International Institute for Applied Systems Analysis
IIASA www.iiasa.ac.at

Address: IIASA, Schlossplatz 1, A-2361 Laxenburg, Austria

Email: permissions@iiasa.ac.at

Young Scientists Summer Program

Distributional Impacts of Different 1.5°C Pathways on Energy Poverty

Mel George (georgemv@umd.edu)

Approved by:

Mentor(s): Shonali Pachauri, Narasimha Rao & Jihoon Min
Program: Energy, Climate, and Environment (ECE)
Date: 30 September 2022

This report represents the work completed by the author during the IIASA Young Scientists Summer Program (YSSP) with approval from the YSSP mentor.

It was finished by September 30, 2022 and has not been altered or revised since.

Mentor signature:

Table of contents

ZVR 524808900

Disclaimer, funding acknowledgment, and copyright information:
IIASA Reports report on research carried out at IIASA and have received only limited review. Views or opinions expressed herein do not necessarily represent those of the institute, its National Member Organizations, or other organizations supporting the work.

The authors gratefully acknowledge funding from IIASA and the National Member Organizations that support the institute, The National Academy of Sciences (NAS), USA.

Abstract

Analyzing distributional effects on vulnerable sections is important for enhancing national mitigation ambition by supporting social objectives. In contrast to existing studies based on single representative households and cost optimal mitigation pathway archetypes, we assess the impacts on national energy priorities and household energy burdens for diverse mitigation pathways to similar climate outcomes, in a consistent framework. We model 17 mitigation pathways varying by pace, technology choices, demand side mitigation options and global effort sharing principles using an integrated assessment model. We examine short & long-term distributional impacts on national energy goals (access, affordability, sustainability, efficiency and security) to identify pathways which offer co-benefits across multiple objectives in 32 global regions. Next, we downscale the impacts to the household deciles in India & the US using household survey data & future income distribution projections, to scrutinize the residential energy burden change for each pathway relative to the business-as-usual scenario. Our results show significant regressive impacts on access and affordability for most mitigation pathways, except those dominated by demand side mitigation approaches and non-CO_2 emission reductions. One of the key findings is that the mitigation pathway choice and design matters for just transition goals and bespoke pathways provide scope for synergies and progressive impacts. We also establish that technology solutions are unable to redress pre-existing inequities and should be complemented with other support policies for the vulnerable. Our work contributes to the scholarship on the need for improved representation of heterogeneity in energy-climate models and offers policy relevance – showing the importance of underlying systemic changes to achieve social & climate goals together. We also demonstrate that consideration of capability and historical responsibility are essential to achieve truly just transitions for the most vulnerable and the use of grandfathering narratives to protect the affluent exacerbates inequities and deprivileges the vulnerable.

About the author

Mel George is a PhD Candidate at the School of Public Policy, University of Maryland – College Park, MD, USA, a Graduate Assistant at the Center for Global Sustainability, and a Visiting Research Fellow at the Joint Global Change Research Institute, Pacific Northwest National Lab, College Park, MD, USA
(Contact: georgemv@umd.edu)

Acknowledgments

Sincere thanks to my mentors at IIASA – Shonali Pachauri, Narasimha Rao & Jihoon Min for supervising this work, regular follow-ups, and excellent research support and suggestions which enabled my project to take a noticeably different direction that originally envisaged. I believe their rigorous and probing questioning (or so it seemed at that time!) pushed me into unchartered waters and likely helped me to become a better researcher. My thanks are also due to the staff at IIASA (Tanja Huber, Aleksanda Cofala, Margit Roth-Ahra, Brian Fath & Fabian Wagner) for enabling the wonderful YSSP opportunity to exchange ideas and resources. The research also benefited through insightful interactions and feedback from Jarmo Kikstra, Benigna Boza-Kiss, Volker Krey & Adriano Vinca.

I must also mention the great support and encouragement I received from Anand Patwardhan, my advisor at the University of Maryland. Haewon McJeon at PNNL was also extremely helpful with examining & improving my modeling methods and discussing results, and I was also well-supported through regular review meetings with my dissertation committee members, Leon Clarke & Nathan Hultman. The modeling assumptions, underlying data and processing scripts I used were built on previous work and discussions with many colleagues and researchers at the Center for Global Sustainability and PNNL. I remain grateful to Kanishka Narayan, Alicia Zhao, Yang Ou, Jay Fuhrman, Jon Sampedro, Siwa Msangi, Patrick O'Rourke, Ryna Cui, Sha Yu, & Gokul Iyer. The research design was also aided by past collaborations with Seth Monteith (ClimateWorks Foundation) and Ajay Gambhir (Grantham Institute/ Imperial College).

I am thankful to the US National Academy of Science, Engineering & Medicine (NASEM), the IIASA National Member Organization (NMO) whose fellowship awarded through the US National Science Foundation (NSF) and travel grant enabled my participation in the YSSP and the pursuit of this research.

1. Introduction

Despite the announcements made at the Conference of Parties (COP-26) at Glasgow last year, the current climate pledges may still fall short of the challenge to keep warming below the Paris Agreement goal of 'well below 2 deg. C' (Ou & Iyer et al. 2021, Rogelj et al. 2021, UNEP 2021, Hohne et al. 2021). Though national governments are publicising long-term pledges to ramp-up mitigation ambition, accelerate decarbonization and achieve net-zero emissions, the changes implied by these targets are potentially far-reaching, involving not only the production of energy, but also its delivery & use. Such energy transitions are unlikely to be a "well-lubricated slide from one reality to another" (Yergin 2021). Whilst historically, energy transitions which involved mere "energy additions" (inclusion of new energy sources over existing options) have been complex and hardly swift, the coming energy transition could be further convoluted and involve "energy substitution" as well as demand pattern changes across commodities.

Mitigation and adaptation actions have been conceptualized as a risk transference between communities (Sovacool et al. 2015). Such transition risks could be unequally distributed (Gambhir & George et al. 2022) and fundamentally alter the nature & viability of many economic activities. Current development pathways have created behavioral, spatial, economic and social barriers (IPCC 2022a), and near-term choices to be made by policymakers, citizens, the private sector and other stakeholders will influence the risk distribution in different pathways. Identifying the bearers of such risks, or the winners & losers of climate action, is important for making low carbon transitions just, equitable and politically 'smooth', and this aspect has been an increasing focus of research and literature in the last decade. There is mounting recognition of the need to view climate change as matter of social justice & equity (NAS 2021), as well as growing acknowledgement of the limitations of energy-climate models which under-represent opportunities for behavioural changes to enhance the quality of life in low-carbon societies (Creutzig et al. 2018). It has been argued that incorporating distributional equity dimensions in energy-climate models remains hard (Peng et al. 2021). Equity is still central for the ratcheting process and when discussing the adequate magnitude of climate finance & support (Robiou du Pont et al. 2017) and the perception of co-benefits from mitigation action alone being sufficient to raise and implement climate action has been a non-starter (Chaturvedi et al. 2021, Rao 2022).

The IPCC (Intergovernmental Panel on Climate Change) does note that an agreement seen as more equitable can lead to more effective cooperation (IPCC 2014). More recently, it suggested that mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emissions reductions (IPCC 2022a). However, maximizing such synergies and avoiding trade-offs poses particular challenges for developing countries and vulnerable populations with limited institutional, technological and financial capacity, and with constrained social, human, and economic capital. There remain innumerable gaps in our collective understanding of how deep the inequalities associated with the energy transition might be, exactly who is on the frontlines of the impacts, what structures exist or are needed to protect them during the transition and what effective policy making would mean for different communities. The complexity of the debate is evident when the IPCC suggests equity and ethics as both a 'driver and constraint' on mitigation ambition (IPCC 2022b). An optimal trade-off between mitigation costs and damage costs of climate change depends on ethical considerations and weights assigned to different priorities by different actors, and simulations from integrated assessment models using different ethical parameters producing different optimal mitigation paths (IPCC 2022b, IPCC 2018, Roy et al. 2018). Distributions perceived to be unfair are less likely to be accepted, even if there are consequences or costs of non-acceptance (Gampfer 2014).

Though results from existing energy-climate models have framed the narrative around 'winners and losers', 'co-benefits and trade-offs' where climate & social development goals are seen in a contradictory perspective, the literature also suggests the possibility of a sustainable development space (van Vuuren et al. 2022), which could enable strategic entry points for supporting mitigation by focusing on selected social goals. It has been shown that pathway specifics influence the distribution of transition risks (Gambhir & George et al. 2022). Can we, then, design or conceptualize pathways to limit these risks and achieve development objectives? These considerations have long been embedded in international climate agreements through concepts such as common but differentiated responsibilities and intergenerational equity but are also reflected in recent proposals like the Green New Deal (Galvin & Healy 2020, Green New Deal 2019) and Build Back Better (White House 2022, Build Back Better Act 2021). These proposals specifically embed equity and social justice within climate change mitigation goals and emphasize commitments to job training and economic development support for individuals and communities that might be adversely affected by a transition to new sources of energy. These efforts also point to an increasingly "bottom-up" or sub-national nature of climate action, against the usual top-down global policy approach. These efforts employ issues around equity, jobs, energy security, energy access and national security to drive climate mitigation progress, instead of the framework using climate as the entry point to deal with equity issues. The consideration of these collateral dimensions or impacts of climate mitigation policy all fall into a broader conceptualization of energy transitions around "just transitions" to a green economy.

These considerations drive the framing of my overarching research question: *How best can we deliver on societal and climate goals?*

Whilst the trade-off between climate action and development goals, such as near-term poverty reduction or energy access and affordability, is a familiar theme based in part on results from existing energy-climate models. It is often assumed that a pathway to a stringent climate target such as limiting end-of-century global mean temperature rise to 1.5°C would cause the burden of a global & national mitigation to fall on the poorest and most vulnerable sections. However, these results ignore the possibility that bespoke pathway design and selection can be used in progressive ways to generate immediate net benefits for the vulnerable.

Despite continually growing evidence of the skewed distributional impacts of climate change mitigation policies, there is little research quantifying the potential consequences of alternative pathways to the same climate goal. Are all pathways to the same climate goal created equal and lead to similar impacts across geographies and vulnerable populations? Which aspects of pathway design could intensify impacts on the vulnerable and which facets may lead to more progressive outcomes? How would this shape impacts across multiple energy goals and hence, pathway choices for different regions? Is it even possible for any pathway to achieve better social outcomes and less environmental impacts, whilst keeping the global economy size unchanged? These are big questions which can be addressed in many ways.

Instead of considering the dominant or representative climate mitigation scenario to 1.5 or 2°C mean temperature rise, we scrutinize the implications of multiple pathways varying by technology, pace, regional mitigation effort share and demand side shifts. A scenario ensemble would provide more robust insights than outcomes based on single pathways (Guivarch et al. 2022). Following the predominant archetype might not only turn out to be a risky policy in terms of distributional consequences for the most vulnerable, it may also limit national climate ambition through the amplification of narratives around a false choice between climate & development goals.

Here, we seek to make a simple & novel contribution - modest in its approach, but novel in the quantification of impacts and consequences on regions and income strata.

2. Current Literature

Existing scholarship around dimensions of UN Sustainable Development Goal, SDG-7 (which relates to achieving the goal of 'clean & affordable energy for all'), has often sought to examine regional impacts though a synergies and tradeoffs narrative (Iyer et al. 2018, Dagnachew et al. 2018, Jewell et al. 2014, Cherp & Jewell 2016). Another flank of the literature examines universal household energy access pathways or attaining part of the SDG-7 metrics at a global (Poblete-Cazenave et al. 2021a, Grubler et al. 2018, Soergel et al. 2021, Rao et al. 2019, Pachauri et al. 2013) or regional levels (Cameron et al. 2016). Some recent work has also examined the role of material requirements for meeting energy needs and the role of affluent sections in driving demands (Millward-Hopkins et al. 2020, Millward-Hopkins 2022). Projections of household energy use have been made assuming attaining higher living standards in developing countries (van Ruijven et al. 2011, Daioglou et al. 2012, Krey et al. 2012), or aspects of curtailment of consumption and income (Umit et al. 2019). Streimkiene et al. (2019) provides a comprehensive review of energy poverty impacts of climate policies in the EU.

There has been growing interest to apply energy-climate models and include more fine-grained analysis at smaller spatial & temporal scales, whilst also addressing broader social objectives such as the SDGs. Since policy design would require targeting subgroups for social protection or support, without which mitigation options can worsen poverty by increasing energy prices and making decent living standards out of reach for some households. The results for the average representative household in region conceal the implications for the most vulnerable households. This fact has been highlighted in recent papers seeking to suggest ways to incorporate poverty & equity dimensions in climate change and specifically, Integrated Assessment Models or IAMs (Rao & Wilson 2022, Klinskey & Winkler 2018). Models of energy systems have generally not considered income distribution, and implicitly operate on the basis of a single representative household (Rao et al.2017, van Soest et al. 2019, Oswald et al. 2021), assuming that differences would balance out in the aggregate. Some studies have examined efforts to integrate income distributions in general equilibrium models in energy system scenarios (van Ruijven et al. 2011, 2015), yet energy demand is typically income-granular after the simulations.

In general, studies more explicitly addressing the implications of heterogeneity amongst regions and representative households for energy demand are rare. There have been very few distribution focused studies. Cameron et al. (2016) was amongst the first efforts to incorporate income classes and household characteristics (rural/ urban) with IAM results and showed the implications of clean cookstove access on climate goals in South Asia. In another recent study, Poblete-Cazenave et al. (2018, 2021a, 2021b) took a significant step forward by incorporating income distributions within an IAM (MESSAGEix) and examining the energy consumption levels under different mitigation scenarios by income strata. Sampedro et al. (2022) was another recent effort to include income distribution as quintile classes for a single region (USA) in the GCAM IAM. All of the above studies concluded that incorporating the effects of heterogeneity influences modelling outcomes on energy consumption behaviour across socioeconomic levels.

Despite the wealth of literature, there is no exploration of the equity implications of different pathways to the same climate goal. Whilst hitherto rare studies such as Poblete-Cazenave et al. (2021a) do report important findings, the pathway choices only vary across the SSP 1-3 dimensions and do not account for the variations in transition pace, technology choices on the supply or demand side changes, or even the distribution of mitigation burden across regions. Whereas the objectives of these previous studies modelling distributional impacts of mitigation pathways are laudable, the approaches reflect a selection of scenarios which ultimately assume a biased distribution of the mitigation burden in favour of wealthier, higher-emitting countries.

Likewise, there is little literature examining the share of household spending on energy needs relative to its net income, often known as the household energy burden (Drehobl & Ross, 2016; Drehobl, Ross & Ayala 2020). The share of household income spent on essential goods could rapidly increase under mitigation scenarios involving changes to subsidy levels or a carbon tax and have extreme impacts for the most vulnerable households. Previous studies have all focused on the levels of consumption (joules) and have not been extended to measure the effect that a household actually faces in terms of expenditure ($) and the concomitant impacts on other choices that the vulnerable households have to make.

Further, while SDG-7 attainment has been a focus, it has often missed the fact that objectives within an SDG could have synergies and tradeoffs as well. These can vary by region or pathway choices. For example, the aspects of energy sustainability or clean energy could impact energy affordability, access or energy security. It has been posited that an 'energy trilemma' exists and there are conflicts between energy security, social impact and environmental sensitivity (Carbon Brief, 2013). This concept has also been explored as an impossible energy trinity recently (Thaler & Hofmann 2022), positing that some regions may be better suited than others in an energy transition. Most regions would have 3 options to cope with the transition while ensuring energy access: a 'dirty option' sacrificing sustainability, an 'expensive option' compromising energy affordability, and an 'insecure option' relinquishing energy sovereignty. This energy trilemma hypothesis is again based on representative pathway results in IAMs and the results could vary by pathway design, and the distributional outcomes could further vary by regional context in each case.

We present a more detailed literature review in Supplementary Information (Section 9.1) on the broader set of societal goals, such as SDGs, and their linkages with climate mitigation pathways.

3. Research Questions & Contributions

Despite progress in the last decade, over 573 million people in many areas of the globe and especially in sub-Saharan Africa have no access to electricity (UN 2019). Almost three billion people remain without access to clean cooking in 2017, posing health and socioeconomic concerns. Under current and planned policies, the number of people without access would be 2.2 billion in 2030 (UN 2019). The world is falling well short of meeting the global energy targets set in the SDGs for 2030. Whilst climate change remains an imperative or singular "existential" question for the developed world, many developing regions struggle with other existential questions and for them, it's a question of "energy transitions" – plural (Yergin 2021).

Given this underlying reality and the overarching research objective to examine different mitigation pathways to achieve both climate & societal development goals together, we outline two specific research questions (RQs) which we seek to address through this work:

RQ-1: What are the co-benefits and trade-offs of different 1.5°C pathways across SDG-7 goals and national energy priorities?

RQ-2: What is the impact of different 1.5°C pathways on household energy burdens across different income tiers?

The first question relates to average impacts for a given region and representative household (i.e the spatial distributional impacts), while the second question examines the downscaled impacts or distributional impacts by income strata. In both cases, we intend to examine the temporal effects as well, considering not just the short-term (2030) effects, but also the longer-term (2050) consequences.

We contribute to addressing the identified gaps in existing literature along multiple dimensions. Firstly, the exploration of distributional impacts of multiple pathways to 1.5°C varying by pace of transition, technology choices, demand side changes and global effort sharing is a key contribution. Despite the rapidly growing number of studies which explore the distributional consequences of mitigation policies across & within regions, there is little research which estimates how mitigation pathway choices can affect outcomes for the vulnerable regions and societies, and consequently their mitigation ambition. This is an important oversight as many of the arguments on trade-offs between climate action and development goals could be impacted when transition risks are really dependent on region, technology choices & socioeconomic dimensions within pathways. As the pandemic showed, slight shifts in socioeconomics could negatively affect clean energy goals (Pachauri et al.2021). Further, existing optimal climate policy calculations which have a built-in bias implying costs to the poorest regions and intergenerational trade-offs in well-being (Nordhaus 2007, Stern 2008, Budolfson et al. 2021) and changes to the global mitigation effort distribution can have implications for just transitions where they are most indispensable.

Indeed, the possibility of alternative pathways which could upend the narrative of intractable compromises of climate policy. The IPCC Special Report states this succinctly: "*very little literature has formally examined distributions under 1.5°C consistent mitigation scenarios*" (IPCC 2018). The societal impacts of multiple pathways to a certain climate goal could vary and analysis based on existing archetypes are fraught with skewed assessments of the energy burdens on households. Whilst few studies have incorporated different pathways & representation of heterogeneity remains an ongoing effort, these aspects have been considered distinctly and we bring the two streams together.

Secondly, we build on the existing literature on energy consumption by income strata and extend it to consider the household energy burden within those strata, and we argue that it is a better representation of the actual impacts felt by the vulnerable. Thirdly, we examine the synergies and trade-offs within an SDG and against other national energy priorities for different pathways and scrutinize the context dependency by region.

4. Methods

Despite the discernable limitations in existing IAMs to represent heterogeneity and distributional impacts, we use an approach employing IAMs in combination with household survey data to answer the two research questions. Since the IAM scenarios feature in the periodic IPCC reports on the state of science and are widely used by different stakeholders such as policymakers, finance & development agencies and researchers to understand implications of future climate policies, they play an important supporting role to assess and track the impacts on social objectives & emission reductions. Secondly, IAMs also model the interlinkages of energy-water-land requirements between different sectors and how they are impacted by different pathways, multiple sectors and corresponding household choices. Thirdly, IAMs offer the benefit of a consistent framework for comparison of the outcomes, whilst remaining tractable with the climate goal.

The scenarios in this study use GCAM (Global Change Analysis Model), an IAM developed by the Joint Global Change Research Institute of the University of Maryland and the Pacific Northwest National Laboratory. GCAM is an open-source, technology-rich model of the energy, economy, agriculture and land use, water, atmosphere and climate systems (Calvin et al. 2019). GCAM is a 5-yr time step, dynamic-recursive market equilibrium model which represents the global economy by disaggregating the world into 32 geopolitical regions, 235 river basins and 384 agro-ecological land-use regions. Apart from featured modeling results in each IPCC report and the SSP representations (Calvin et al. 2017), GCAM has been used extensively for a wide range of applications to explore the implications of changes in key driving forces such as technology and economic growth on national and international policies and pathways and inter-model comparison studies (Wise et al. 2009, Iyer et al. 2018, McCollum et al. 2018, Bertram et al. 2020).

GCAM ver.5.4 (JGCRI 2022a), as used in this study, is calibrated to a historic base year (2015), with trajectories to different temperatures in these scenarios specified using fossil fuel and industry CO_2 constraints (and GHG constraints, in the case of NDCs). All emission constraints are assumed to begin in 2025 (except for the NDCs, which begin in 2020). GCAM uses assumptions about population growth and changes in labour productivity, along with representations of resources, technologies and policies, and solves for the equilibrium prices and quantities of various energy, agricultural and CO_2/GHG markets in each 5-yr model period from 2015 (the calibration year) to 2100 at different spatial resolutions. Primary energy (that is, coal and other fossil fuels), agricultural products and biomass are traded globally. GCAM calculates the CO_2 prices required to meet the emissions constraint imposed in each model period. Land-use change emissions are in addition to the constraint and their price is determined as an exogenously specified proportion of the fossil emissions price. This is done because, whereas fossil fuels are largely a market commodity, much of the land use and agriculture occurs outside of regulatory frameworks in many countries.

GCAM tracks emissions of 24 GHGs, aerosols and short-lived species endogenously on the basis of the resulting energy, agriculture and land systems activity. Emissions can then be passed to the climate–carbon cycle module – Hector (JGCRI 2022b, Hartin et al. 2015) and converted to concentrations, radiative forcing, temperature and other responses to the climate system. Further descriptions of other GCAM v.5.4 model specifications (and other releases) can be found in the online GCAM documentation (JGCRI 2022a).

The modeling effort for this work focuses on the buildings sector in GCAM, which disaggregates it into residential and commercial sectors and models three aggregate services (heating, cooling, and other). Within each region, each type of building and each service starts with a different mix of fuels supplying energy. The future evolution of building energy use is shaped by changes in (1) floorspace, (2) the level of building service per unit of floorspace, and (3) fuel and technology choices by consumers. Floorspace depends on population, income, the average price of energy services, and exogenously specified satiation levels which relate to the income elasticity of demand. GCAM also includes the option to specify floorspace exogenously. The level of building service demands per unit of floorspace depend on climate, building shell conductivity, affordability (relating to price elasticity of demand), and satiation levels. The approach used in the buildings sector is documented in Clarke et al. 2018, which has a focus on heating and cooling service and energy demands.

