoni, 2021; Kallbekken et al., 2011; Orbons et al., 2024; Steckel et al., 2021). These transfers often do not go beyond redistributing revenues on an equal per capita basis, irrespective of differences in socio-economic status or climate vulnerability. Studies focused on specific countries in specific years do include a broader set of compensatory policy mechanisms. Broadly, these may be classified as targeted compensation, investments in improving education and awareness, investments in green energy infrastructure and energy transition, and contribution to global climate funding efforts (Andersson & Atkinson, 2020; Carattini et al., 2018; Douenne & Fabre, 2020; Gaikwad et al., 2022).

In addition to direct transfers of recycled revenues, targeted compensation covers a broad spectrum of mechanisms, such as carbon tax rebates on the poorest, subsidising and promoting uptake of energy-efficient clean technology devices (e.g., electric stoves, air conditioners), with or without strengthened regulations and standards (e.g., residential insulation codes, tax and subsidy reforms). A deeper analysis of the measures and how they may be modelled could lead to more valuable and actionable policy insights than revenue recycling with additional co-benefits in line with other connected societal objectives such as the Sustainable development Goals (SDG 1: No poverty, SDG 7: Access to affordable and clean energy, SDG 10: Reduced inequalities, among others).

5. Conclusion

We have aimed to inform just climate policies by examining the dynamics of sub-national distributional consequences of both climate change impacts and cost-optimum mitigation policies determined by IAMs. A number of conclusions can be drawn based on the results presented in this study.

Reduced emissions in mitigation scenarios can lead to progressive distributional outcomes in the long term from avoided climate damages. The poorest income groups are most likely to suffer the most from climate damages, and thus also benefit the most from climate policy in terms of avoided damages. As climate impacts with or without mitigation increase over the century, the greatest distributional benefits of mitigation are seen only in the long term. Especially for poorer (and generally hotter) regions, the degree of regressivity prevented through avoided damages in the long term is greater than the degree of increased regressivity via higher energy expenditures in the short term. Most of these regions avoid a greater degree of increased income inequality from avoided damages in mitigation scenarios compared to the corresponding impact from unequal energy expenditures. The only exceptions are found in parts of Africa, where households are already suffering from energy poverty and low access to modern energy services.

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In the absence of complementary redistributive policies, climate mitigation policies relying solely on carbon prices can lead to increased inequalities within regions through their unequal impact on residential energy expenditures. Climate policies modelled via uniform carbon prices result in an overall reduction of dependence on fossil fuels in the residential energy mix in order to meet targeted mitigation levels. At the same time, they risk exacerbating existing inequalities in energy burdens across income quintiles, with poorer quintiles being affected disproportionately higher. This is typically the case if energy expenditures represent a higher share of income. Furthermore, richer income groups can "pay their way out of" carbon pricing by adopting cleaner and more efficient capital-intensive technologies, which poorer households often cannot afford. As a consequence, poorer households can even descend down the energy ladder. Supporting policies which can reduce this regressivity should focus on making clean fuels affordable to poorer household (including provision of adequate infrastructure), ensuring access to basic energy services, and decarbonisation of the electricity system.

Mitigating climate change indicates eventual net-progressive outcomes, thus especially beneficial for poorer income groups, but unequal burdens and impacts need to be considered. In most regions, climate policies in the residential sector in the form of carbon pricing likely lead to net-progressive outcomes in the long term, when accounting for avoided damages, even in the absence of any modelled redistributive policy. However, in the short to mid-term, poorer income groups could likely bear the brunt of a cost-optimal carbon-price without additional support to transition into a low-carbon future. Equitable, needs-based redistributive policies would allow these vulnerable populations to bear the disproportionate energy burdens, consequently avoiding regressive impact from unmitigated damages in both short and long terms. This is crucial since the potential regressivity of the distributional impacts influences the perceived fairness and thus the successful implementation of climate policies. Complementary policies incentivising the transition into clean energy use can also prevent the negative impact on health and air quality as poor income groups in many regions risk descending down the energy ladder. Addressing these equity concerns is likely to garner broad societal support for climate policy. The estimated annual global policy costs may be taken into consideration by policymakers alongside related investment needs towards equitable sustainable development(Kulkarni et al., 2022). Considerations of fair effort sharing and just transitions of energy systems to meet global climate goals are incomplete without accounting for distributional consequences at the sub-national level.

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