

## ABSTRACT

Title of Dissertation:

ENERGY EQUITY & JUSTICE  
IMPLICATIONS OF CLIMATE CHANGE  
MITIGATION PATHWAYS

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Doctor of Philosophy, 2023

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Analyzing distributional effects on vulnerable sections is important for enhancing climate mitigation ambition by supporting social objectives. Discounting the impacts on the most vulnerable, prior research underestimates the skew in investments required to meet sustainable development goals. Its focus on representative households and cost optimal mitigation pathway archetypes also amplifies false narratives around societal and developmental tradeoffs of mitigation policies.

This study demonstrates that bespoke pathway design can support simultaneous attainment of multiple national energy priorities. Using a consistent framework and accounting for interactions between different sectors, it evaluates a set of diverse mitigation pathways to similar climate

outcomes. It examines short & long-term distributional impacts on national energy goals to identify pathways which offer synergies across multiple objectives and regions.

Next, the impacts are downscaled to the household income deciles in India & the US using household survey data & future income distribution projections, to scrutinize the residential energy burden changes under different mitigation policies. The results show regressive impacts on access and affordability for most mitigation pathways, except those propelled by demand side mitigation strategies and non-CO<sub>2</sub> emission reductions. Thereafter, it expands the conceptualization of energy poverty beyond unitary dimensions, binary classifications and income relationships. Applying an alternative framework to identify vulnerable households experiencing energy poverty in India, this study showcases the disparities across dimensions. It then envisions an intersectionality context and proffers empirical evidence of the increased likelihood of households at the overlap of multiple deprivations being entrapped in more severe forms of energy poverty and the concomitant effects on gender inequity.

A key finding of this study is that mitigation pathway choice and design matters for just energy transition goals and tailored pathways addressing underlying local and global inequities provide latitude for synergies and progressive impacts. It also establishes that technology solutions alone are unable to redress pre-existing inequities and should be complemented with other support policies for the vulnerable. This study 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.

ENERGY EQUITY & JUSTICE IMPLICATIONS OF CLIMATE CHANGE  
MITIGATION PATHWAYS

by

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Dissertation submitted to the Faculty of the Graduate School of the  
University of Maryland, College Park, in partial fulfillment  
of the requirements for the degree of  
Doctor of Philosophy  
2023

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## Dedication

*To my mother, for her goodness, caring, tenacity & sacrifice; the person who inspired me to write, the reader I've always wanted, but who may never read any of this work*

## Acknowledgements

So, I did come a long way – in space, time, philosophy, research methods, interests, and as a person recognizing the limits of my knowledge, skills and beliefs; and am indebted to the many people who got me here! There are many reasons why I should not even have been here; but providence gave me an opportunity to continue learning. The transformation has been far-reaching; from the hard-charging, jet-setting, devil-may-care enforcer and designer of grandiose public projects, putting the gloss on an industry notorious for its influence on climate change, and in some ways representing what Hannah Arendt called the “banality of evil”, to a docile, mild-mannered, easy going researcher trying to fathom the societal impacts of energy-climate policies. This transformation was not the result of a Saul on the road to Damascus moment, but one with the assistance of umpteen people and situations across time and space.

I must start by acknowledging the amazing support I have received from my committee & research collaborators; I have been fortunate to have the opportunity of working with “A-list” researchers across my dissertation & other research projects. They have all been incredibly accommodating with scheduling conflicts across time zones and despite their own busy schedules.

I am eternally grateful to my sage-like advisor, **Anand Patwardhan**, who lent a patient ear to every frivolity, unperturbed by the noise, he trusted me to deliver, pressed me to seek challenges and build networks, helped me see themes that I missed. Unfettered by the constraints of our interactions often across multiple time zones, he sought to provide me every opportunity to advance this research.

Sometimes, I felt he knew me better than I knew myself! My co-advisor, **Nate Hultman**, sharpened my analysis, and taught me how to see the big picture and frame policy-relevant and positive research questions. He also ensured that I gained the benefits from the wider community at the Center for Global Sustainability (CGS).

**Haewon McJeon** mentored me on almost everything – from the nuts and bolts of GCAM, dealing with logistical challenges, managing my engagement with the Joint Global Change Research Institute (JGCRI), to identifying novelty in research and setting a high bar. In a “pandemic PhD”, he was often the only person I was regularly

interacting with for long periods of time, my regular sounding board, unwearingly answering every question at any hour, however tangential. Am not sure how he put up with umpteen moronic comments and questions, often suppressing it under a terse “that’s interesting.” Given that it was a steep learning curve for me, he has been incredibly tolerant, engaged and exacting enough to set me up for success, whilst also teaching me to be strategic, prioritizing between options, and being efficient. I have generally failed to measure to his expectations on the last aspect but console myself in the belief that I made significant improvement.