4.1 Scenario choices

We model a broad array of 17 pathways (Table 1) to the end-of-century climate goal of 1.5°C (±2%), which vary by pace of transition (the global net zero CO_2 emissions attainment year), technology choices, and demand side changes. Apart from these cost-optimal pathways which assume the existence of a global carbon market, we model pathways with regionally disaggregated carbon markets and differential effort sharing as a fourth category of pathways. The specific assumptions and input file changes relating to the technology pathways and demand side pathway are listed in the Supplementary Information (Section 9.2).

Table 1: *List of scenarios modelled in this study*

Scenario set	Criterion	Pathway name	Short description
I	**Reference**	BAU	The 'business as usual' or 'no new policy' scenario, the standard SSP-2 implementation in GCAM including Covid-19 GDP impacts
II	**Pace of transition**	NZ2040	Achieving global net zero CO_2 emissions in 2040
		NZ2050	Achieving global net zero CO_2 emissions in 2050
		NZ2060	Achieving global net zero CO_2 emissions in 2060
III	**Technology choices**	RE	High preference and advanced, cheaper renewable energy (wind, solar, geothermal)
		CCS/NUC	High preference and cheaper CCS (Carbon Capture & Sequestration) and advanced nuclear technologies
		DAC	Moderate levels of direct air capture technology (5 $GtCO_2$)
		ELE	Increased preference to electrification in buildings, industry & transport
		NTB	Complete ban on use of traditional biomass in residential services
IV	**Demand side changes**	BEH	Behavior changes & societal transformation (dietary shifts, demand reduction, transport behavior, smaller houses) (George et al. 2021)
		ALL	A scenario using a combination of all mitigation options from the supply side (high RE + low NUC + high ELE + constrained bioenergy), along with significant improvements on the demand side (HFC reductions + higher efficiency in all sectors + improved agri. Practices +

			assumptions in the BEH scenario) (George & Gambhir et al. 2022, ClimateWorks Foundation 2020)
V	**Regional effort sharing**	CO	Based on the 'least cost principle', a cost optimal pathway, SSP 2 to attaining 1.5°C in 2100
		CAP-A	Variant based on Capability Principle, staged net zero based on GDP/cap. relative to Brazil's 2050 level.
		CAP-B	Scenario variant based on the Capability Principle, net zero year immediately on attaining GDP/cap. PPP exceeding Brazil's 2050 level
		SOV	Based on the Sovereignty Principle with nations free to determine their commitments, which we base on their stated NDC pledges at COP-26 and continuing at similar rates of reduction for all regions so as to meet 1.5°C in 2100
		GF	Based on the Grandfathering Principle, future emission rights & responsibilities based on 2015 levels
		RESP	Based on the Historical Responsibility principle, cumulative per capita emissions since 1850 accounted against global carbon budget and corresponding financial transfers in a global carbon market

The regional mitigation effort sharing principles were adapted from van den Berg et al. (2019), as far as they relate to capability, grandfathering rule, sovereignty & historical responsibility. It is important to note here that relative to grandfathering, the 'ability to pay' or 'capability' pathways may have somewhat more defensible bases. We adopt two approaches to the Capability Principle, (a) CAP-A is a gradual transition period with regions moving their net zero attainment years ahead by 5-10 years based on per capita GDP and (b) CAP-B is an immediate enhancement to the net zero goals based on per capita GDP. Brazil's GDP/cap. Was chosen as the reference level since it was the lowest on PPP basis amongst all the regions with a net zero emissions target year of 2050. The concession in the first approach is rationalised on the basis of avoiding technically implausible reduction rates (Robiou du Pont et al. 2017). With the rapid decline in the global carbon budget, a slow shift to net zero emissions does imbibe elements of grandfathering and a bias against poorer and lower-emitting countries and hence we also consider the implications of the second approach as well.

Further, unlike many studies which exclude or discount the consideration of the Responsibility Principle – that the largest contributors to global GHG concentrations must do the most to reduce their emissions, we emphasize this key principle of common, but differentiated responsibilities cited in the Rio Convention and the UNFCCC. This pathway is modelled based on the cumulative per capita emissions for each region since the dawn of the industrial age (1850) and an equivalent financial transfer from the regions with negative carbon budgets to those with positive balances.

4.2 Approach: Pathway interactions with regional energy priorities

For each mitigation pathway, we examine the relative impacts for different regions across the 4 dimensions of SDG-7 targets (access, affordability, clean energy, energy efficiency). Whilst nations strive to address the interactions within these SDG-7 dimensions and climate policy, they also have to contend with the energy security dimension. Energy security concerns have increasingly dominated the energy policies due to recent geopolitical events such as the Russia-Ukraine conflict and the cascading effects it has had on global energy supply chains. We, therefore, consider energy security to be an intrinsic, inseparable and unstated dimension of SDG-7 as in Iyer et al. (2018) and Jewell et al. (2016). We limit this analysis to the sovereignty perspective of energy security, which relates to the degree of control that national governments have over energy systems and is rooted in historic and recent events such as embargoes by powerful actors. We acknowledge that alternate interpretations of energy security exist in the literature, such as diversity or reliability of supply. Different trade modeling paradigms could also lead to different estimates of imports/exports even in the same set of scenarios and the framework within GCAM could affect those results. Trade in other fuels (e.g., bioenergy), technologies (e.g. solar cells) may be important in future. Thus, we consider 5 national energy priorities to be attained by each pathway (Figure 1) and assess the effects for multiple global regions.

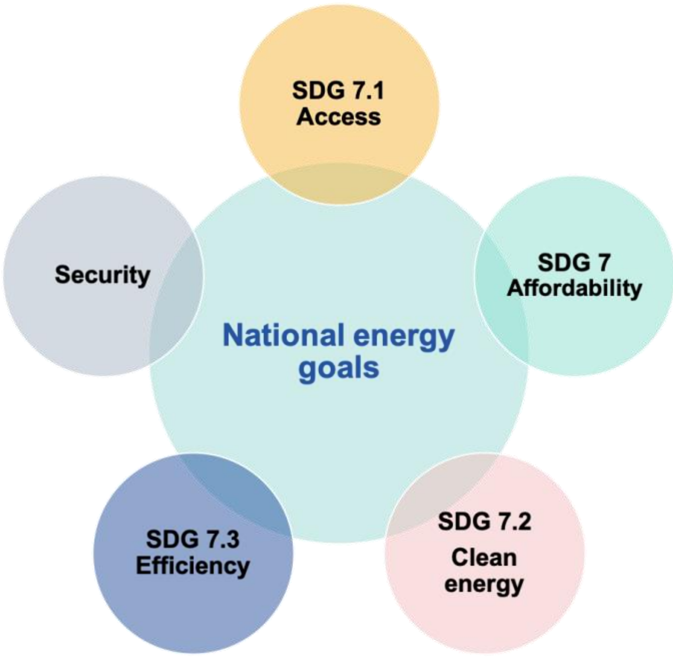


Fig. 1: *The 5 national energy priorities considered in this study, based on stated and implicit SDG-7 goals*

Whilst several metrics have been used in the literature for each of these energy goals, we apply the set of indicators listed in Table 2. These indicators, although not extensive, are broadly representative of the central dimensions sought to be achieved under each goal. We analyze the results for 2030 (near term) & 2050 (long-term) across all 32 geographical regions in GCAM. All results are shown relative to the benchmark or "no new policy" scenario. The synergies and tradeoffs are measured as the ratio of the given metric in the scenario to that of the metric in the benchmark or reference scenario.

Table 2: *National energy goals and corresponding metrics*

National energy goal	Metric/ Indicator chosen for this study
Access	Share of residential energy from non-solid fuels (natural gas, LPG, biofuels, electricity etc.)
Affordability	Share of average annual household income spent on residential energy needs
Clean energy	Share of renewable energy in the residential electricity mix
Efficiency	The primary energy intensity of GDP, assuming average fossil efficiency for other primary energy sources
Security	Share of energy imports in annual regional consumption

The share of non-solid fuels in residential energy use demonstrates the access and shift to modern and cleaner cooking options in any given region. While this involves a normative determination of the relative "cleanliness" of each source, especially those which may be derived from petroleum sources, given the current consumption mix in the least developed regions of the world which includes significant amounts of traditional biomass (twigs, cow dung, wood, copra, other residual biomass etc.) or other solid fuels such as coal, we believe measuring non-solid fuel usage would be ideal. Though considering electrification alone may be desirable, most of the Global South is still quite distant from the leap to electric cooking and current access policies are often directed towards liquified petroleum gases or other liquid fuels derived from fossil fuels. Conventional access metrics (as in the SDG 7.1) define access in terms of number of connections, which may conceal true availability and ability to consume. Also, measuring connections would restrict the choice to few fuels and is not tractable from IAM results anyway.

We use the share of household spending on energy relative to income to measure affordability instead of the usual metrics like fuel prices. The fuel price conceals the level of household consumption which matters in the overall burden faced by the household. This is also in line with other energy poverty or energy burden metrics which use a greater than 5 or 10% spending threshold to imply energy poverty. We do not specifically employ the threshold here since the limits are dependent on regional context.

The quantum of clean energy is measured based on the share of renewable energy sources in the electricity mix. We restrict the analysis here to electricity and not all fuels used in residences since the share of biofuels is exceedingly small relative to other options such as natural gas or those derived from petroleum refining, even under these mitigation scenarios. Since increasing electrification and share of renewable energy sources (including wind, solar, hydro, geothermal etc.) is commonly associated with increased mitigation efforts, and the exclusion of other minor fuels does not meaningfully affect the analysis here, we believe this metric is justified.

Energy efficiency measurements and metrics can vary by the type of application & sector and a generally acceptable definition is not available to account for different contexts. Here, we adopted the specific definition in SDG 7.3 which relates to energy intensity of GDP, with higher energy intensity implying lower efficiency. This metric has also been used in NDCs of major regions such as India and presents a "30000 feet" view of the direction of energy efficiency at the national level.

We include the share of imports as a metric for energy security as it is often understood in the context of energy sovereignty. Whilst alternate definitions of energy security have been discussed in other works, for the limited purpose of this analysis and given the importance of this aspect in the current geopolitical context, we trust this metric is not just reasonable, but also warranted.

4.3 Approach: Pathway interactions with household income tiers

Since the average household effect in a region would rarely represent the actual distributional effects, we next explore the equity dimension using contrasting case studies of the United States of America & India using household survey data in combination with IAM outputs. Both are large economies and significant contributors to carbon emissions, in different stages of development, resource sufficiency and technology choices and provide critical & contrasting case studies of how distributional impacts can vary by pathway. Both countries are also absolutely indispensable to the GHG mitigation efforts.

For the US, we use the well-known RECS – Residential Energy Consumption Survey 2015 conducted by the US Energy Information Administration (EIA 2022). The data for the most recent survey is still to be released and hence the choice of the last available survey. For India, we employ the nationally representative and detailed India Human Development Survey or IHDS-II (Desai & Reeve 2018). Again, we had to use survey data from 2011 since more recent data with similar granular detail and surveys at nationally representative scale were not publicly available.

For each of 17 pathways varying by pace of transition, technology & socioeconomic challenges to mitigation, we showcase the differences in access and affordability for households in different income deciles. For this, we use a lognormal distribution & projected Gini coefficient from Rao et al. (2019), additionally accounting for the mitigation costs & additional changes to household food expenditures as done in Soergel et al. (2021).

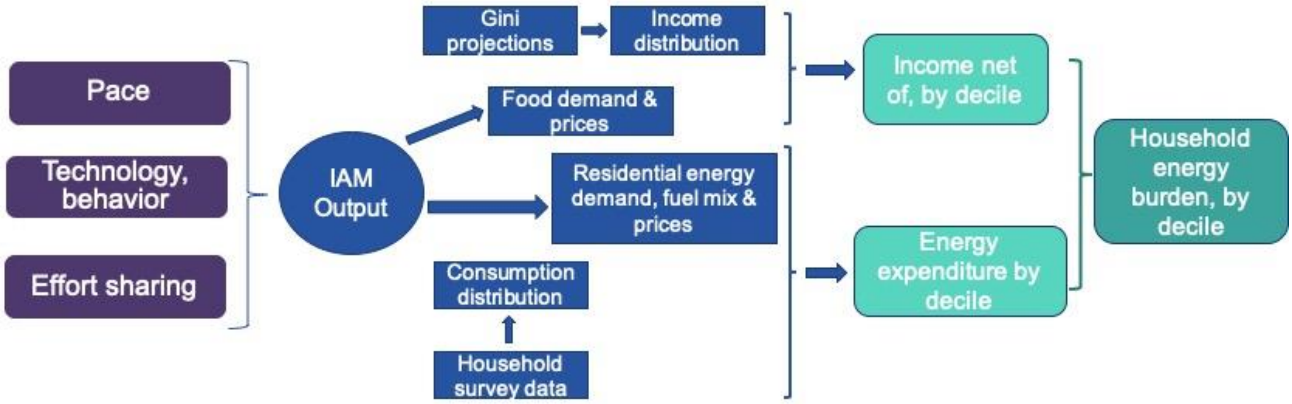


Fig. 2: *Flowchart of approach to RQ-2, from downscaling scenario results in combination with income distribution and household survey trends*

We include the effect of food expenditures since it is one of the essential household needs for many regions and since the outcomes can be measured in this IAM. The analysis is performed for each income decile in India & USA and results are reported as change in household energy burden (viz. share of net income after food expenditures that the average household in each income decile spends on residential energy services), relative to the benchmark scenario.

$$Household\ energy\ burden = \frac{(Expenditure\ on\ energy\ needs)}{\left(\frac{GDP}{cap}\right) - (expenditure\ on\ food)} \qquad \text{(E. 1)}$$

We recognize that this approach to downscaling based on the current distribution of energy consumption in household surveys could miss households without any access to modern energy services and the choices they may make between different fuels for services such as cooking. Whilst it is currently not possible to use a detailed household choice model in IAMs, we perform a sensitivity analysis for additional heterogeneity parameters and behavior trends by income strata. This additional analysis for both India & USA incorporates more diversity in household types. The details of this approach and corresponding indicative results are shown in the SI (Section 9.3-9.5).

5. Results

The mitigation scenarios listed in Table 1 were modeled in GCAM and were all able to attain the 1.5°C goal in 2100 (Fig. 3). However, each scenario had differing trends in residential fuel prices and consumption levels, which would lead to divergent trends in consumption and spending levels for households in each income tier. A representative trend of these variations for electricity and gas prices in India & USA is shown the panel (Fig. 4 a- d), where observe that demand and supply changes, differing income & price elasticities together affect fuel prices. It is interesting to note here that pathways involving demand side shifts (BEH & ALL) tended to have lower energy prices relative to cost optimal pathways or those dominated by other technologies.

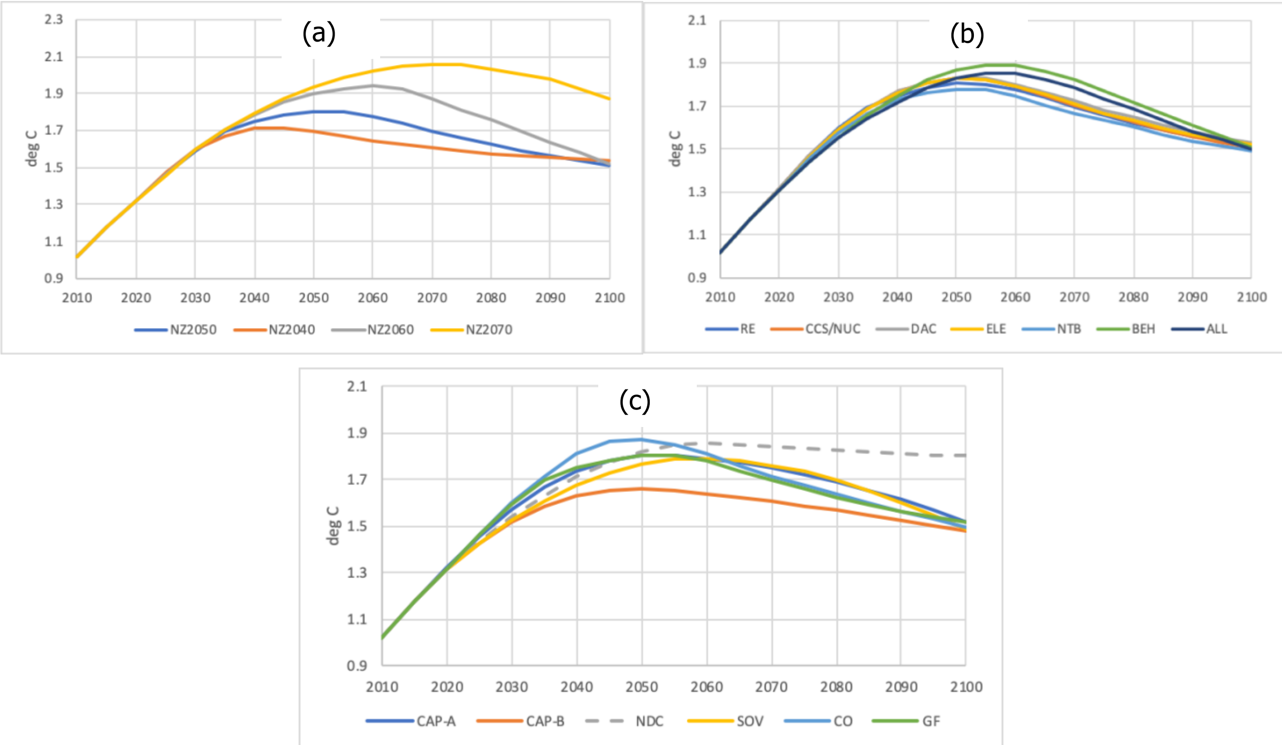


Fig. 3: *Global mean temperature rise trend across all the modeled scenarios, with all scenarios attaining 1.5C goal in 2100 with mid-century overshoots in-line with existing literature. Panel (a) represents scenarios with changes to pace of transition. The scenario with net zero CO_2 emissions attained in 2070 was unable to meet the 1.5C goal. Panel (b) represents scenarios varying by technology and demand side responses, while panel (c) shows temperature rise trends for pathways differing by regional effort sharing levels. The dotted line represents the continuing NDC pledges based on COP-26 announcements, which falls short of 1.5C goal.*

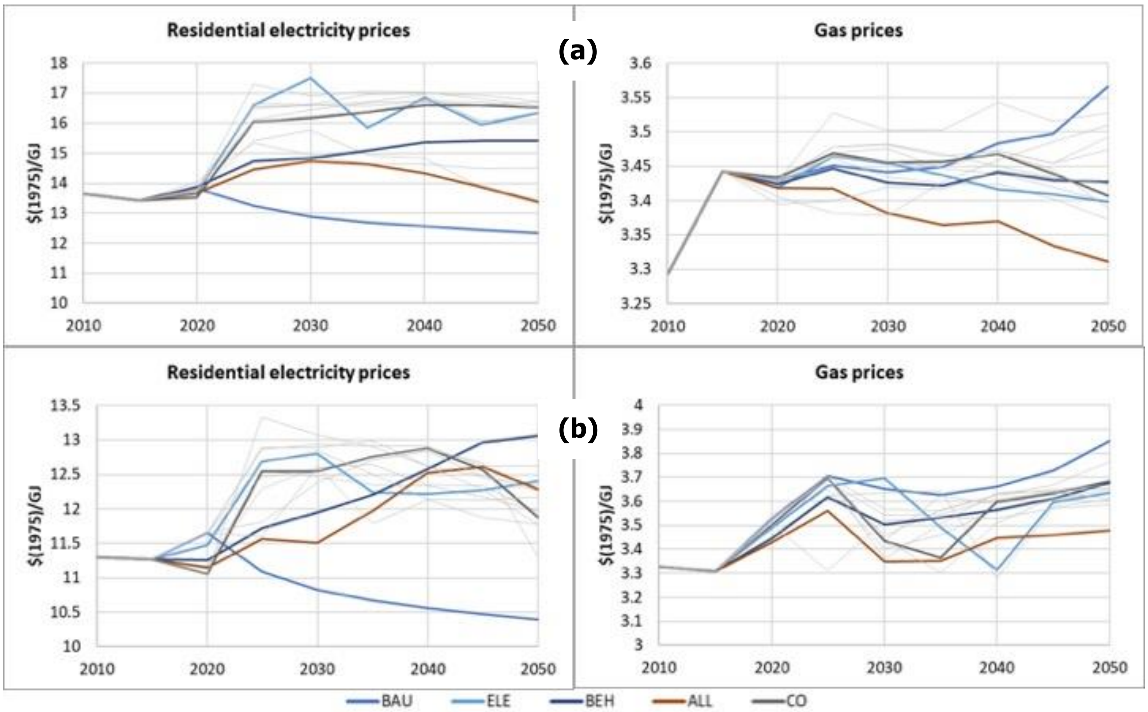


Fig. 4: *Variation of electricity and gas prices for buildings sector across different 1.5C pathways in GCAM, for (a) India and (b) USA*

An important aspect to note here is that these changes in residential energy fuel prices lead to not just a consumption reduction, but also a shift between fuel options depending on demand price elasticity for each application and fuel, apart from household income levels. An example is India – higher mitigation costs lead to an increase in traditional biomass consumption in a 1.5C scenario against the reference scenario (Fig. 5)

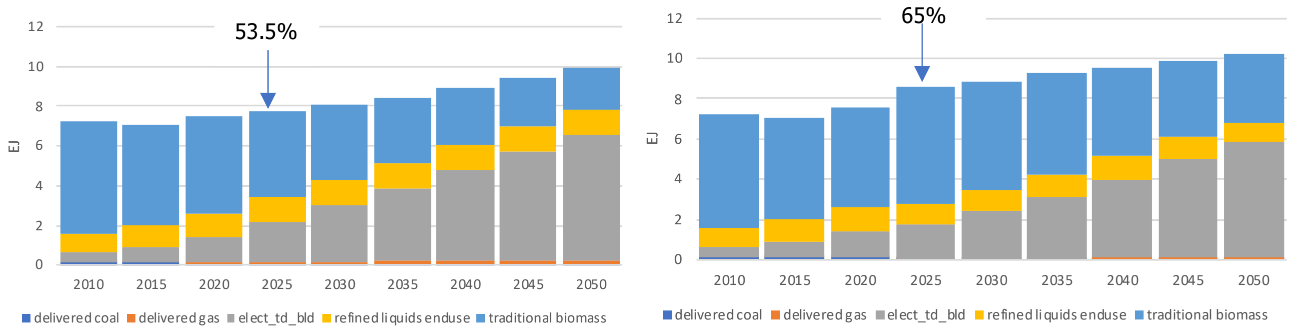


Fig. 5: *The left panel shows the residential energy fuel consumption in India for the reference scenario while the right panel represents the same for the cost optimal mitigation pathway to 1.5 deg. C. The arrows indicate the share of traditional biomass in total residential energy consumption, which increases from 53.5% in the reference scenario to about 65% in the mitigation scenario. This implies a shift towards non-solid & poorer fuels due to affordability issues. Whilst these results are for the average or representative household, fuel choices would vary by income tiers since the demand price elasticity would vary by fuel, application and income levels.*

5.1 Spatial distribution of synergies & trade-offs in national energy goals

We demonstrate and discuss the results for the 4 major regions (USA, EU-15, China & India) in this section (Fig. 6 a-c) and supplement these observations with additional results for other developing and underdeveloped regions of interest in the SI (Section 9.6 shows results for South Africa, Western, Eastern & Sub-Saharan Africa, Indonesia & Brazil).

Across any 1.5°C mitigation scenario varying merely by pace (Fig. 6(a)), the burden of mitigation falls overwhelmingly on the developing regions. The countries in the Global South face significant compromises on energy access & affordability as well, implying a double whammy of sorts relative to the BAU case. In contrast, there are no effects on the access dimension for the Global North. As expected, slower pace of transition reduces the level of interlinkages. Admittedly, the key trade-offs in US & EU-15 relate to affordability aspects of energy services. The shift towards cleaner energy sources in mitigation scenarios leads to obvious co-benefits on SDG 7.2 and significantly improves the energy trade balance across all regions. The trade-offs on energy security observed for the US is mainly due to its current levels of export of fossil fuels which would have rapidly falling demands in mitigation scenarios. Across all regions, these short-term impacts remain largely visible even in the long-term (SI, section 9.7).

For pathways varying by technology choices, we observe that most technology choices (RE, CCS/ NUC, DAC) involve access & affordability trade-offs for the Global South (Fig. 6(b)). In the long term, some of these pathways do improve access levels in China, but not in other developing regions. On the other hand, pathways which promote electrification or eliminate the use of solid fuels like traditional biomass, significantly improve the access related metric across all region. The flip side of such technology implementation shows up on the affordability dimension, where energy prices and household spending rapidly increase in line with higher demand. None of the purely technology-based pathways are able to demonstrate synergies across all dimensions for all regions.

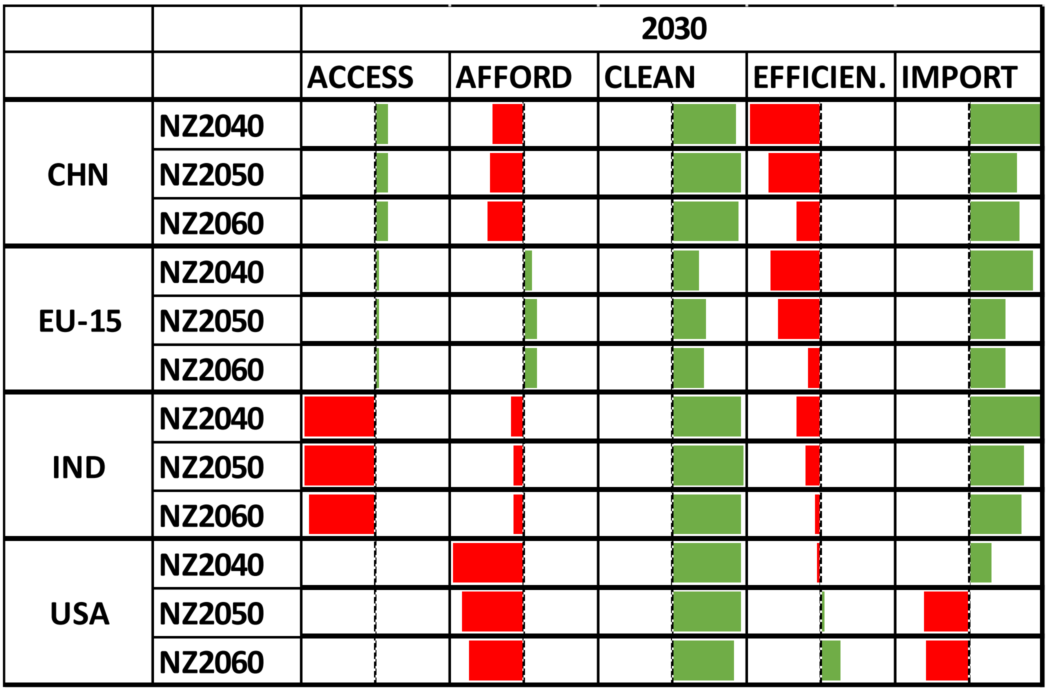


Fig. 6(a): *Magnitude of synergies (green bars) and trade-offs (red bars) across national energy goals in the near term (2030) for pathways varying by global net zero CO2 emission year for key regions. The synergies and trade-offs are measured as ratio of the metrics (from table 2) in the given scenario to same metrics in the BAU or reference scenario*

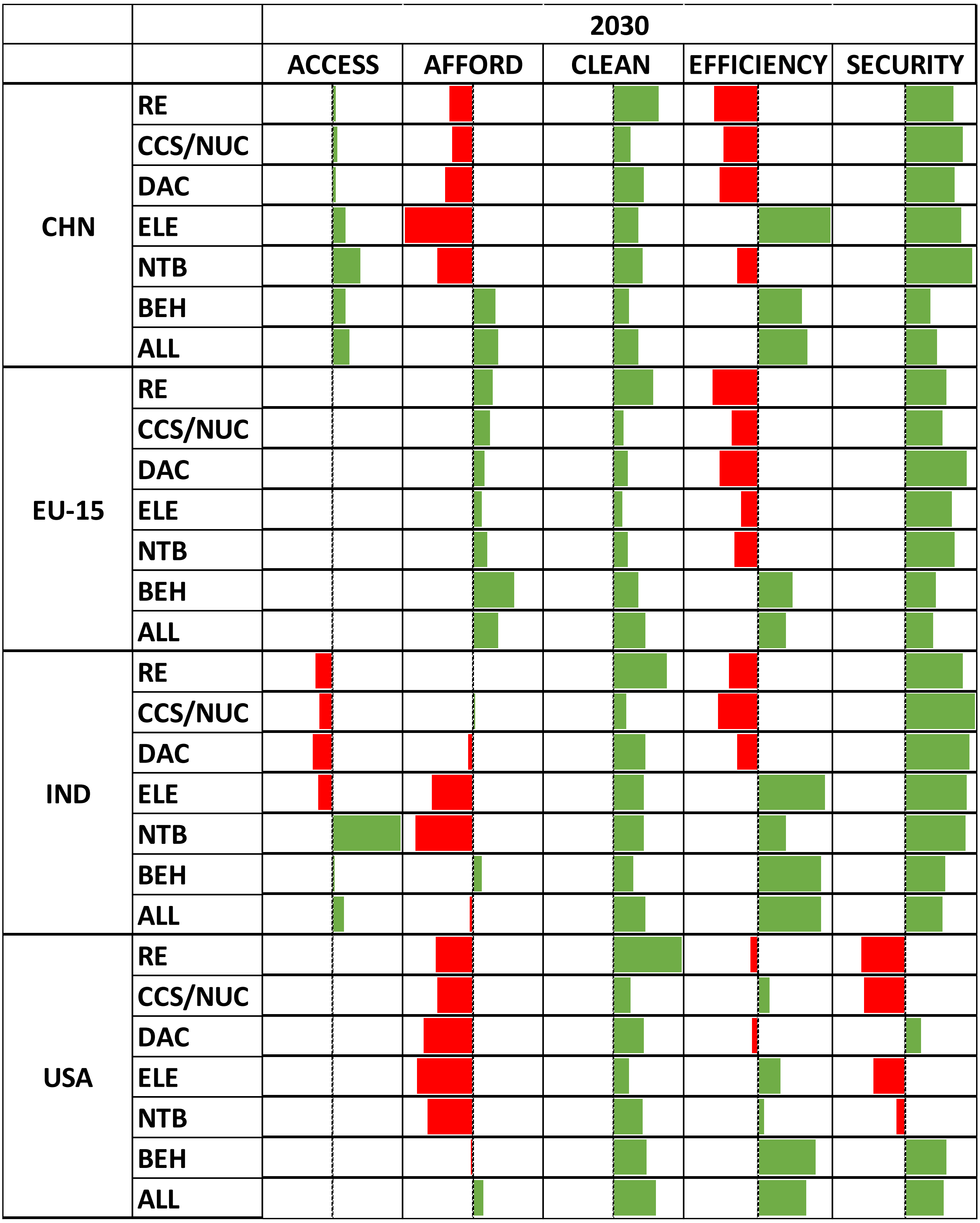


Fig. 6(b): *Magnitude of synergies (green bars) and trade-offs (red bars) across national energy goals in the near term (2030) for pathways varying by technology choices and demand side mitigation options for key regions*

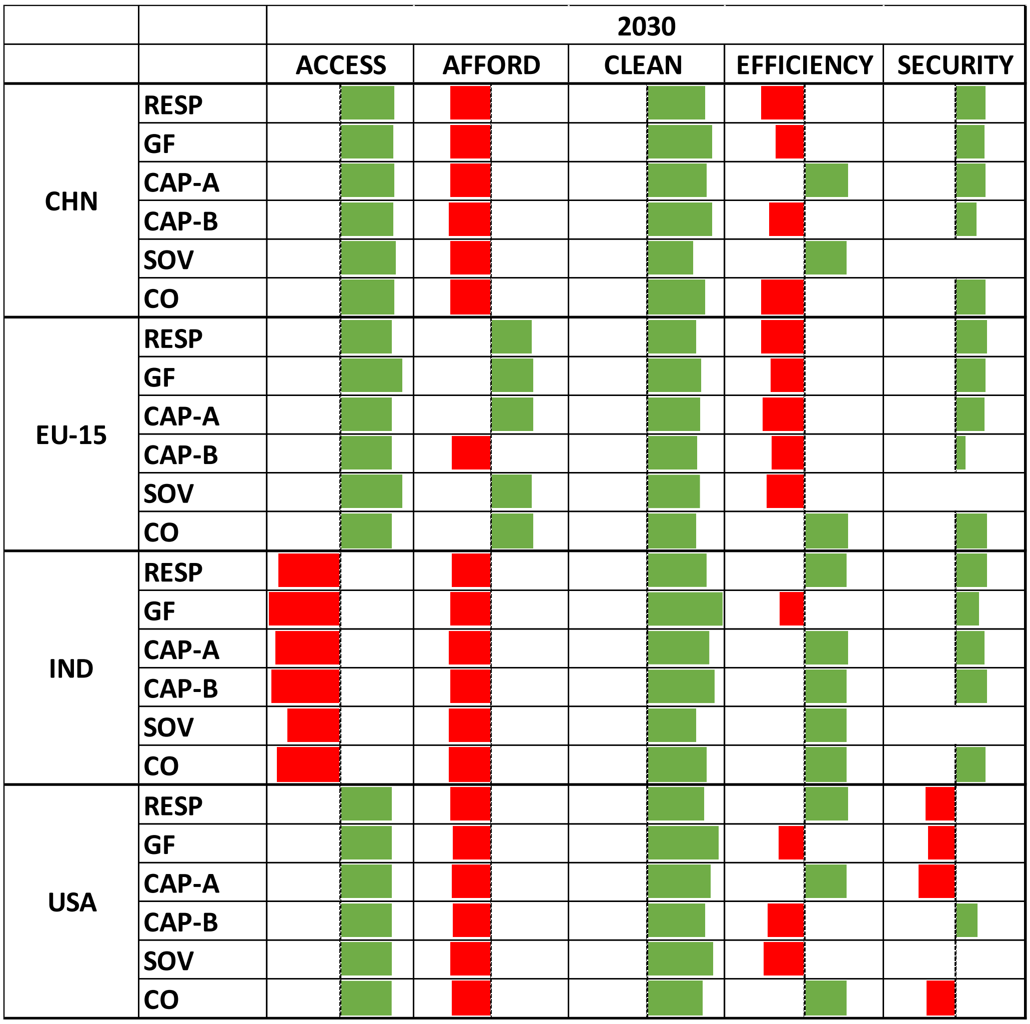


Fig. 6(c): *Magnitude of synergies (green bars) and trade-offs (red bars) for pathways across national energy goals in the near term (2030) varying by regional effort sharing principles employed*

For pathways based on demand side changes, we observe synergies across all dimensions, especially for the Global South (Fig. 6 b). The near-term co-benefits are strengthened in the long term as well.

The final set of pathways based on regional effort sharing also shows losses relative to BAU for developing regions, especially in pathways applying principles such as grandfathering (Fig. 6 c). While financial transfers based on historical responsibility alleviate some of these compromises, the increased consumption levels lead to household affordability trade-offs. The unfairness of the grandfathering principle is matched by the results for the Global North when stringent pathways involving financial transfers or expedited net zero commitments are imposed. Self-determined pathways like the NDCs do have relatively minor effects for India, but the increased mitigation ambition later in the century also increases the strength of observable trade-offs.

These general results and trends also hold for other major regions shown in the SI. The only deviations seem to be based on unique regional contexts which allow other mitigation options (Brazil), or a higher level of development, in which case the trade-offs tend to resemble those of the Global North than the South.

5.2 Distributional impacts by income tiers

The second set of results shown here (Fig 7 a-f) are for the changes in household energy burdens for the poorest decile (D1), the middle decile (D5) and the richest decile (D10) in India & USA. Our results for variation in transition pace (Fig. 6 a-b) agree with most results in current literature based on representative and cost optimal pathways, showing regressive impacts for the poorest households in both regions. The reduction in rate of mitigation efforts does reduce these effects, but only marginally. We also see that poorest households in India would face a noticeably higher change in energy burden compared to the US. Further, there is significant variation in the impacts across income tiers in India, with insignificant impacts for the richest decile. In contrast, the impacts, though still regressive in character, are relatively more balanced in the US. This is due to the higher income levels, as well as higher energy consumption in the US, leading to increased expenditure.

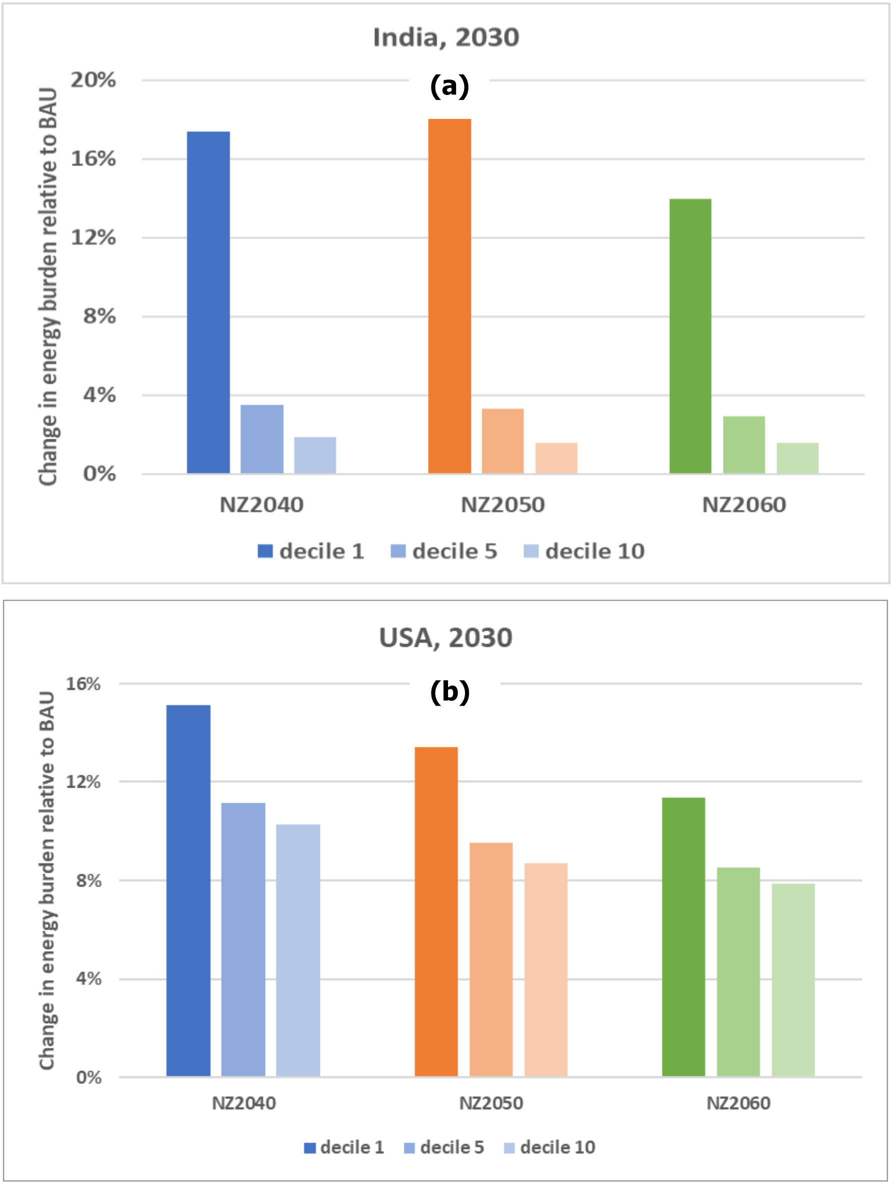


Fig. 7 (a-b): *Short term impacts of pathways varying by global net zero year targets on household energy burden changes for the poorest, middle & richest decile in (a) India and (b) USA*

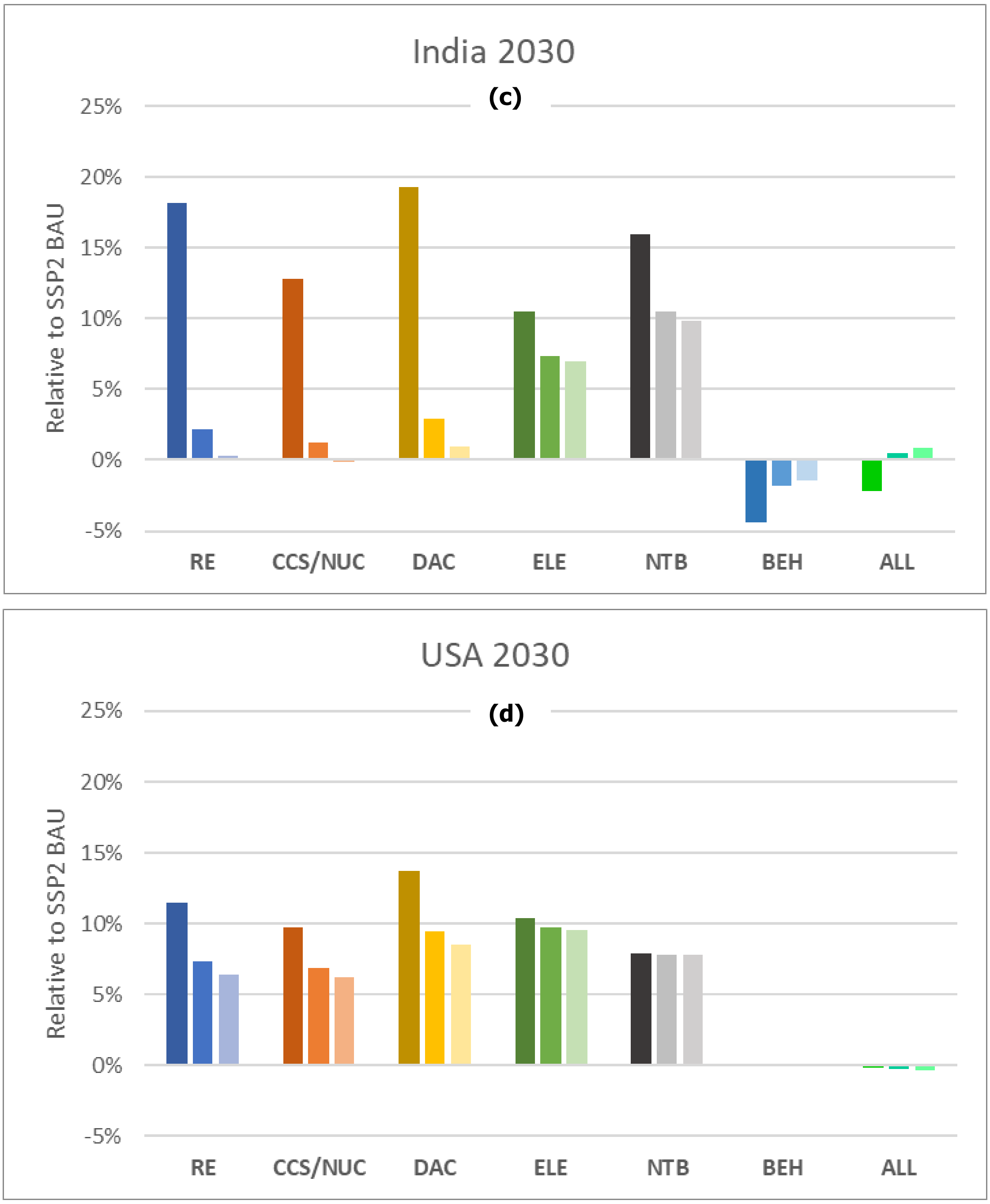
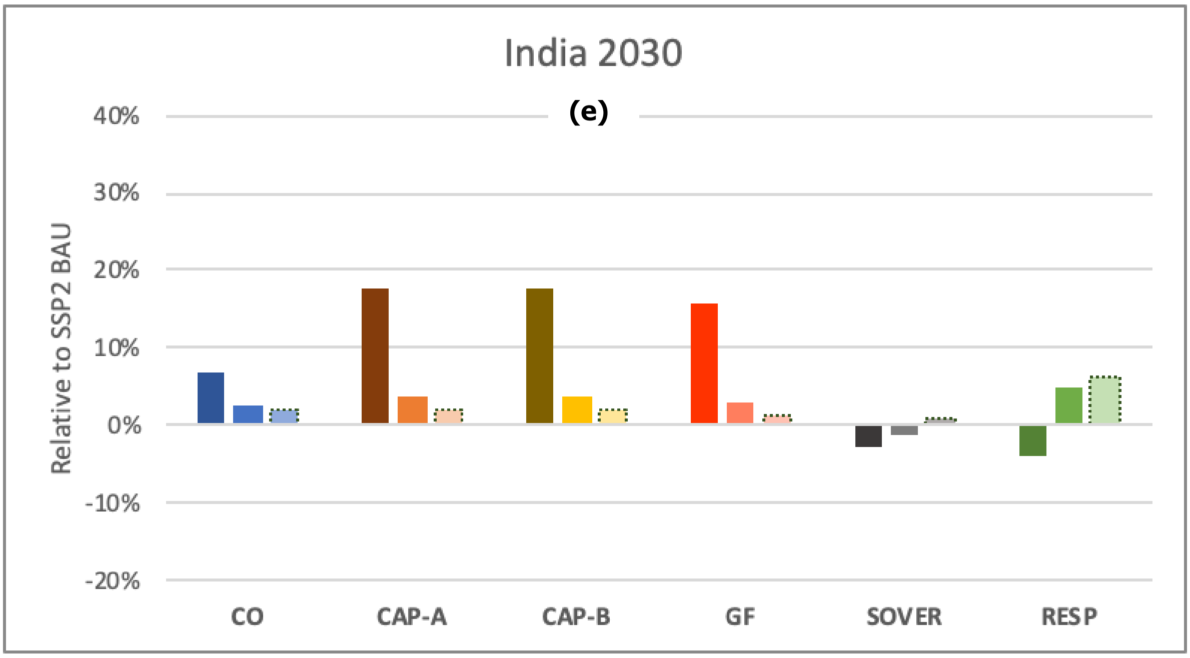


Fig. 7 (c-d): *Short term impacts of pathways varying by technology choices and demand side mitigation options on household energy burden changes for the poorest, middle & richest decile in (c) India and (d) USA*

Technology-based pathways also show similarly regressive impacts in both regions (Fig. 7c & d), but we notice increased household expenditure in the middle and top deciles in scenarios implementing electrification or eliminating traditional biomass fuel usage. The higher demand and higher fuel prices would be driving higher energy burdens for these households. However, these scenarios have a relatively balanced impact across deciles in the US since they do not affect underlying fuel choices in the developed world where access issues are insignificant.