**Leon Clarke** helped me succinctly summarize research findings, organize the research, and scrutinize the results beyond the modeling tools used. His approach to “thinking without the model” was immensely valuable to discerning the real findings from the outcomes merely representing the model inputs or assumptions.

An exceptionally fruitful stint at the International Institute for Applied Systems Analysis (IIASA), Austria where **Shonali Pachauri** strengthened the research structure, was key to this dissertation. She showed deep interest, commitment and offered discerning critique and helped me draw major insights from the results. At every point where I was stuck, she was able to suggest a mediating approach to solve issues. Whilst they could not be formally part of my advisory committee, **Narasimha Rao** (Yale University/ IIASA) and **Jihoon Min** (IIASA) asked incisive questions and drove me to pursue directions that improved this work significantly and helped my development as a better researcher. A true visionary, Narasimha also helped me understand and appreciate the real-world purpose behind the research.

As the Dean’s Representative, **Maureen Cropper** has supported my work, showing interest in the findings and always promptly responded to the vagaries of scheduling and helped reviewing key results.

**Dr. Rob Sprinkle** and **David Crocker** (Professor Emeritus) helped me understand philosophy as a field of study as important to today’s research as it has been in the past. My interactions and courses with them drove me to question many of the assumptions about the world and my beliefs. They shaped my thinking on incorporating social sciences into mathematical modeling. They also compassionately supported me and led me by the hand, all of which I shall forever treasure.

I benefited immensely and often unwittingly through my exchanges with **Poorti Sapatnekar**, amongst the smartest persons I have met, who opened up new ways of thinking through nuances and complexities of the real world. I am also grateful to **Kavita Surana & Yueming 'Lucy' Qiu** for the research exposure they helped provide, the different research tools, imparting the importance of rigor in research, and presenting findings.

Special thanks are also due to my good old friend, **Gokul Iyer**, without whose suggestion I would not have even been here. Guiding me to apply, connecting me with the best mentors in the field, and helping me to settle in a very new environment, are some of the many ways in which he was instrumental to my success.

I have been incredibly fortunate to have had the opportunity to work with and be guided by some of the best researchers & associates, including **James 'Jae' Edmonds, Sha Yu, Ajay Gambhir** (Imperial College, UK) and **Seth Monteith** (Climateworks Foundation). These interactions were invaluable to building the research approach here, and I was able to pluck some learning from each of those projects and plug it into my dissertation.

My research path was nurtured and supported through interactions with many researchers and collaborators at multiple institutions, and I would like to thank all of them for some valuable insight based on findings, some question that motivated a reanalysis, a snippet of code that was invaluable, attending to logistical challenges, keeping the funding flowing, making accommodations to help my research, spending time in explaining something in the model, or just helping me to get it running when nothing seems to work!

- At CGS: **Ryna Cui, Alicia Zhao, Aphi Daigler, Justin Teng**
- At JGCRI: **Patrick O'Rourke, Kanishka Narayan, Yang Ou, Jay Fuhrman, Jon Sampedro, Sean Eustis**
- At IIASA: **Adriano Vinca, Jarmo Kikstra, Setu Pelz, Volker Krey, Fabian Wagner, Brian Fath, Tanja Huber, Margit Roth-Ahra**
- At the School of Public Policy & University of Maryland: **Lori Ganey, Taryn Faulkner, Nancy Guevara, Tara Johnston**

Whilst not directly funded by any project, parts of my dissertation research have been supported by the funding from various graduate assistantships and fellowships from the **University of Maryland, the School of Public Policy, the Kulkarni Summer Research Endowment, the US National Science Foundation (NSF)** grant to Kavita Surana, **Climateworks Foundation** and the **International Emissions Trading Alliance (IETA)** funding through CGS, and the **NSF Fellowship** and **US National Academy of Science, Engineering & Medicine (NASEM)** grant for IIASA.

Friendships developed across vibrant past & current PhD cohorts at the School of Public Policy were influential in guiding me through the nitty-gritty, assistance with personal issues, insights on navigating the labyrinth, figuring out the way as we muddled forward together, or just helping me locating the proverbial light switch! I am grateful to *Anjali Sharma, Arijit Sen, Jennifer Richmond, Clif Cottrell, Simran Singh, Siobhan Kerr, Linlang He, Xingchi Shen, Jiehong Lou, Aichiro Suryo Prabowo, Kowan O'Keefe, Neeraj Negi* & the *late Elizabeth Mata Lorenzo* apart from *Gesang Yangji & Nora Krenmayr* (my workmates at IIASA) for lighting the way along this journey.

*Rangan Banerjee* (IIT Bombay/ Delhi) played a key role in inspiring me to pursue a PhD abroad, and I also benefited from the support I received from *Anand Rao* (IIT Bombay). My friend *Rajarshi Guha* always encouraged me to take the plunge and was a safety net and sounding board over these years. *Mathew John, Biswanath Saha* and *Deepak Yadav* also helped fortify my resolve to pursue a PhD after many years away from academia.