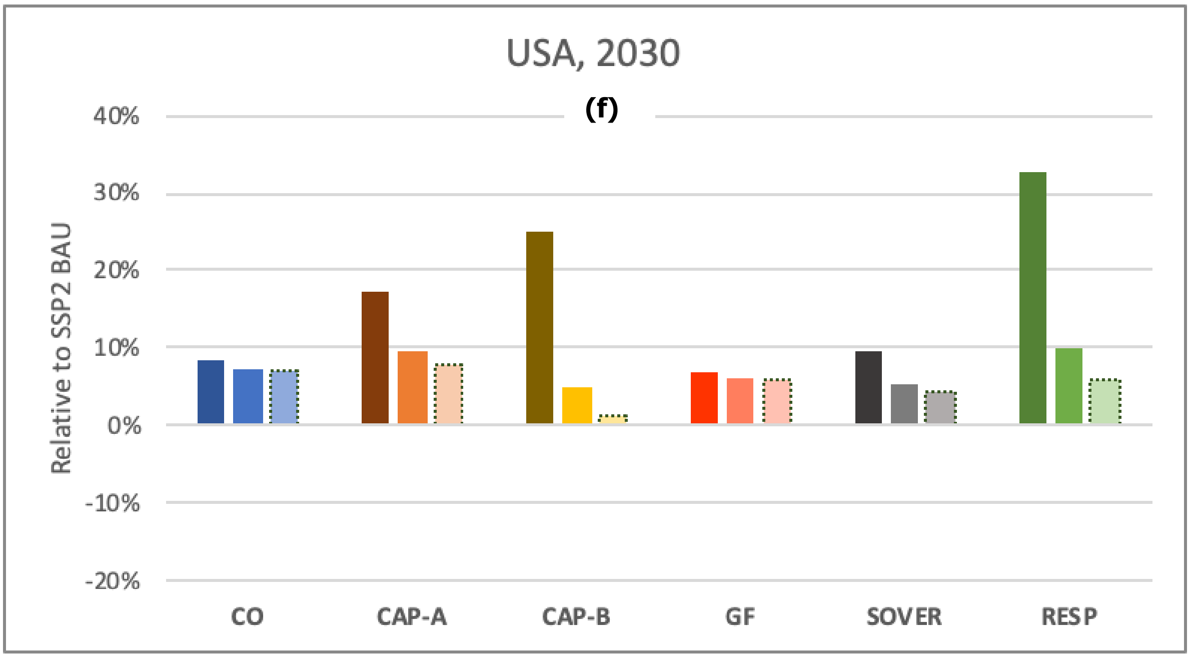


Fig. 7 (e-f)*: Short term impacts of pathways varying by implementation of global effort sharing principles on household energy burden changes for the poorest, middle & richest decile in (e) India and (f) USA*

For pathways involving differential effort sharing, the regressive impacts are most noticeable for India with regard to application of the grandfathering principle and those based on current capability. Similar levels of impacts are seen in the US for financial transfers against historical responsibility, which would predominantly hurt the poorest populations since the transfers are equally shared by the population. Pathways forcing an immediate net zero goal on the US based on its capability also have disproportionate impacts on the poorest. In contrast, with financial transfers from the developed world being apportioned equally in regions like India, there are almost progressive impacts for the poorest decile. This indicates the dynamic of global effort sharing having implications for local just transitions, and how regional context and principle matters.

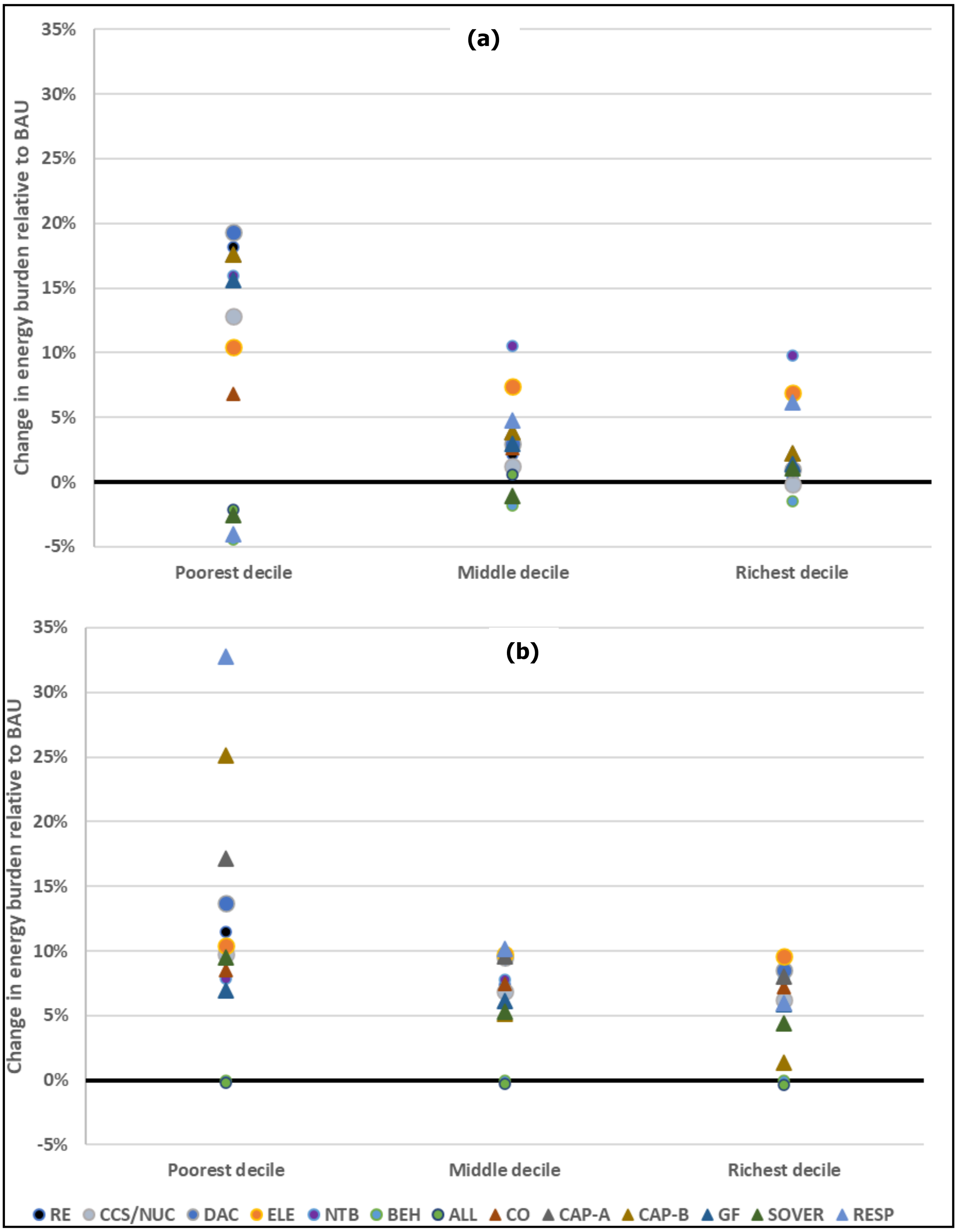


Fig. 8: *Changes to household energy burdens relative to the reference case in (a) India and (b) USA for different technology-based, demand side and global effort sharing pathways modelled in this study. The results shown here are for 2030. Pathways showing reduced energy burdens and progressive impacts lie below the X-axis. Extremely regressive effects are also evident in pathways which significantly increase burdens on the poorest income decile.*

The demand side mitigation pathways also show progressive impacts for the bottom deciles. The reduction in demand and increased space for mitigation by reduction in non-CO_2 emissions enables the poorest sections to increase consumption levels and be better off in both the short and long term. While both BEH & ALL pathways show progressive impacts across India & US, the effects are slightly muffled for the ALL scenario due to the additional technology factors enforced. We summarize the implications of all technology, effort sharing & demand side pathways in Fig. 8. Apart from the near-term results shown here, the long-term results are presented in the SI (Section 9.8). We find that only pathways employing demand side mitigation options enable progressive impacts for the poorest populations within a country. Similarly, at the global level, the pathways which accounted for historical responsibility for GHG emissions facilitated attainment of societal goals for the vulnerable and poorest.

6. Discussion

Based on the results showcased in the previous section, we argue that climate protection and energy access goals do not always have to result in trade-offs across regions. Although most technology pathways resulted in detrimental effects on access or affordability or both for different regions, we also found that pathways employing demand side control measures had greater synergies across multiple national energy priorities. This implies that pathways which focus exclusively on technology shifts on the supply side without support on the demand side or backing technology with corresponding efforts to support vulnerable populations making the transition had adverse and unfair outcomes. While international financial transfers accounting for historical responsibility do help limit some of these outcomes, they are insufficient to actually compensate for the mitigation trade-offs in exposed regions. The key takeaway and good news for climate & feasibility of attaining climate & energy access goals here is that pathway design incorporating elements of demand side mitigation can help meet both goals together.

The second set of results demonstrated within-region distribution of mitigation policy impacts by income strata. Once again, we found that mere focus on technology pathways unsupported by other mechanisms or redistribution failed to address underlying inequities within regions. In fact, some pathways exacerbated these inequalities. Scenarios which employed demand side mitigation options had evident progressive impacts. Another aspect to note here is the reduction in non-CO_2 emissions in pathways like BEH & ALL from diet shifts and HFC (Hydro-fluoro carbon) emission reductions. The enhanced action on non-CO_2 emissions creates development space for vulnerable regions and could enable them to limit regressive impacts.

Global effort sharing is shown to have different local effects by region. 'Grandfathering' as an allocation principle privileges historically high-emitting regions, when apportioning future emission entitlements, and it ignores equity and is merely presented here since many developed countries seek to implicitly argue for and follow it. We show that such a principle is extremely unfair for the most vulnerable populations. On the other hand, the regions chiefly responsible for historical emissions would face similarly regressive impacts when a mechanism of financial compensation to other regions is employed.

In summary, one of the main results of this work is that the mitigation pathway choice and design matters and that bespoke pathways can allow synergies and progressive impacts. These pathways should have a significant component of demand side mitigation efforts especially in the developed regions. This is in line with findings by other researchers that employing sufficiency conditions for affluent populations could address inequities resulting from mitigation policies (Rao & Min, 2018, Scherer et al. 2018, Millward-Hopkins 2022). Also, pursuit of low hanging fruit like non-CO_2 emission reductions should be strongly encouraged as a focus of future climate targets put forth by countries. Another principal finding is to demonstrate how different burden sharing principles change the distribution of impacts across & within regions. Some principles like grandfathering are extremely unfair and exacerbate deprivations, while financial transfers could also be regressive. This suggests that truly just transitions should use a judicious choice and tools like technology transfers which could address the historical responsibility of cumulative emissions. Lastly, we show the importance of incorporating heterogeneity and income distributions in energy-climate models and how the distributional impacts could look very different compared to the single representative consumer or household as currently assumed in IAMs.

We must also account for some of the caveats with our modelling and assumptions, and the exact numbers are to be taken with a large grain of salt and should not be considered empirical data. For example, the model does not represent extreme instances of poverty or wealth, and household decisions on choices between energy needs, food, healthcare, education etc. Another limitation to these conclusions is that they rest on limited changes to consumer preferences and income elasticities of demand in line with historical ranges. If these were to change drastically, as may happen in the face of profound climate change impacts or cultural shifts, the relationship could exhibit different traits. An example of such shift could be one away from globalization, or catastrophic large-scale conflicts.

Our results are, in part, dependent on the choice of the downscaling model. For instance, we found a different fuel choice distribution when accounting for additional heterogeneity factors such as the rural-urban divide, and more granular representation of cooking fuel choices (see SI, Sec. 9.3-9.5). However, the overall regressive trends in our results remain stable even under the use of a different downscaling approach, the only shift being the higher energy burden moving to the second or third decile since the lowest deciles move to much cheaper fuels (an avoided consumption due to varying demand price elasticity by income tiers and other socioeconomic factors). Another concern would be the choice of IAM and internal assumptions on technology and marginal abatement costs for different regions, which could affect results. While GCAM may assume a certain underlying distribution of such costs, a different IAM could divide the mitigation burden somewhat differently. Whilst we do not expect this to drastically change any of our results or key trends, some regions may see slightly different results. Further, the effort sharing pathways demonstrated by us do not account for some of the ethical notions relevant for emissions allocations, which may include the relative moral relevance of consumption versus production-based emissions, survival versus luxury emissions etc. These normative choices could also drive changes beyond the scope of this work.

Whilst this modelling effort, like others, is clearly not a fully accurate description of reality, the approach here has proved useful in answering our specific research questions on pathways which may be best suited to meet the dual goals of development & climate change mitigation. The main contribution lies in illuminating the directional relationships on between pathways, across & within regions and both the near- and long-term implications. The employment of an IAM framework also allowed a consistency in comparison and accounting for interlinkages. We should consider these results as relative impacts between pathways and hence most of the caveats listed above are either obviated or not debilitating for our main findings.

7. Conclusion

7.1 Summary & policy implications

These findings are relevant for both scholarship and policy. In terms of scholarship, we build on existing models and combine with household surveys to show distributional implications across spatial, temporal and income scales. We also buttress the importance of modeling heterogeneity for just transition research. In terms of policy, our findings outline some of the key features required in climate change mitigation efforts, especially around the consideration of emissions from wealthy regions and affluent income tiers within those regions.

Despite our relatively unpretentious modeling in an IAM framework, we demonstrate multiple novel results and our findings are particularly relevant for policy makers at both the global and national levels. We demonstrated that it is possible to achieve the dual goals of energy access & climate change mitigation, if we promote the early diffusion of appropriate technology and take sufficiency into account as a mitigation strategy for the affluent. Pathways employing demand side mitigation options were overwhelmingly successful at attaining multiple national energy goals and also supporting progressive impacts for the poorest and most vulnerable sections. Achieving just transitions would, therefore, require an enhanced focus on societal transformations and behavior changes and employing policies which support a shift in acceptance by the affluent.

In addition, our findings imply that targeted technology deployment with income support or subsidization programs for vulnerable populations is key for the transitions to achieve progressive outcomes. Contrary to popular expectations of technocratic solutions as silver bullets for societal problems, mere shifts in technology would not lead to progressive impacts unless these measures are complemented by domestic policies to offset underlying inequities. This also implies that enhanced efforts be made to identify different vulnerable populations and to tailor policies accordingly to address deleterious impacts.

Another important policy implication is that focusing on the full basket of GHG emissions and going beyond CO_2 based targets could create development space for the most vulnerable. Countries should, therefore, be explicitly encouraged to incorporate enhanced mitigation goals for non-CO_2 emissions related to diet and HFC reductions when putting forth updated mitigation pledges in future climate negotiations.

Our research also addresses a previously understudied relationship between global effort sharing and within-region distributional implications. Consideration of capability and historical responsibility are essential to achieve truly just transitions for the most vulnerable and the use of grandfathering narratives to protect the affluent only exacerbates inequities and deprivileges the vulnerable. While financial transfers for past emissions alone may not address the distributional consequences, complementing such transfers with technology sharing and capacity building for enhanced mitigation ambition in vulnerable countries is important for a fair climate regime. The principle of 'common but differentiated responsibilities' retains importance even under the net-zero emission target driven paradigm.

The probability of keeping global warming to tolerable levels by ratcheting ambition across the world could improve significantly if there is more robust consideration of fairness & equity in both the global burden of mitigation and the local implementation of policies.

7.2 Future work

There are technical aspects of this study which future research can build on. For instance, vulnerabilities go beyond income alone and involve intersections of multiple deprivations in different regional contexts. Our current work does not delve into specifics beyond income poverty and furthering this analysis with additional axes of deprivations would be an important analysis for just transition objectives. An effort towards this is made in our SI (Sec. 9.3-9.5). Whilst we demonstrate a difference with rural-urban populations, incorporating additional representations of heterogeneity and furthering the granularity and segmentation within IAMs remains key. We also lack systematic understanding of how consumption patterns contribute to wellbeing in different societies and contexts (Rao & Wilson 2022). While conventional residential energy, health or well-being surveys at the national level could be a valuable starting point, collection of new data and community engagement with disadvantaged sections which may be under-sampled in these surveys would also be an essential and possible next step.

Recent work has hypothesized that redistribution of carbon tax revenues can alleviate the tradeoffs of climate policies (Budolfson et al. 2021, Soergel et al 2021). Much of the literature examining redistribution approaches has focused on an equal per capita refund as the revenue recycling option (Cullenward et al. 2016, Fawcett et al. 2018, Jorgenson & Goettle 2013, Mathur & Morris 2014, Metcalf 2018, Rausch et al. 2011), whilst other options remain understudied. However, redistribution levels could be very different based on pathway design and underlying socioeconomics. Pathways which prioritize equity may require lower redistribution levels. As a next step, we shall explore the redistribution question using a compensating variation approach, leaving households at least as well as they currently are (the 'proportionate approach'). The alternate and higher redistribution goal would be to determine the compensation to attain decent living energy standards (the 'progressive approach', defined in Metcalf 2017). Multiple redistribution options, including changes to underlying income distributions through alternate tax mechanisms, would be subject of such future work.

A third dimension to cover in future work would be the implications of different household spending on essential goods like energy & food and the implications for income inequality by pathway. Lastly, alternate pathways representing different forms of regional mitigation effort sharing but employing technology transfers instead of financial compensation mechanisms would an interesting angle to pursue.

The goal of this research is not to propagate naïve or overtly optimistic narratives on demand side measures being a silver bullet for progressive consequences. Significant shifts in demand would not happen overnight and would need increased awareness of consequences of consumption patterns with systemic changes and support policies. However, we do believe that the evidence supporting the case for progressive impacts from behavioural and societal transformations, and global effort sharing is compelling enough in order to be taken seriously and studied in more detail in specific regional and societal contexts.

8. References

Bertram, C., Hilaire, J., Kriegler, E., Beck, T., Bresch, D. N., Clarke, L., ... & Yu, S. (2020). NGFS Climate Scenarios Database: Technical Documentation.

Blasiak, R., Spijkers, J., Tokunaga, K., Pittman, J., Yagi, N., & Österblom, H. (2017). Climate change and marine fisheries: Least developed countries top global index of vulnerability. *PLoS One*, *12*(6), e0179632.

Budolfson, M., Dennig, F., Errickson, F., Feindt, S., Ferranna, M., Fleurbaey, M., ... & Zuber, S. (2021). Climate action with revenue recycling has benefits for poverty, inequality and well-being. Nature Climate Change, 11(12), 1111-1116.

Build Back Better Act, 2021. HR 5376, 117th Congress (https://www.congress.gov/bill/117th-congress/house-bill/5376, last accessed May 6 2022)

Burke, J., Fankhauser, S., Kazaglis, A., Kessler, L., Khandelwal, N., O'Boyle, P., & Owen, A. (2020). Distributional impacts of a carbon tax in the UK: Report 2–Analysis by income decile. London: Grantham Research Institute on Climate Change and the Environment et al.

Calvin, K., Bond-Lamberty, B., Clarke, L., Edmonds, J., Eom, J., Hartin, C., ... & Wise, M. (2017). The SSP4: A world of deepening inequality. *Global Environmental Change*, *42*, 284-296.

Calvin, K., Patel, P., Clarke, L., Asrar, G., Bond-Lamberty, B., Cui, R. Y., ... & Wise, M. (2019). GCAM v5. 1: representing the linkages between energy, water, land, climate, and economic systems. *Geoscientific Model Development*, *12*(2), 677-698.

Calvin, K., Mignone, B. K., Kheshgi, H. S., Snyder, A. C., Patel, P., Wise, M., ... & Edmonds, J. (2020). Global market and economic welfare implications of changes in agricultural yields due to climate change. *Climate Change Economics*, *11*(01), 2050005.

Cameron, C., Pachauri, S., Rao, N. D., McCollum, D., Rogelj, J., & Riahi, K. (2016). Policy trade-offs between climate mitigation and clean cook-stove access in South Asia. Nature Energy, 1(1), 1-5.

Campagnolo, L., & Davide, M. (2019). Can the Paris deal boost SDGs achievement? An assessment of climate mitigation co-benefits or side-effects on poverty and inequality. World Development, 122, 96-109.

Carbon Brief, 2013. Climate rhetoric: What's an energy trilemma, Dec. 2013, accessed at: https://www.carbonbrief.org/climate-rhetoric-whats-an-energy-trilemma#:~:text=The%20idea%20of%20an%20'energy,social%20impact%20and%20environmental%20sensitivity, last accessed Sep 6, 2022

Carley, S., & Konisky, D. M. (2020). The justice and equity implications of the clean energy transition. Nature Energy, 5(8), 569-577.

Chaturvedi, V. (2021). A vision for a net-zero energy system for India. Energy and Climate Change, 2, 100056.

Cherp, A., Jewell, J., Vinichenko, V., Bauer, N., & De Cian, E. (2016). Global energy security under different climate policies, GDP growth rates and fossil resource availabilities. Climatic Change, 136(1), 83-94.

Clarke, L. E., Jiang, K., Akimoto, K., Babiker, M., Blanford, G. J., Fisher-Vanden, K., ... & Zwickel, T. (2015). Assessing Transformation Pathways. In: Climate Change 2014: Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (No. PNNL-SA-102686). Pacific Northwest National Lab.(PNNL), Richland, WA (United States).

Clarke, L., Eom, J., Marten, E. H., Horowitz, R., Kyle, P., Link, R., ... & Zhou, Y. (2018). Effects of long-term climate change on global building energy expenditures. *Energy Economics*, *72*, 667-677.

ClimateWorks, 2020. Monteith, S. & Menon, S. *Achieving Global Climate Goals by 2050: Actionable Opportunities for this Decade* ; https://www.climateworks.org/report/achieving-global-climate-goals-by-2050-actionable-opportunities-for-this-decade/

Creutzig, F., Roy, J., Lamb, W. F., Azevedo, I. M., Bruine de Bruin, W., Dalkmann, H., ... & Weber, E. U. (2018). Towards demand-side solutions for mitigating climate change. *Nature Climate Change*, *8*(4), 260-263.

Cronin, J. A., Fullerton, D., & Sexton, S. (2019). Vertical and horizontal redistributions from a carbon tax and rebate. *Journal of the Association of Environmental and Resource Economists*, *6*(S1), S169-S208.

Cui, R. Y., Waldhoff, S., Clarke, L., Hultman, N., Patwardhan, A., & Gilmore, E. A. (2022). Evaluating the regional risks to food availability and access from land-based climate policies in an integrated assessment model. *Environment Systems and Decisions*, 1-9.

Cullenward, D., Wilkerson, J. T., Wara, M., & Weyant, J. P. (2016). Dynamically estimating the distributional impacts of US climate policy with NEMS: A case study of the Climate Protection Act of 2013. *Energy Economics*, *55*, 303-318.

Dagnachew, A. G., Lucas, P. L., Hof, A. F., Gernaat, D. E., de Boer, H. S., & van Vuuren, D. P. (2018). The role of decentralized systems in providing universal electricity access in Sub-Saharan Africa–A model-based approach. Energy, 139, 184-195.

Daioglou, V., Van Ruijven, B. J., & Van Vuuren, D. P. (2012). Model projections for household energy use in developing countries. Energy, 37(1), 601-615.

Dennig, F., Budolfson, M. B., Fleurbaey, M., Siebert, A., & Socolow, R. H. (2015). Inequality, climate impacts on the future poor, and carbon prices. *Proceedings of the National Academy of Sciences*, *112*(52), 15827-15832.

Desai, S., Reeve V. and National Council of Applied Economic Research. India Human Development Survey-II (IHDS-II), 2011-12. Inter-university Consortium for Political and Social Research [distributor], 2018-08-08. https://doi.org/10.3886/ICPSR36151.v6

Drehobl, A., & Ross, L. (2016). Lifting the high energy burden in America's largest cities: How energy efficiency can improve low income and underserved communities.

Drehobl, A., Ross, L., & Ayala, R. (2020). How High Are Household Energy Burdens. *An Assessment of National and Metropolitan Energy Burdens across the US*.

Fawcett, A. A., McFarland, J. R., Morris, A. C., & Weyant, J. P. (2018). Introduction to the EMF 32 study on US carbon tax scenarios. *Climate Change Economics*, *9*(01), 1840001.

Fragkos, P., Fragkiadakis, K., Sovacool, B., Paroussos, L., Vrontisi, Z., & Charalampidis, I. (2021). Equity implications of climate policy: Assessing the social and distributional impacts of emission reduction targets in the European Union. Energy, 237, 121591.

Fricko, O., Parkinson, S. C., Johnson, N., Strubegger, M., van Vliet, M. T., & Riahi, K. (2016). Energy sector water use implications of a 2 C climate policy. Environmental Research Letters, 11(3), 034011.

Fuhrman, J., McJeon, H., Patel, P., Doney, S. C., Shobe, W. M., & Clarens, A. F. (2020). Food–energy–water implications of negative emissions technologies in a+ 1.5 C future. *Nature Climate Change*, *10*(10), 920-927.

Fujimori, S., Hasegawa, T., Krey, V., Riahi, K., Bertram, C., Bodirsky, B. L., ... & van Vuuren, D. (2019). A multi-model assessment of food security implications of climate change mitigation. Nature Sustainability, 2(5), 386-396.

Galvin, R., & Healy, N. (2020). The Green New Deal in the United States: What it is and how to pay for it. Energy Research & Social Science, 67, 101529.

Gambhir, A., George, M., McJeon, H., Arnell, N. W., Bernie, D., Mittal, S., ... & Monteith, S. (2022). Near-term transition and longer-term physical climate risks of greenhouse gas emissions pathways. *Nature Climate Change*, *12*(1), 88-96.

Gampfer, R. (2014). Do individuals care about fairness in burden sharing for climate change mitigation? Evidence from a lab experiment. Climatic change, 124(1), 65-77.

Gazzotti, P., Emmerling, J., Marangoni, G., Castelletti, A., Wijst, K. I. V. D., Hof, A., & Tavoni, M. (2021). Persistent inequality in economically optimal climate policies. *Nature communications*, *12*(1), 1-10.

George, M., Yu, S., Clarke, L., & Edmonds, J. (2022). *Global emission trade market design and local outcomes on the water-energy-land nexus* (No. EGU22-6964). Copernicus Meetings.

George, M., McJeon H., Monteith S., Disentangling the Food-Energy-Water Implications of Lifestyle Changes, Technology Substitution & Energy Efficiency in a 1.5C Green Growth Scenario, 14th Integrated Assessment Modeling Consortium Annual Meeting, Dec. 2021

George, M., Yu, S., Clarke, L., & Edmonds, J. (2021). Spatial & Multisectoral Impacts of Paris Agreement Article 6 under Different Equity-driven Emissions Mitigation Pathways, AGU 2021

Gilmore, E. A., & Buhaug, H. (2021). Climate mitigation policies and the potential pathways to conflict: Outlining a research agenda. Wiley Interdisciplinary Reviews: Climate Change, 12(5), e722.

Green New Deal, 2019. H.Res.109 - Recognizing the duty of the Federal Government to create a Green New Deal. 116th Congress (https://www.congress.gov/bill/116th-congress/house-resolution/109/text, last accessed May 6, 2022)

Green, F., & Gambhir, A. (2020). Transitional assistance policies for just, equitable and smooth low-carbon transitions: who, what and how?. Climate Policy, 20(8), 902-921.

Grubler, A., Wilson, C., Bento, N., Boza-Kiss, B., Krey, V., McCollum, D. L., ... & Valin, H. (2018). A low energy demand scenario for meeting the 1.5 C target and sustainable development goals without negative emission technologies. Nature energy, 3(6), 515-527.

Guivarch, C., Le Gallic, T., Bauer, N., Fragkos, P., Huppmann, D., Jaxa-Rozen, M., ... & Wagner, F. (2022). Using large ensembles of climate change mitigation scenarios for robust insights. *Nature Climate Change*, *12*(5), 428-435.

Hallegatte, S., & Rozenberg, J. (2017). Climate change through a poverty lens. Nature Climate Change, 7(4), 250-256.

Hartin, C. A., Patel, P., Schwarber, A., Link, R. P., & Bond-Lamberty, B. P. (2015). A simple object-oriented and open-source model for scientific and policy analyses of the global climate system–Hector v1. 0. *Geoscientific Model Development*, *8*(4), 939-955.

Hejazi, M., Edmonds, J., Clarke, L., Kyle, P., Davies, E., Chaturvedi, V., ... & Kim, S. (2014). Long-term global water projections using six socioeconomic scenarios in an integrated assessment modeling framework. Technological Forecasting and Social Change, 81, 205-226.

Höhne, N., Gidden, M.J., den Elzen, M. et al. (2021), Wave of net zero emission targets opens window to meeting the Paris Agreement. Nat. Clim. Chang. 11, 820–822

Hubacek, K., Baiocchi, G., Feng, K., & Patwardhan, A. (2017). Poverty eradication in a carbon constrained world. Nature communications, 8(1), 1-9.

IPCC, 2022a: Summary for Policymakers. In: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA.

IPCC 2022b: Grubb, M., C. Okereke, J. Arima, V. Bosetti, Y. Chen, J. Edmonds, S. Gupta, A. Köberle, S. Kverndokk, A. Malik, L. Sulistiawati, 2022: Introduction and Framing. In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change

IPCC, 2018: Global Warming of 1.5°C an IPCC special report on the impacts of global warming of 1.5 °C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change. [Masson-Delmotte, V. et al., (eds.)].

Iyer, G., Calvin, K., Clarke, L., Edmonds, J., Hultman, N., Hartin, C., ... & Pizer, W. (2018). Implications of sustainable development considerations for comparability across nationally determined contributions. Nature Climate Change, 8(2), 124-129.

Jakob, M., & Steckel, J. C. (2014). How climate change mitigation could harm development in poor countries. Wiley Interdisciplinary Reviews: Climate Change, 5(2), 161-168.

Jiang, Z., & Shao, S. (2014). Distributional effects of a carbon tax on Chinese households: A case of Shanghai. Energy Policy, 73, 269-277.

Jewell, J., Cherp, A., & Riahi, K. (2014). Energy security under de-carbonization scenarios: An assessment framework and evaluation under different technology and policy choices. Energy Policy, 65, 743-760.

JGCRI 2022a. http://jgcri.github.io/gcam-doc/v5.4/toc.html (last accessed Sep 25, 2022)

JGCRI 2022b. https://github.com/JGCRI/hector (accessed Sep 25, 2022)

Jorgenson, D. W., Goettle, R. J., Ho, M. S., & Wilcoxen, P. J. (2013). *Double dividend: environmental taxes and fiscal reform in the United States*. MIT Press.

Klinsky, S., & Winkler, H. (2014). Equity, sustainable development and climate policy. Climate Policy, 14(1), 1-7.

Krey, V., O'Neill, B. C., van Ruijven, B., Chaturvedi, V., Daioglou, V., Eom, J., ... & Ren, X. (2012). Urban and rural energy use and carbon dioxide emissions in Asia. Energy Economics, 34, S272-S283.

Lamb, W. F., Antal, M., Bohnenberger, K., Brand-Correa, L. I., Müller-Hansen, F., Jakob, M., ... & Sovacool, B. K. (2020). What are the social outcomes of climate policies? A systematic map and review of the ex-post literature. Environmental Research Letters, 15(11), 113006.

Markard, J. (2018). The next phase of the energy transition and its implications for research and policy. Nature Energy, 3(8), 628-633.

Markkanen, S., & Anger-Kraavi, A. (2019). Social impacts of climate change mitigation policies and their implications for inequality. Climate Policy, 19(7), 827-844.

Marmot, M., & Bell, R. (2018). The sustainable development goals and health equity. Epidemiology, 29(1), 5-7.

Mathur, A., & Morris, A. C. (2014). Distributional effects of a carbon tax in broader US fiscal reform. *Energy Policy*, *66*, 326-334.

McCollum, D., Gomez Echeverri, L., Riahi, K., & Parkinson, S. (2017). Sdg7: Ensure access to affordable, reliable, sustainable and modern energy for all.

McCollum, D. L., Zhou, W., Bertram, C., De Boer, H. S., Bosetti, V., Busch, S., ... & Riahi, K. (2018). Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. Nature Energy, 3(7), 589-599.

Meinshausen, M., Lewis, J., McGlade, C., Gütschow, J., Nicholls, Z., Burdon, R., ... & Hackmann, B. (2022). Realization of Paris Agreement pledges may limit warming just below 2° C. Nature, 604(7905), 304-309.

Metcalf, G. E. (2017). Implementing a carbon tax. Washington, DC: Resources for the Future.

Metcalf, G. E. (2018). *Paying for pollution: why a carbon tax is good for America*. Oxford University Press.

Millward-Hopkins, J., Steinberger, J. K., Rao, N. D., & Oswald, Y. (2020). Providing decent living with minimum energy: A global scenario. *Global Environmental Change*, *65*, 102168.

Millward-Hopkins, J. (2022). Inequality can double the energy required to secure universal decent living. *Nature communications*, *13*(1), 1-9.

NAS (2021). National Academies of Sciences, Engineering, and Medicine. Global change research needs and opportunities for 2022-2031.

Nerini, F., Tomei, J., To, L. S., Bisaga, I., Parikh, P., Black, M., ... & Mulugetta, Y. (2018). Mapping synergies and trade-offs between energy and the Sustainable Development Goals. *Nature Energy*, *3*(1), 10-15.

Nordhaus, W. D. (2007). A review of the Stern review on the economics of climate change. *Journal of economic literature*, *45*(3), 686-702.

Oswald, Y., Steinberger, J. K., Ivanova, D., & Millward-Hopkins, J. (2021). Global redistribution of income and household energy footprints: a computational thought experiment. *Global Sustainability*, *4*.

Ou, Y., Iyer, G., Clarke, L., Edmonds, J., Fawcett, A. A., Hultman, N., ... & McJeon, H. (2021). Can updated climate pledges limit warming well below 2° C?. Science, 374(6568), 693-695.

Pachauri, S., Poblete-Cazenave, M., Aktas, A., & Gidden, M. J. (2021). Access to clean cooking services in energy and emission scenarios after COVID-19. Nature Energy, 6(11), 1067-1076.

Pachauri, S., van Ruijven, B. J., Nagai, Y., Riahi, K., van Vuuren, D. P., Brew-Hammond, A., & Nakicenovic, N. (2013). Pathways to achieve universal household access to modern energy by 2030. *Environmental Research Letters*, *8*(2), 024015.

Pahle, M., Tietjen, O., Osorio, S., Egli, F., Steffen, B., Schmidt, T. S., & Edenhofer, O. (2022). Safeguarding the energy transition against political backlash to carbon markets. Nature Energy, 7(3), 290-296.

Pai, S., Emmerling, J., Drouet, L., Zerriffi, H., & Jewell, J. (2021). Meeting well-below 2 C target would increase energy sector jobs globally. One Earth, 4(7), 1026-1036.

Parkinson, S., Krey, V., Huppmann, D., Kahil, T., McCollum, D., Fricko, O., ... & Riahi, K. (2019). Balancing clean water-climate change mitigation trade-offs. Environmental Research Letters, 14(1), 014009.

Peng, W., Iyer, G., Bosetti, V., Chaturvedi, V., Edmonds, J., Fawcett, A. A., ... & Weyant, J. (2021). Climate policy models need to get real about people—here's how, Nature, 594, 174-176

Poblete-Cazenave, M., Pachauri, S., Byers, E., Mastrucci, A., & van Ruijven, B. (2021a). Global scenarios of household access to modern energy services under climate mitigation policy. Nature Energy, 6(8), 824-833.

Poblete-Cazenave, M., & Pachauri, S. (2021b). A model of energy poverty and access: Estimating household electricity demand and appliance ownership. *Energy Economics*, *98*, 105266.

Poblete-Cazenave, M., & Pachauri, S. (2018). A structural model of cooking fuel choices in developing countries. *Energy Economics*, *75*, 449-463.
Rao, N. D., van Ruijven, B. J., Riahi, K., & Bosetti, V. (2017). Improving poverty and inequality modelling in climate research. Nature Climate Change, 7(12), 857-862.

Rao, N. D. (2022). Towards a "fair-efforts" metric for climate pledges. *PloS Climate*, *1*(9), e0000069.

Rao, N. D., & Wilson, C. (2022). Advancing energy and well-being research. *Nature Sustainability*, *5*(2), 98-103.

Rao, N. D., Sauer, P., Gidden, M., & Riahi, K. (2019). Income inequality projections for the shared socioeconomic pathways (SSPs). Futures, 105, 27-39.

Rao, N. D., & Min, J. (2018). Less global inequality can improve climate outcomes. Wiley Interdisciplinary Reviews: Climate Change, 9(2), e513.

Rausch, S., Metcalf, G. E., & Reilly, J. M. (2011). Distributional impacts of carbon pricing: A general equilibrium approach with micro-data for households. *Energy economics*, *33*, S20-S33.

Robiou du Pont, Y., Jeffery, M. L., Gütschow, J., Rogelj, J., Christoff, P., & Meinshausen, M. (2017). Equitable mitigation to achieve the Paris Agreement goals. *Nature Climate Change*, *7*(1), 38-43.

Rogelj, J. et al. (2021). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631–639

Rogelj, J. et al. (2021). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. Nature 534, 631–639

Roy, J., Tscharket, P., Waisman, H., Abdul Halim, S., Antwi-Agyei, P., Dasgupta, P., ... & Suarez Rodriguez, A. G. (2018). Sustainable development, poverty eradication and reducing inequalities.

Sampedro, J., Smith, S. J., Arto, I., Gonzalez-Eguino, M., Markandya, A., Mulvaney, K. M., ... & Van Dingenen, R. (2020). Health co-benefits and mitigation costs as per the Paris Agreement under different technological pathways for energy supply. Environment International, 136, 105513.

Sampedro, J., Iyer, G., Msangi, S., Waldhoff, S., Hejazi, M., & Edmonds, J. A. (2022). Implications of different income distributions for future residential energy demand in the US. *Environmental Research Letters*, *17*(1), 014031.

Scherer, L., Behrens, P., de Koning, A., Heijungs, R., Sprecher, B., & Tukker, A. (2018). Trade-offs between social and environmental Sustainable Development Goals. *Environmental science & policy*, *90*, 65-72.

Sharma, A., & Banerjee, R. (2021). Framework to analyze the spatial distribution of the labor impacts of clean energy transitions. Energy Policy, 150, 112158.

Soergel, B., Kriegler, E., Bodirsky, B. L., Bauer, N., Leimbach, M., & Popp, A. (2021). Combining ambitious climate policies with efforts to eradicate poverty. Nature communications, 12(1), 1-12.

Sovacool, B. K., Linnér, B. O., & Goodsite, M. E. (2015). The political economy of climate adaptation. Nature Climate Change, 5(7), 616-618.

Spijkers, O. (2018). Intergenerational equity and the sustainable development goals. Sustainability, 10(11), 3836.

Stern, N. (2008). The economics of climate change. *American Economic Review*, *98*(2), 1-37.

Streimikiene, D., Lekavičius, V., Baležentis, T., Kyriakopoulos, G. L., & Abrhám, J. (2020). Climate change mitigation policies targeting households and addressing energy poverty in European Union. Energies, 13(13), 3389.

Taconet, N., Méjean, A., & Guivarch, C. (2020). Influence of climate change impacts and mitigation costs on inequality between countries. Climatic Change, 160(1), 15-34.

Tait, L., & Winkler, H. (2012). Estimating greenhouse gas emissions associated with achieving universal access to electricity for all households in South Africa. Journal of Energy in Southern Africa, 23(4), 8-17.

Thaler, P., & Hofmann, B. (2022). The impossible energy trinity: Energy security, sustainability, and sovereignty in cross-border electricity systems. Political Geography, 94, 102579.

Umit, R., Poortinga, W., Jokinen, P., & Pohjolainen, P. (2019). The role of income in energy efficiency and curtailment behaviours: Findings from 22 European countries. Energy Research & Social Science, 53, 206-214.

UN (2019). Sustainable development goals. The energy progress report. Tracking SDG, 7.: Main Report (English). Washington, D.C.: World Bank Group. http://documents.worldbank.org/curated/en/517781558037625254/Main-Report

UNEP (2021). Emissions Gap Report 2021: The Heat is On – A World of Climate Promises Not Yet Delivered https://www.unep.org/resources/emissions-gap-report-2021 (United Nations Environment Programme, 2021).

Ürge-Vorsatz, D., Herrero, S. T., Dubash, N. K., & Lecocq, F. (2014). Measuring the co-benefits of climate change mitigation. Annual Review of Environment and Resources, 39, 549-582.

Van den Berg, N. J., van Soest, H. L., Hof, A. F., den Elzen, M. G., van Vuuren, D. P., Chen, W., ... & Blok, K. (2020). Implications of various effort-sharing approaches for national carbon budgets and emission pathways. *Climatic Change*, *162*(4), 1805-1822.

van Ruijven, B. J., Van Vuuren, D. P., De Vries, B. J., Isaac, M., Van Der Sluijs, J. P., Lucas, P. L., & Balachandra, P. (2011). Model projections for household energy use in India. Energy policy, 39(12), 7747-7761.

Van Ruijven, B. J., O'Neill, B. C., & Chateau, J. (2015). Methods for including income distribution in global CGE models for long-term climate change research. Energy Economics, 51, 530-543.

Van Soest, H. L., Van Vuuren, D. P., Hilaire, J., Minx, J. C., Harmsen, M. J., Krey, V., ... & Luderer, G. (2019). Analysing interactions among sustainable development goals with integrated assessment models. *Global Transitions*, *1*, 210-225.

van Vuuren, D. P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D., ... & Soergel, B. (2022). Defining a sustainable development target space for 2030 and 2050. *One Earth*.

van Vuuren, D. P., Zimm, C., Busch, S., Kriegler, E., Leininger, J., Messner, D., ... & Soergel, B. (2022). Defining a sustainable development target space for 2030 and 2050. One Earth.

von Stechow, C., Minx, J. C., Riahi, K., Jewell, J., McCollum, D. L., et al. (2016). 2° C and SDGs: united they stand, divided they fall?. Environmental Research Letters, 11(3), 034022.

Von Stechow, C., McCollum, D., Riahi, K., Minx, J. C., Kriegler, E., Van Vuuren, D. P., ... & Edenhofer, O. (2015). Integrating global climate change mitigation goals with other sustainability objectives: a synthesis. *Annual Review of Environment and Resources*, *40*, 363-394.

Wang, R., Moreno-Cruz, J., & Caldeira, K. (2017). Will the use of a carbon tax for revenue generation produce an incentive to continue carbon emissions?. Environmental Research Letters, 12(6), 064001.

White House 2022, The Build Back Better Framework, accessed at: https://www.whitehouse.gov/build-back-better/ (last accessed May 6, 2022)

Wilkinson, R. G., & Pickett, K. E. (2009). Income inequality and social dysfunction. Annual review of sociology, 35, 493-511.

Wise, M., Calvin, K., Thomson, A., Clarke, L., Bond-Lamberty, B., Sands, R., ... & Edmonds, J. (2009). Implications of limiting CO2 concentrations for land use and energy. *Science*, *324*(5931), 1183-1186.

Yergin, D. (2021), Why the Energy Transition Will Be So Complicated, The Atlantic, Nov. 2021, accessed at: https://www.theatlantic.com/international/archive/2021/11/energy-shock-transition/620813/ (last accessed on Sep 29, 2022)

Yu, S., Edmonds, J., Forrister, D., Munnings, C., Hoekstra, J., Steponaciviute, I., Lochner, E., (2021) The Potential Role of Article 6 Compatible Carbon Markets in Reaching Net-Zero, Working Paper, International Emissions Trading Alliance, Oct. 6 2021, accessed at: https://www.ieta.org/resources/Resources/Net-Zero/Final_Net-zero_A6_working_paper.pdf (last on Sep. 29, 2022)

Zachmann, G., Fredriksson, G., & Claeys, G. (2018). The distributional effects of climate policies. Bruegel. Blueprint Series, 28.

Zimm, C., Sperling, F., & Busch, S. (2018). Identifying sustainability and knowledge gaps in socio-economic pathways vis-à-vis the Sustainable Development Goals. Economies, 6(2), 20.

WRI 2022. ClimateWatch Historical Emissions Database, accessed at: https://www.wri.org/initiatives/climate-watch and https://www.climatewatchdata.org/ghg-emissions?source=PIK (Aug. 21, 2022)

9. Supplementary Information

9.1 Extended literature survey

The unequal distribution of the costs and benefits of mitigation is important for the stability of institutions and the credibility of energy and climate governance (Carley & Konisky, 2020) and protecting the energy transition from political backlash (Pahle et al. 2022). Inequalities in the distribution of emissions and in the impacts of mitigation policies within countries affect social cohesion and the acceptability of mitigation and other environmental policies. It has implications for conflict risks (Gilmore and Buhaug 2020), and broader impacts on democratic stability.

The IPCC has repeatedly emphasized that low-income communities globally are the most likely to face the disproportionate burden of climate change, as well as the efforts to mitigate its effects. Research has repeatedly shown that poor people may be heavily affected by climate change even when impacts on the rest of the population remain limited (Hallegatte & Rozenberg 2017). On the mitigation dimension, in the climate economics literature, the effects are generally shown to be regressive for low-income regions and progressive for regions with a high GDP/capita, in the absence of any form of revenue recycling (Budolfson et al. 2021, Denning et al. 2015, Cronin et al. 2019). To further explore this relationship, we conducted a review of the literature around societal implications of mitigation policy, predominantly accounted under the UN sustainable development goals (SDGs).

As mentioned before, current literature has often focused on how synergies between climate action and other SDGs can be fully exploited through rapid and coordinated action and how co-benefits alone could drive enhanced mitigation ambition in recalcitrant regions. Many previous studies have explored the synergies and trade-offs across societal objectives in the context of integrated assessment models (IAMs) (Clarke et al. 2015, von Stechow et al. 2016, Zimm et al. 2018) or multi region input-output analysis tools (Scherer et al. 2018). IAMs have often proven particularly useful in understanding such synergies and trade-offs and the consequent implications for policy because most state-of-the-art IAMs employ long-term, multi-region frameworks that couple models of both human and earth system processes. The literature regularly highlights equity and justice issues as critical components in local politics and international diplomacy regarding all Sustainable Development Goals (SDGs), such as goals for no poverty, zero hunger, gender equality, affordable clean energy, reducing inequality, but also for climate action (Goal 13) (Marmot and Bell 2018; Balsiak et al. 2017, Spijkers 2018). These narratives have often been framed around cobenefits and tradeoffs of mitigation action (Nerini et al. 2018, Urge-Vorsatz et al. 2014, von Stechow et al. 2015), or unintended consequences. However, a transformation towards sustainability requires tackling multiple crises simultaneously.

A subset of such studies assesses single mitigation pathways to an objective goal of 2 or 1.5 deg. C, or the implications of different NDCs. Within this, they analyze only a single sustainability dimension, but different regional and sectoral impacts such as energy access and poverty (Cameron et al. 2016, Dagnachew et al. 2018, McCollum et al. 2018), economic growth, poverty alleviation and income inequality goals (Jakob & Steckel 2014, Hubacek et al. 2017, Sampedro et al. 2022, Taconet et al. 2020, Gazzotti et al. 2021), food or nutrition security (Cui 2022, Fujimori et al. 2018), air pollution and health impacts (Sampedro et al. 2020, Cameron et al. 2016), water use (Fricko et al. 2016, Hejazi et al. 2014, Parkinson et al. 2019). Other single objective works have recently widened to cover the just transition framing as well and deal with employment growth (Sharma & Banerjee 2021, Pai et al. 2021) and have widened the methodology to use input-output models in combination with IAM outputs.

Another category of works considers mitigation pathway effects on multiple SDG dimensions – a subset of metrics and how Paris commitments affect them (Iyer et al. 2018, Campagnolo et al. 2019) or a combination of dimensions defined under the "food-energy-water" nexus. Examples of the latter include Fuhrman et al. (2020) which explored different direct air capture and technology pathways, and Calvin et al. (2020) exploring land use, food price and energy implications of different pathways.

A third category of works involve examining the costs or needs to attain some or all of the SDGs. These have often taken the form of seeking to develop a 'sustainable development pathway' through reduction in energy use (Grubler et al. 2018, Soergel et al. 2021), examining the costs to attain SDGs (McCollum et al. 2018),

Non-IAM studies have focused on impacts of single policies and have often delved into distributional impacts by social classes or regions, such as a climate tax and effects by income deciles in the UK (Burke et al. 2020), in Shanghai (Jiang & Shao 2014), or achieving energy access in South Africa (Tait & Winkler 2012).

There have also been overarching review studies of societal impacts of climate policy, such as Lamb et al. (2020) and Marrakanen & Anger-Kraavi (2019) which call for careful planning and multi-stakeholder engagement. The general conclusion one can draw from this body of work is that though synergies and tradeoffs exist between societal and climate goals, these can be addressed by a comprehensive approach. Markard (2018) reviews the pace of energy transitions and shows implications for policy making and future research, concluding that transitions are context dependent though underlying aspects may be the same.

9.2 Scenario modeling & assumptions

The reference pathway is the standard GCAM implementation of the SSP-2 without any mitigation policies, also referred to here as the "BAU" scenario or "no new policy" scenario. It does include the effects of COvid-19 on near term GDP trends and follows the assumptions in Ou & Iyer et al. (2021) to incorporate these impacts.

For the pathways varying by pace of transition, the global net CO_2 emissions (including fossil fuels, industry & land use change) constraint is exogenously specified and follows a linear reduction to zero emissions in 2040/2050/2060 as the case may be, and then at a progressively reduced rate of reduction so as to match 1.5°C mean temperature rise target in 2100.

The specific assumptions in the technology and effort sharing pathways are listed in table SI 9.2(a). The RE, CCS/NUC, DAC, ELE, NTB, BEH and ALL pathways all follow least cost pathways to 1.5°C end of century climate goal, while including these assumptions in addition to the standard SSP-2 scenario.

Table SI 9.2(a*):* *Assumptions over SSP-2 baseline in mitigation scenarios modeled in this report*

Pathway name	Key assumptions	Remarks on implementation, if any
RE	- Wind power capital costs fall at a higher rate initially, starting at 7% every 5 years to 0.1% fall by 2100 - Solar power costs fall significantly, starting at 14% in 2020-25, and then gradually by 2100. Overall, capital costs of solar fall by 50% by 2100. Capital cost of Photovoltaic storage falls by 40% by 2100 - Capital costs for geothermal power reduce by 25% till 2100 - Renewables are equally preferred as other options, starting 2020 i.e. the choice between generation options is purely based on costs	Assumptions in line with the high RE levels in SSP-1 implementation in GCAM. The last assumption was added to account for grid parity for RE and increased acceptance of the technology.
CCS/ NUC	- CCS costs are 1/5 or 0.2X of SSP2 assumptions - Advanced nuclear (Gen III) is available and capital costs decline by approx. 2% every 5 years	Assumptions in line with high CCS and high nuclear implementation in GCAM for SSP-5
DAC	- DAC is limited to a level of 5 GtCO2 - DAC has lower preference over other negative emission technology options, and gradually rises to equal preference by 2050	Similar to SSP-1 implementation of DAC in GCAM
ELE	- Doubled preference (share-weights) for electricity as a fuel for buildings & industry sectors, increasing along a linear trend from 2020. - Doubled preference for electric vehicles across the entire transport sector (rail, bus, cars, trucks, 2 wheelers) by 2050, increasing linearly from	

	current values (2020) in GCAM. The electric vehicle preference doubles every 25 years thereafter.	
NTB	- Zero share-weights for traditional biomass as a fuel for buildings sector across all regions starting 2030, and linear reduction from the 2020 preference levels.	
CAP-A	Implements a staged net zero target enhancement for developed regions. Regions currently with twice the GDP/cap. (PPP basis) compared to Brazil's projected level in 2050 advance their net zero emission target years by 10 years. Regions with 1.5 to 2 times Brazil's GDP/cap. enhance this goal by 5 years and those with GDP/cap. Between 1-1.5 times of Brazil's would match the net zero goal as pledged by Brazil (2050). Regions with GDP/cap levels below Brazil's, attain their net zero emissions in the year in which they match or exceed Brazil's 2050 income levels. The net CO2 emission constraints are exogenously specified for each region as linear reduction from 2020 to the net zero year in each case.	A version of this pathway and the broad principle has been demonstrated in George et al. (2022) and Yu & Edmonds (2020)
CAP-B	A drastic variant of the same principle in CAP-A pathway. Regions exceeding Brazil's GDP/cap. (PPP) in 2050 today would move to net zero in the immediate net time step (2025 for US, EU-15 etc.) and so on. Regions with lower GDP/cap. Than Brazil would achieve net zero only in the year they match Brazil's 2050 level	
SOV	Countries continue to reduce their emissions beyond 2030 in line with their commitments till 2030 as in the NDCs. For regions with net zero targets, we assume the net zero attainment trendline as specified in the NDC or assume a linear reduction where unspecified. Since NDC pathway falls short of the 1.5C goal, we continue the rate of emission reductions for all regions at half the specified rate for 10 years post-net zero and a further reduction to $1/4^{th}$ in the subsequent 10 years and so on, representing a gradual and exponential tapering of mitigation ambition in the negative emission regions.	Modified version of the NDC Increased Ambition scenario in Ou & Iyer et al. 2021.

GF	A variant of cost optimal pathway, but while constraining all regions to the same proportion of emission rights (till the global net zero) and responsibilities (for the negative emissions required thereafter). The proportion is based on the 2015 emission shares. The reference year was chosen assuming the Paris agreement as a baseline.	
RESP	Also a variant of the cost optimal pathway, but with financial transfers in proportion to the per capita carbon budget share exceeded by each region. The financial transfers are computed as the (excess emissions over budget in a 5 year time period * carbon price in that period), and these feed into a global fund which is then redistributed to regions which have not exceeded their carbon budgets at that point. The financial transfers represent an addition or subtraction to the GDP values in GCAM (based on the region) and are then exogenously specified for a second iteration of the cost optimal scenario with the revised GDP values.	

The historical emissions for each region were computed from the ClimateWatch database maintained by the World Resources Institute (WRI 2022). The specific dataset used here is the PIK-PRIMAP, which covered the period from 1850, and also accounted for the Kyoto GHGs – which we believe is the extent of desirable coverage for the purposes of this analysis.

The pathways involving demand side mitigation efforts involve a more detailed set of assumptions (Table SI 9.2 b) and are also run as cost-optimal scenarios with other SSP-2 assumptions. These assumptions are in line with those for scenario no. 11 demonstrated in Gambhir & George et al. (2022), the "omnibus" scenario in George et al. (2021) and the detailed assumptions and basis can be found in ClimateWorks (2020).

Table 9.2 (b): Assumptions in demand side mitigation pathways

Pathway	Assumptions
BEH	- Dietary shifts involving a move away from beef/meat consumption with a reduction of 25% in income elasticity of demand. This also corresponds to an increased preference for other proteins (pulses & fish) and a minor increase in sheep/goat meat consumption. - Lowered demand for industrial goods (cement, etc.), indicating less materialistic tendencies. Implemented as a gradual reduction of 2% in income elasticity of demand across all regions every 5-year period. Equivalent reduction in feedstocks.

	- Reduced floor space and smaller houses, limiting to an average of 30 sq.m/cap. Implemented through satiation values - Increased preference for ridesharing options, gradually increasing vehicle load factors by 25% to 2050. - Increased preference for public transport, akin to SSP-1 - Reduced demands for aviation & shipping, a 20% reduction in income elasticity of demand across regions - Increased preference for electric vehicles, as in the ELE scenario
ALL	A combination of the BEH scenario, the ELE scenario (buildings & industry), low CCS, high RE & DAC, in addition to the following: - Full implementation of the Kigali Amendment to the Montreal Protocol for reduction in HFC emissions by 85% by 2055, and staged inclusion of regions during 2018-2030. - Constraining bioenergy to 100 EJ levels in 2100, a linear increase from current values - Lower preference for Nuclear technologies due to concerns on safety; Nuclear is only $1/4^{th}$ as preferred compared to other equally priced technologies. - Gradual afforestation, involving a roughly equally balanced share of NETs in 2050 between DAC, forests and CCS - Reduction in oil & gas methane leaks as in SSP-1 - Reduced non-CO_2 from shipping (lower demand) - Complete ban on fossil fuel vehicle sales after 2050 for road transport options - Increased efficiency in cement, industrial feedstock conversion by 20% till 2050 and constant thereafter - Smarter buildings and increased energy efficiency, implemented through technology change rates doubling over the century

9.3 Heterogeneity in energy consumption behavior – India example

Our downscaling model does not include a component to account for the fuel consumption pattern shifts between different classes of households. We assume the fuel choices of the average household as applicable to all income strata. However, in the real world, different households face different demand price elasticities and such elasticities further vary with time. Household decisions on fuel choice are also complicated and involve tradeoffs with other objectives and needs. One possible justification for our assumption to still be valid is that though poorer households are more likely to move away as non-solid fuels become more expensive with a carbon price, this avoided consumption is still a form of regressive impact which needs to be considered.

However, to demonstrate the actual impacts of such behavior, we employ a fuel choice model, MESSAGE-Access (Cameron et al. 2016) which downscales the results to account for fuel choice behavior by income and geography (rural & urban households). This model is still restricted only to cooking fuel choices and does not cover all dimensions. It incorporates different classes of households from rural poor to rural rich (represented as R1 to R4) and the urban poor & richer household spectrum represented as U1 - U4.

One complication here is that the residential sector in GCAM comprises residential heating, residential cooling and all other end-uses like home appliances, lighting and cooking are covered under "residential other". To estimate and separate the cooking energy needs for this analysis, we assume that cooking energy use is directly proportional to population and the balance in "residential other" after subtracting cooking covers all other household appliances. We use the cooking fuel to electricity proportions from the National Sample Survey for India (Round 66/ year 2012) since it is closest to the survey data we used for the main analysis (2011 IHDS-II). The IHDS does not provide a breakup of energy consumption by application and fuel mix and hence the use of another nationally representative survey which can provide this information.

The basic calculation steps to decompose residential other to cooking and other appliances:

$$('Residential\ other'\ energy\ use\ in\ GCAM\ output) = (Energy\ use\ for\ cooking) + (Energy\ use\ for\ all\ appliances, excluding\ heating\ \&cooling) + (Energy\ use\ for\ lighting) \qquad \text{(E. 2)}$$

We assume,

$$(Energy\ use\ for\ cooking\ in\ year\ y) \propto (population\ in\ year\ y) \qquad \text{(E. 3)}$$

Next, we derive the proportion of "energy use for cooking" from household survey data for 2010 and compute the same for 2030 using the ratio of populations in 2030 & 2010. Lastly, we use this computed value of cooking fuel energy in MESSAGE-Access, along with fuel prices from GCAM output. It then derives a fuel mix for each category of household based on the total cost of food preparation. These results show in the next section are purely to indicate the effect of heterogeneity and do not match precisely with our other modeling results. This is partly due to the fact that the fuels in GCAM are different from those in the MESSAGE-Access model, and the range of prices is also quite dissimilar.

The purpose of this example is to show the possibilities of future work with improving the downscaling model, adopting the MESSAGE-Access framework for GCAM specificities and developing a similar tool for income deciles.

9.4 India results from MESSAGE-Access

The results in this section are purely indicative of the effects of heterogeneity in household behavior and choices. We can see that the fuel choice distribution varies by the type of household in the BAU scenario (Fig. 9.4a), with greater use of traditional biomass fuels in rural areas, as well as the urban poor. In contrast, the urban rich, and to some extent the rural rich households (R4, U4..), have significantly lower use of biomass. Next, we show the results for India with this model in a mitigation scenario, viz. the net zero 2050 goal. Once again, we notice the shifting demands within groups. The share of traditional biomass increases for poorer sections, while there is almost insignificant change in U4. Households in R1-R3 reduce their consumption levels and also miss out on the technologies for cleaner fuels in transport. For urban households, again we see demand curtailment and fuel shits in some income strata, and hardly any changes in the most affluent tiers which has high demand elasticity.

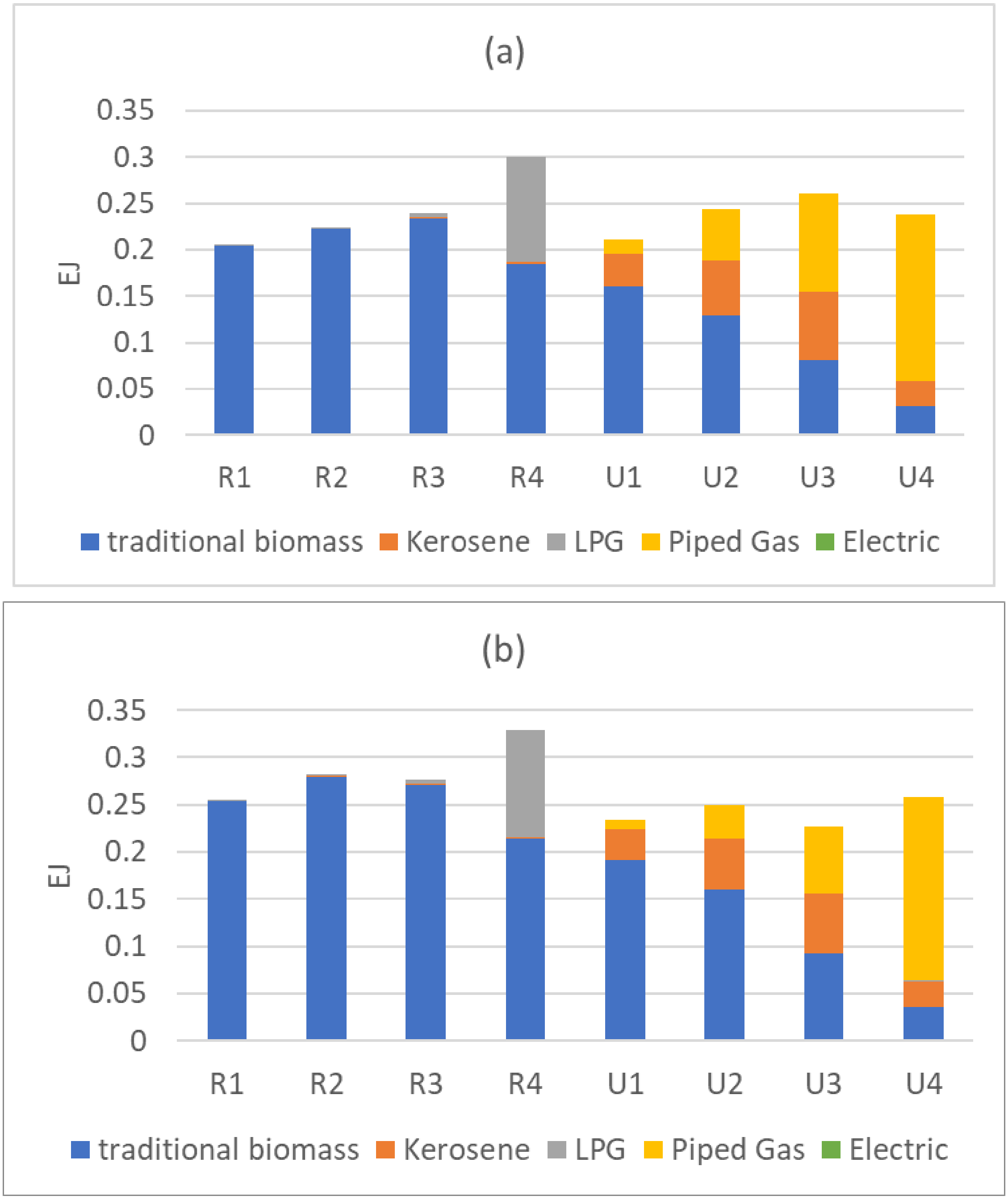
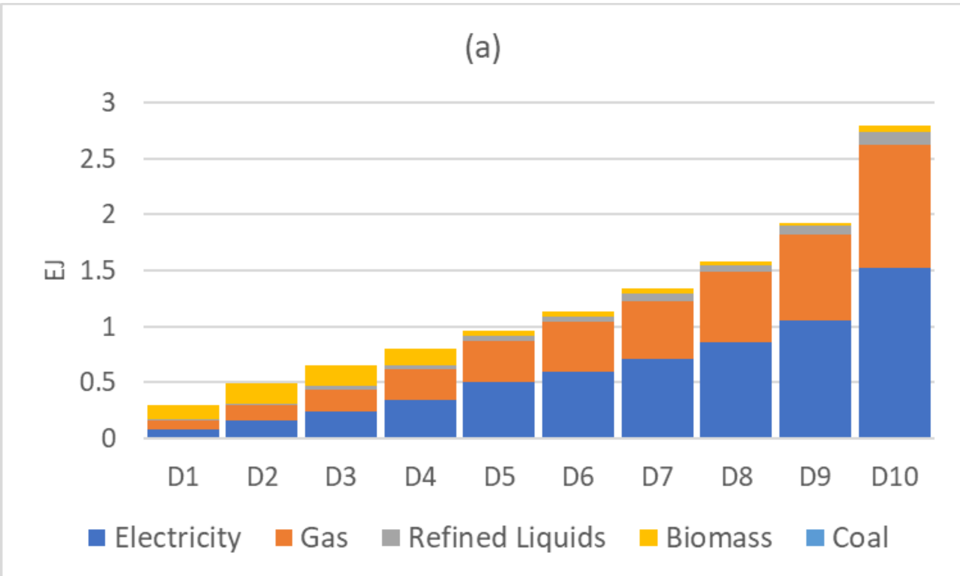


Fig. 9.4: *Downscaled results for rural (R1-R4) and urban (U1-U4) households in India showing energy consumption levels in the BAU (panel a) and net zero CO_2 2050 mitigation pathway (panel b).*

9.5 Impact of household heterogeneity in USA results

Similar to the example above with India, we now demonstrate the impact for USA, though we adopt a different approach by using income and price elasticity of demand by each decile. This is because MESSAGE-Access was designed for the specific example for South Asia and the assumptions need to be adjusted for other regions like the US. The downscaled results shown in Sec. 5.2, despite the representation of income deciles, assume the fuel choice representation based on the average household. However, in reality, poorer households consume a different set of fuels than more affluent ones. Also, different income deciles have different price elasticity by fuel. Therefore, with increasing fuel price due to the impact of mitigation policies such as a carbon price, the choices made by different deciles could further diverge.

For example, poorer deciles consume lesser proportion of electricity and higher proportions of biomass-based fuels in the US; and the converse holds true for the top deciles. To account for this difference, we examined the results for the BAU scenario from the representation of income quintiles for USA in Sampedro et al. (2022). We performed a linear interpolation to determine the price elasticity and income elasticity for each fuel and residential service/ application (heating, cooling, others). We can see this in fig. 9.5(a), while the current downscaling model we have demonstrated assumes the same fuel choice distribution as the average household to hold for all deciles (Fig. 9.5 b). The difference in fuel choices by income strata between the two models are noticeable for the BAU scenario in this study when we compare the two approaches, with richer households consuming greater shares of electricity and less of biofuels (Fig. 9.6 e).



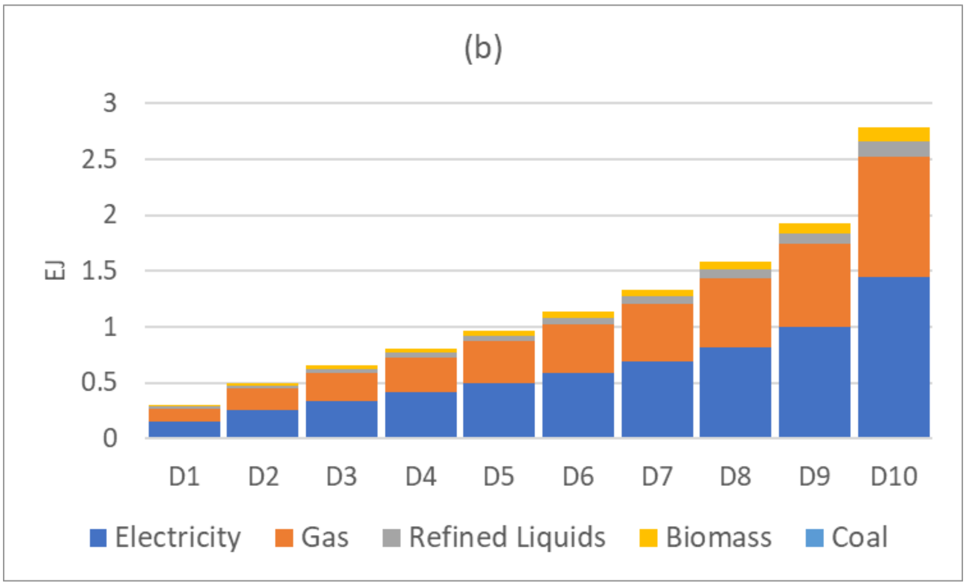
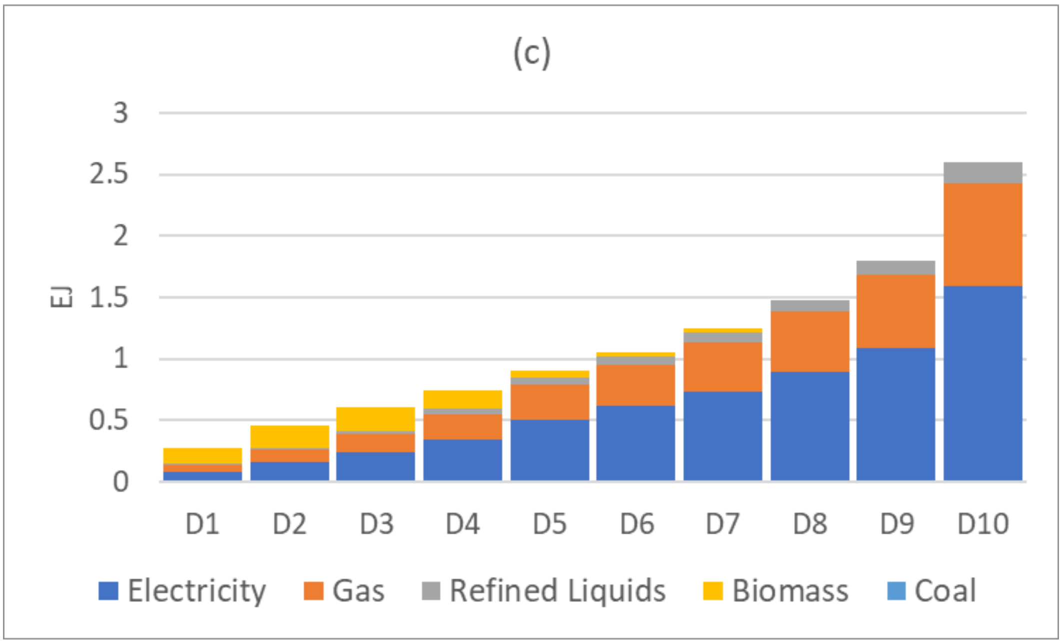


Fig. 9.5*: (panel a) Incorporating fuel choices by income strata gives a different fuel distribution for the income deciles (D1 to D10) in USA under the "no new policy" BAU scenario, while current downscaling model assumes similar fuel distribution across deciles (panel b)*

The demand price elasticity for electricity may be almost 0 for the richest households and closer to 0.5 for the poorest ones. For the affluent households, this means that there would be very small changes to electricity consumption with price increase, while poorer households would reduce consumption, as well as shift to other cheaper fuels under mitigation scenarios. We show an example of this below where the current downscaling model (Fig. 9.5 d) and the model derived from Sampedro et al. (Fig. 9.5 c) are compared. The increasing costs force not just a demand reduction, but also a fuel choice shift which varies by decile. Poorer deciles increasingly move towards cheaper fuel options (Fig. 9.5 f).



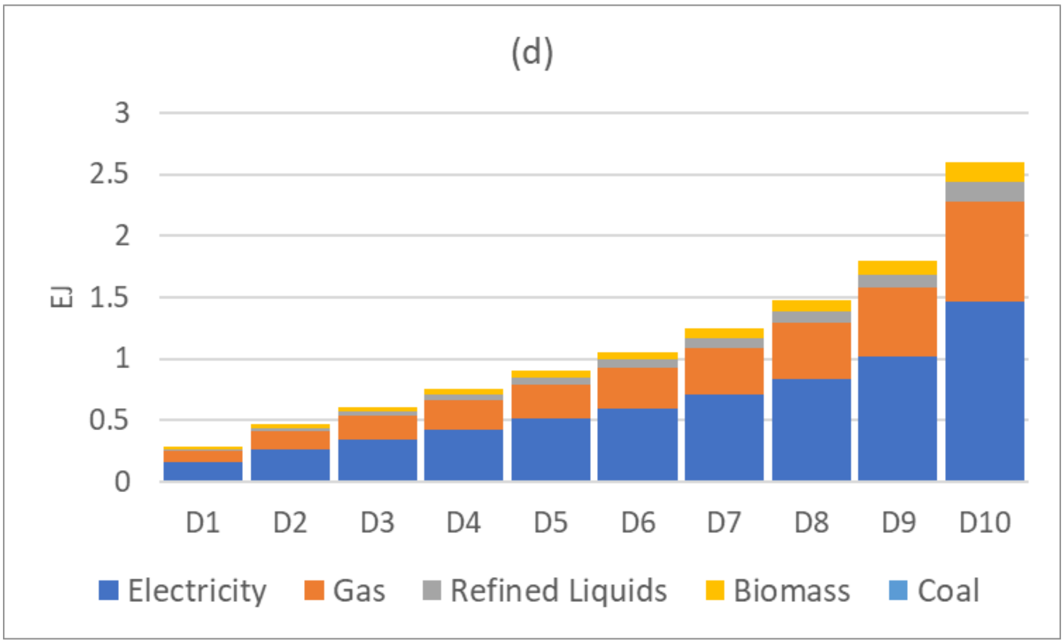
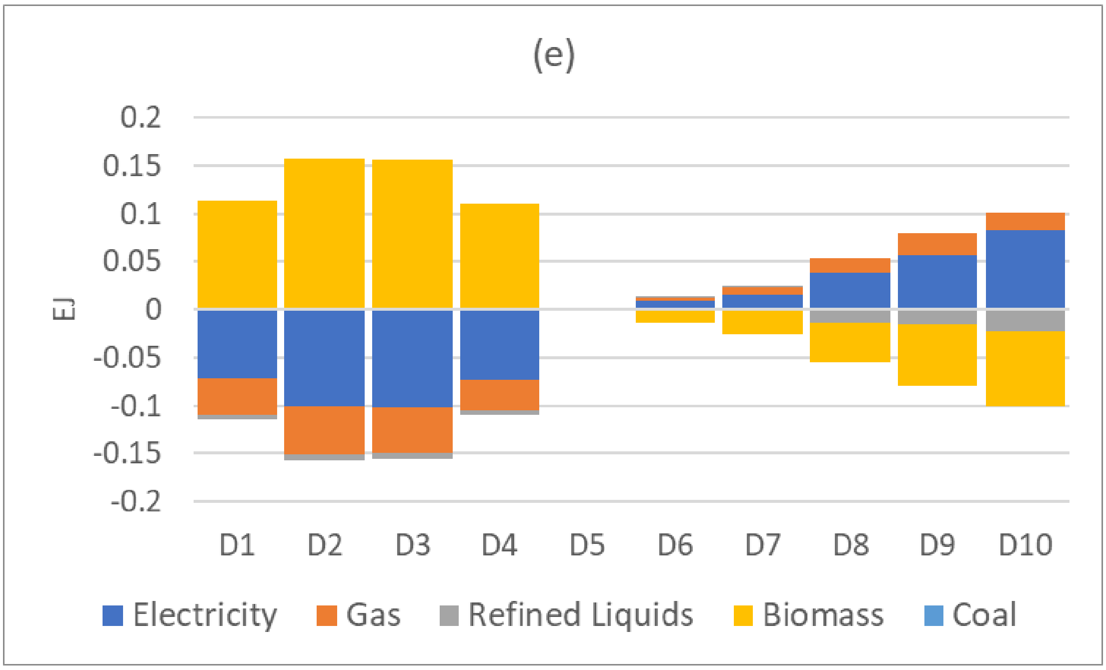


***Fig. 9.5**: (panel c) Incorporating fuel choices by income strata gives a different fuel distribution for the income deciles (D1 to D10) in USA under the mitigation scenario example here (net zero CO_2 emissions in 2050), while current downscaling model assumes similar fuel distribution across deciles (panel d)*

These shifts in fuels and the original distribution would imply certain changes to our downscaled results, especially the aspects about regressive impacts being faced by the bottom decile. With the new fuel choices, the poorest deciles have moved away to cheaper options while the second/ third deciles would likely face the most regressive impacts since they consume higher levels of the costlier fuels relative to the poorest decile.



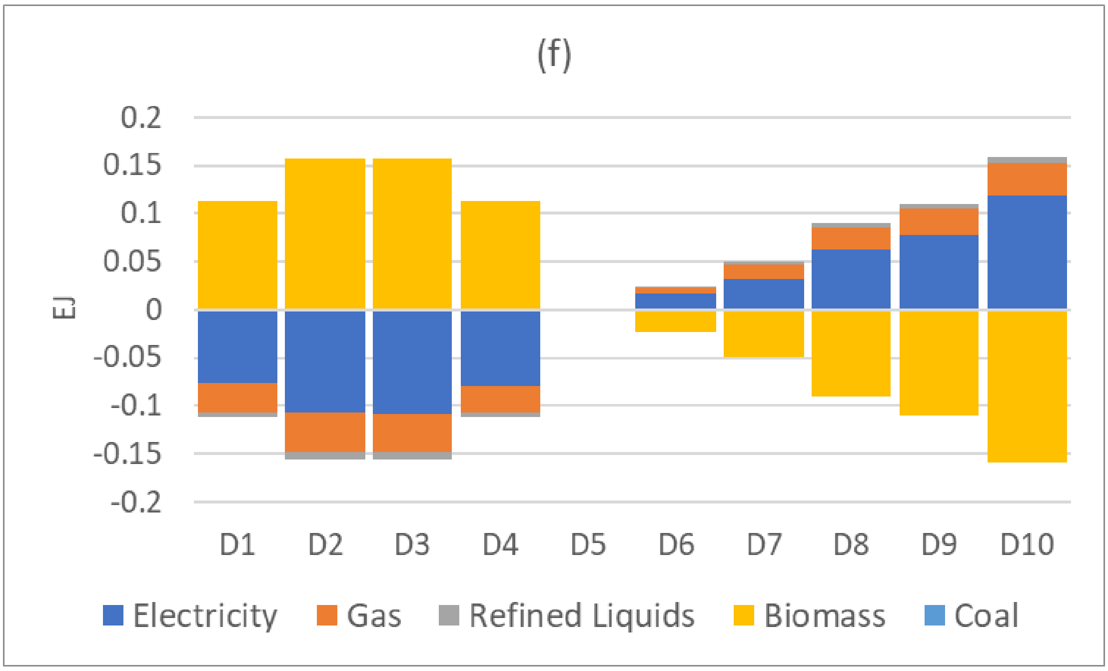


Fig. 9.5: *Difference in fuel choices by deciles compared when using the fuel choice model versus the current downscaling approach in this work, for the BAU scenario (panel e) and mitigation scenario (panel f)*

The key inference of this revised approach is that representation of household heterogeneity in IAMs and downscaling approaches are imperative to examine distributional consequences. There is still another regressive effect due to the avoided consumption of better and more convenient fuels which the monetary burden does not measure here. These changes do not directly affect our conclusions on comparison of effects between pathways which since we focus on the directional impacts and relative magnitudes of impacts between pathways and not specifically on the decile which is most impacted. However, future work would seek to account for these aspects.

9.6 Synergies/ tradeoffs for other developing/ less developed regions

In this section, we show additional results for section 5.1, the regional energy policy tradeoffs for other developing regions viz. Africa East, West, South, South Africa, Brazil & Indonesia. Once again, we see the access for all of the least developed regions. We examined this specific set of regions because they include some of the least developed countries facing energy access concerns or other development considerations weighed against climate goals. The countries encompassed in GCAM for some of these regions include almost all of Central and Sub-Saharan Africa (as listed below), apart from the separate region for South Africa:

<u>Africa East:</u> Burundi, Comoros, Djibouti, Eritrea, Ethiopia, Kenya, Madagascar, Mauritius, Reunion, Rwanda, Sudan, Somalia, Uganda

Africa West: Benin, Burkina Faso, Central African Republic, Cote d'Ivoire, Cameroon, Democratic Republic of the Congo, Congo, Cape Verde, Gabon, Ghana, Guinea, Gambia, Guinea-Bissau, Equatorial Guinea, Liberia, Mali, Mauritania, Niger, Nigeria, Senegal, Sierra Leone, Sao Tome and Principe, Chad, Togo

Africa South: Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe

Akin to the results in 5.1, the access tradeoffs reduce with slower pace of mitigation and could also turn into co-benefits for some regions with a global net zero goal of 2060 (Fig. 9.6a). An interesting aspect is the influence of country context. The results are slightly different for the more developed amongst these regions (South Africa – SAF), showing an affordability tradeoff and an improvement in access, which matches the developed world observations. The co-benefits such as increase in clean energy share relative to the reference case are also significantly lower for parts of Africa where the mitigation is more likely based on land use emission reductions and less on supply side changes.

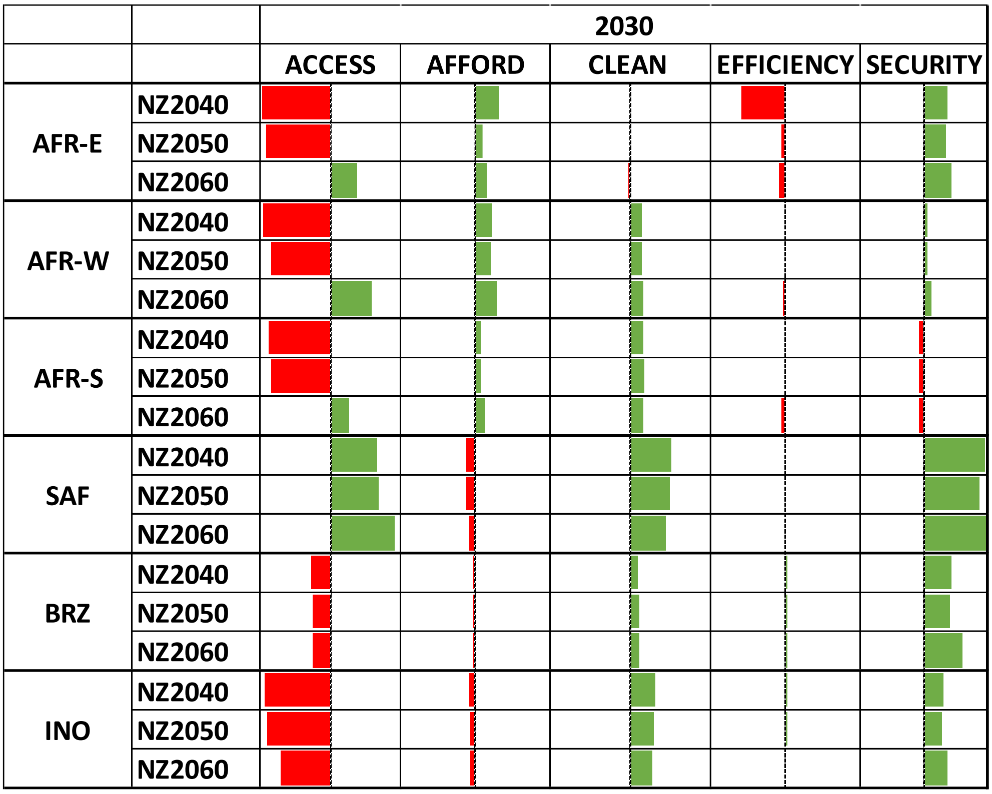


Fig. 9.6(a): *Synergies & tradeoffs for national energy goals for pathways varying by pace of transition*

For the technology & demand side pathways (fig. 9.6b), again we see similar behavior as before, though the relative magnitudes are muted to some extent by regional context. A forced elimination of traditional biomass increase access significantly, but with a significant tradeoff on affordability. The demand side pathways almost always have co-benefits across the board. Energy security is generally improved, except for the regions which may be significant exporters in the BAU.

The access tradeoffs are very high for the poorest regions of Sub Saharan Africa in all the cost-optimal or grandfathering principle-based pathways. Accounting for historical responsibility & financial transfers alleviates these tradeoffs to a significant degree. South Africa, and to some extent Brazil, are outliers in this case and the higher development levels may seem to resemble the Global North in some ways. Though noticeable affordability tradeoffs are observed for South Africa, the effects are almost negligible for Brazil irrespective of the pathway. This could be attributed to the uniquely substantial land-based mitigation options available in the region, as well the electricity generation mix dominated by hydro sources.

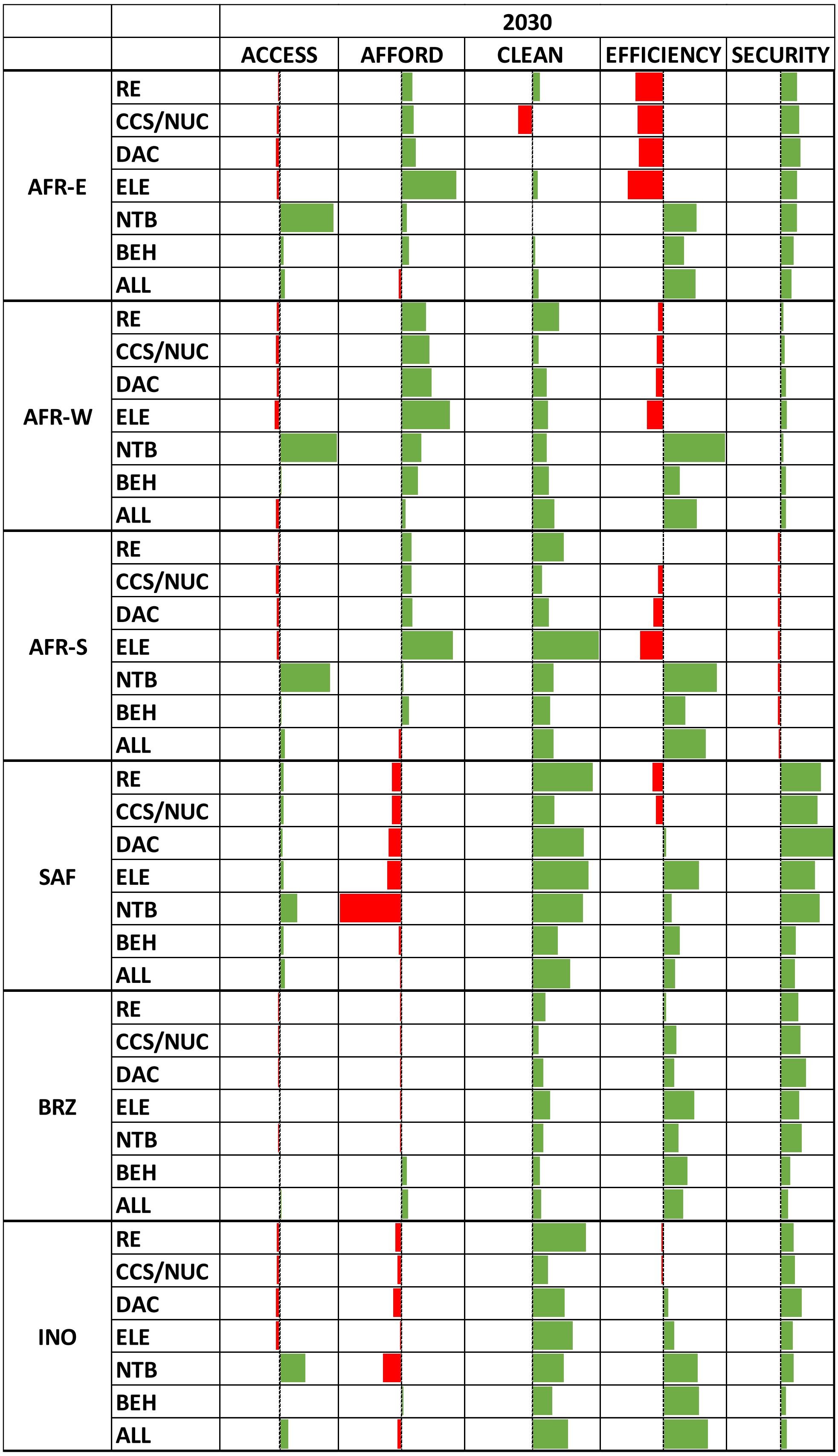


Fig. 9.6(b): *Synergies & tradeoffs for national energy goals for pathways varying by technology choices and demand side mitigation options*

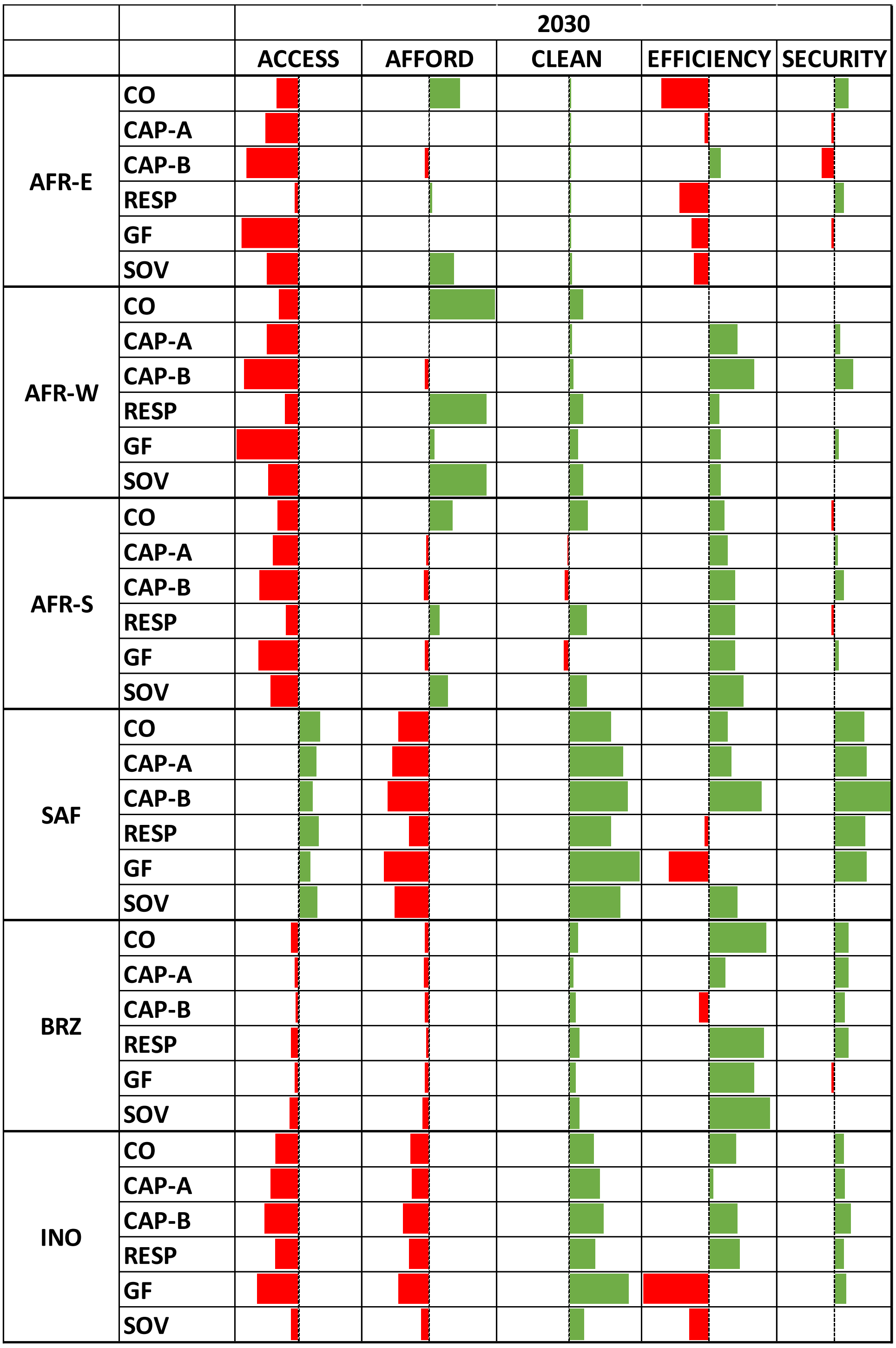


Fig. 9.6(c): *Synergies & tradeoffs for national energy goals for pathways varying by effort sharing principle*

9.7 Synergies & tradeoffs (long term/ 2050 results)

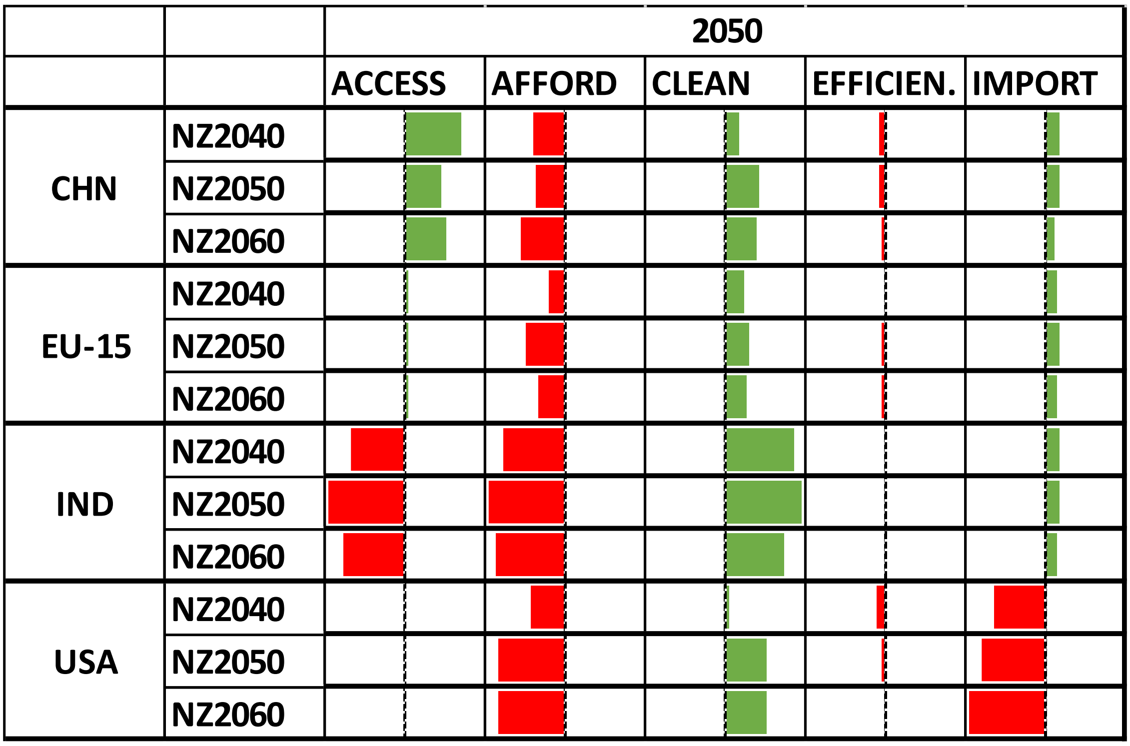


Fig. 9.7 (a): *Synergies & tradeoffs for national energy goals for pathways varying by pace of transition, long-term results for the year 2050*

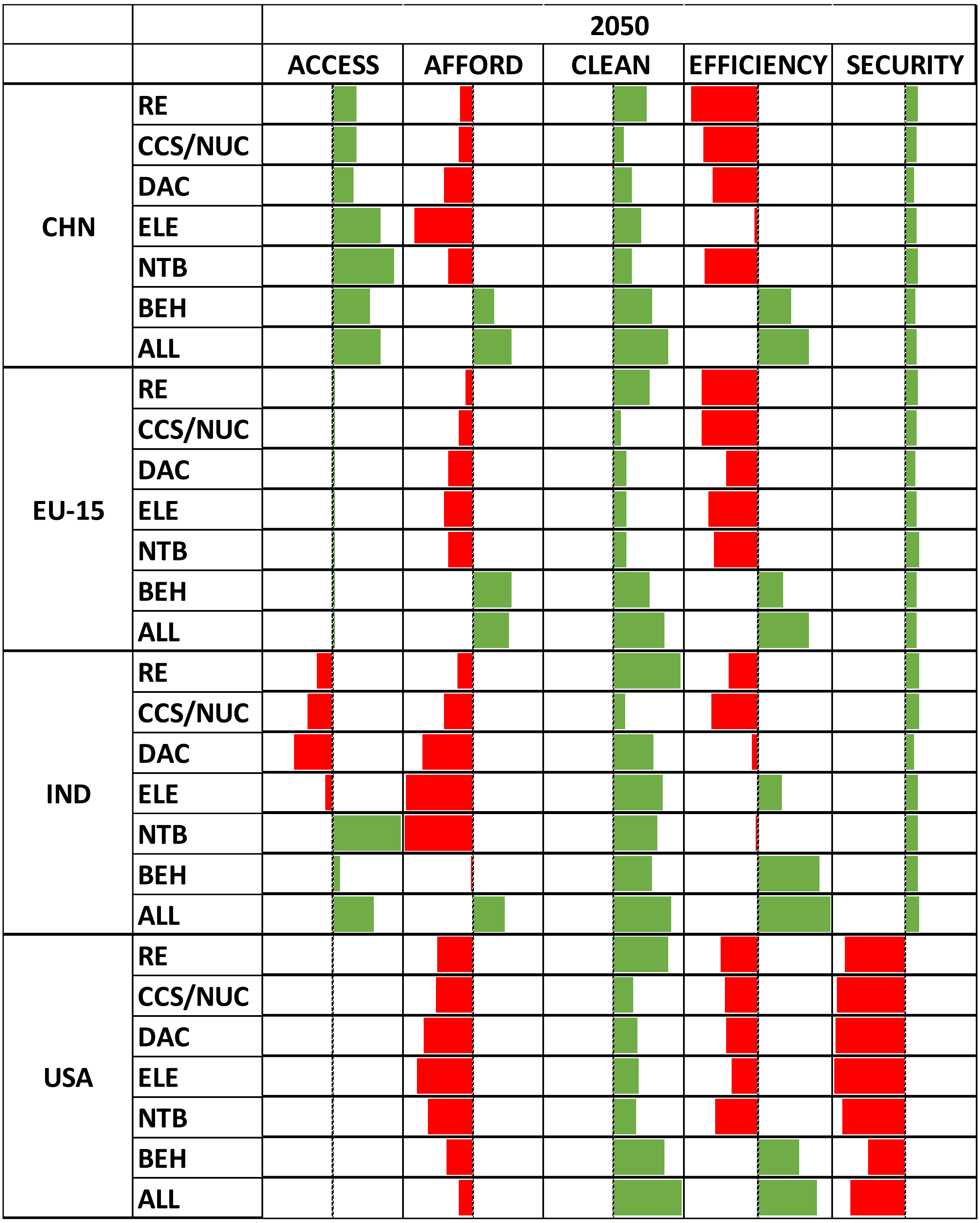


Fig. 9.7 (b): *Synergies & tradeoffs for national energy goals for pathways varying by technology & demand side mitigation options, long-term results for the year 2050*

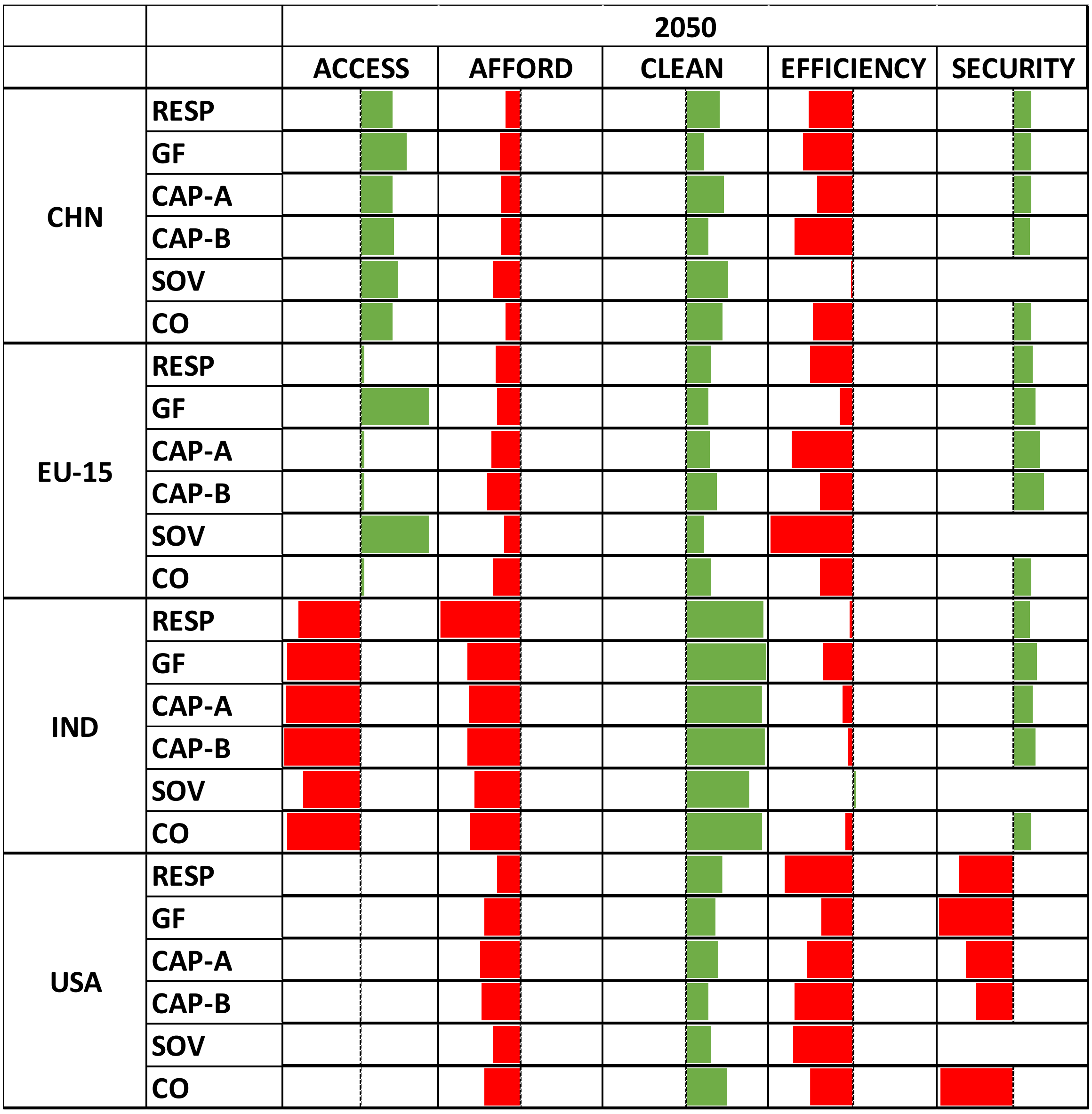


Fig. 9.7 (c): *Synergies & tradeoffs for national energy goals for pathways varying by technology & demand side mitigation options, long-term results for the year 2050*

Following from section 5.1 results, fig 9.7 (a-c) showcase the longer-term synergies (green bars) and tradeoffs (red bars) of different mitigation pathways for select regions varying by (a) pace of transition (b) technology & demand side mitigation options and (c) global effort sharing principles.

9.8 Impacts by income strata (long term/ 2050 results)

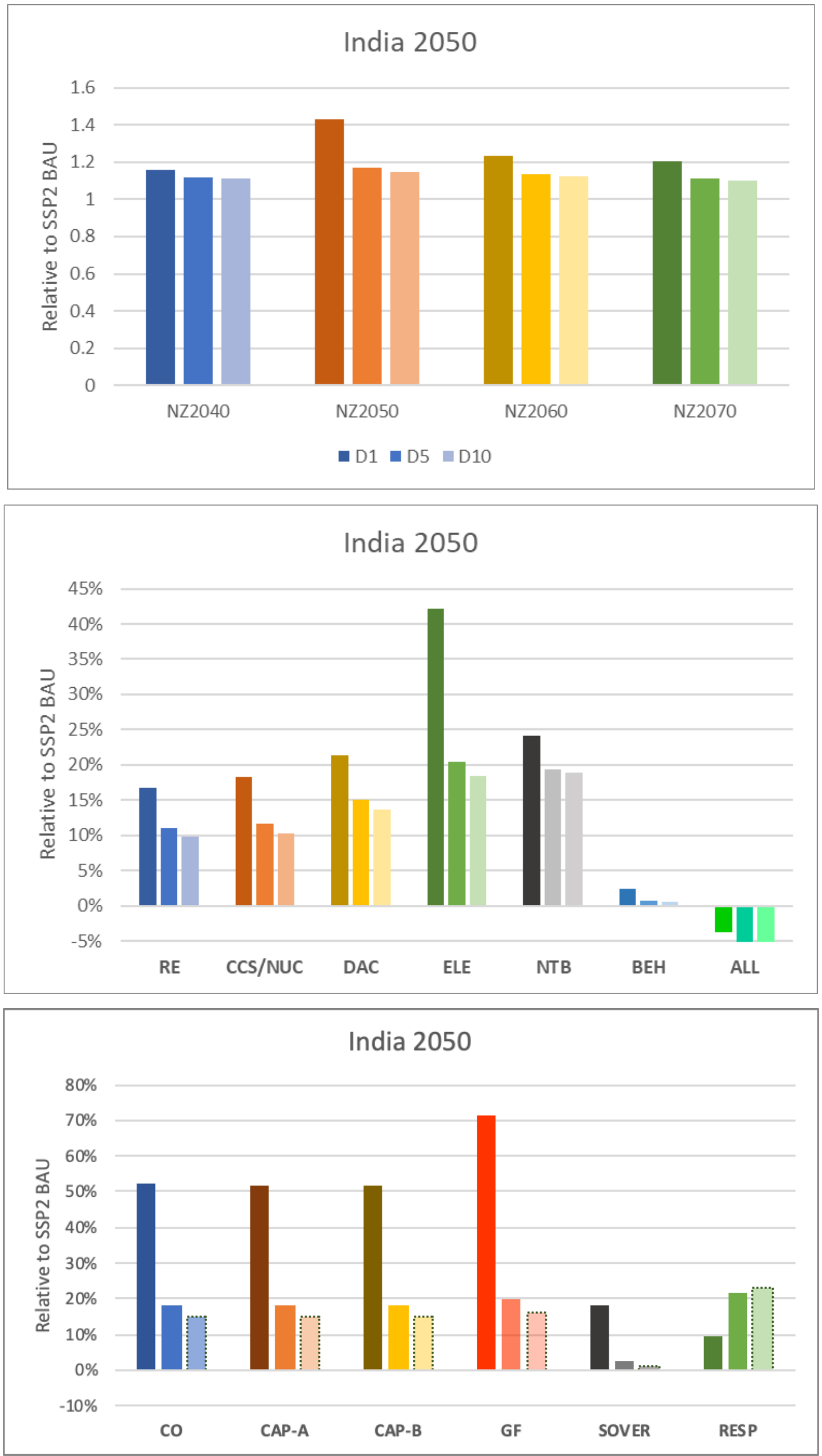


Fig. 9.8 (a) Long term distributional impacts of mitigation policy on income deciles ranging from the poorest (D1), middle (D5) and richest (D10) in India for different mitigation pathways to 1.5C varying by pace of transition, technology & demand side mitigation options and effort sharing principles

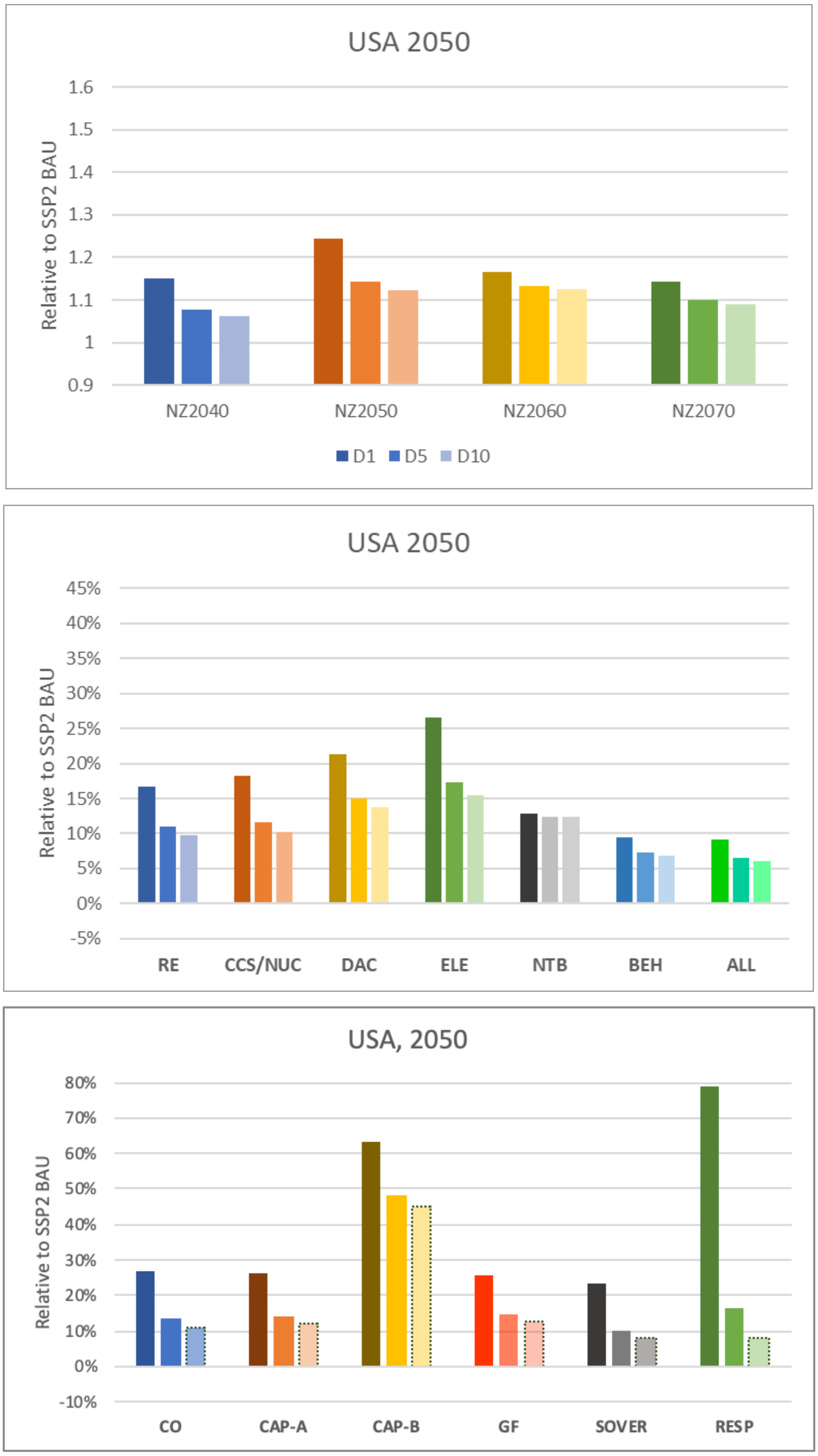


Fig. 9.8 (b) Long term distributional impacts of mitigation policy on income deciles ranging from the poorest (D1), middle (D5) and richest (D10) in India for different mitigation pathways to 1.5C varying by pace of transition, technology & demand side mitigation options and effort sharing principles