The pursuit of this dissertation whilst trying to support a growing family would not have been possible without the priceless support I received at key moments from *Radhika Iyer, Dheeraj Gedam & Dr. Pravin Gedam. Renny Andrew, Remya Renny, Chithra Vishwanath, Ankur Verma, Mohan Yama* offered honest friendships and sage counsel.

I am also indebted to *Nishanth Nair & Asha Krishna*, my neighbors in College Park over these years. From regular check-ins to assistance on problems big or small, from great conversations to innumerable idlis, they never let me feel the absence of my family.

I am grateful to *my father* for keeping the faith and every advantage he sought to provide me. My in-laws, *Joy Jacob & Marykutty Joy* deserve a special mention – supporting me in pursuing freely, managing all my family obligations during my prolonged absences, and for just being the most incredible grandparents my son could have! *Asha*, my sister-in-law, also chipped in gamely for every emergency and unforeseen circumstance.

The four-and-half years is a window that closed too quickly, a fraction of a fraction of the unimaginable vastness of time; but the days with my son, *Abel*, have been the greatest wonder and privilege of my life. Having children has been characterized as ‘all joy and no fun’ in the best of times and doing so facing the penury of a grad student, in the middle of a raging pandemic should have been worse. But my experiencing & remembering selves tell me that nothing provided more joy and fun in the dreary landscape of a PhD pursuit. He added more to life than mere happiness, something deeper having to do with satisfaction, purpose & meaning. Though it has been a strange admixture of terror, pain and delight, being away from him for long periods has taught me that ‘it hurts just as much as it is worth.’

And finally, my wife, *Deepa* –I am incredibly grateful for what she chose to give up, allowing me to take this chance to start again and pursue what I loved. It was a long way to Tipperary, but my heart was right there! From the day she bid goodbye, scrambling cross-country with flights cancelled and roads inundated as once-in-a-generation flood waters engulfed my state, she has waged a lone battle, often calmly facing extraordinary stresses and my odd working hours. The greatest sacrifice I made was only being an appalling husband and father. I am blessed to have had her support throughout; from encouraging me to take the plunge, to rowing alongside as I swam into the deep, and also being the lighthouse on the shore. I am eternally indebted to her for being the best version of herself so that I could seek to be a slightly better version of me.

Paraphrasing Pascal – I would have written a shorter acknowledgement section, but I did not have the time (or be any less grateful to the innumerable people who made this feasible)!

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## List of Abbreviations

BAU	Business As Usual
CBDR	Common and Differentiated Responsibilities
CCS	Carbon Capture and Sequestration
CDR	Carbon Dioxide Removal
CMIP	Coupled Model Intercomparison Project
COP	Conference of Parties
DAC	Direct Air Capture
EIA	Energy Information Administration
GCAM	Global Change Analysis Model
GDP	Gross Domestic Product
GHG	Green House Gas
HFC	Hydro Fluoro Carbon
IAM	Integrated Assessment Model
IHDS	Indian Human Development Survey
IPCC	Intergovernmental Panel on Climate Change
NDC	Nationally Determined Contribution
NSSO	National Sample Survey Organization
RE	Renewable Energy
RECS	Residential Energy Consumption Survey
SDG	Sustainable Development Goal
SSP	Shared Socioeconomic Pathway
UNFCCC	United Nations Framework Convention on Climate Change

# Chapter 1: Introduction & Framing

## *1.1 Equity & justice as drivers for ratcheting mitigation ambition*

Limiting end-of-century global warming to 1.5- or 2-deg. C would require rapid and deep emission reductions across all sectors of the global economy (IPCC 2022a). The Working Group III Report of Sixth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) shows that despite a slowdown due to the Covid-19 pandemic, carbon emissions have continued to grow, and it will be “impossible” to stay below 1.5 deg. C with “no or limited overshoot” without stronger climate action this decade. Despite the announcements made at the Conference of Parties (COP-26) at Glasgow, the current climate pledges also increase 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, Meinshausen et al. 2022). Ratcheting mitigation ambition is also critical to limit the impacts of mid-century peak warming (Iyer et al. 2022).

Such emissions cuts are part of the energy transition that could be achieved through significant reductions in fossil fuel use, energy efficiency, electrification, the rapid uptake of low emission technologies and the use of alternative energy carriers, including hydrogen. Further, carbon dioxide removal (CDR) will likely be “unavoidable” to reach net-zero emission goals (IPCC 2022a). Other demand side

measures could include more sustainable diets and consumption patterns, which could minimize the CDR needed (van Vuuren et al. 2018).

In theory, such an energy transition for climate mitigation goals might seem like a “well-lubricated slide from one reality to another” (Yergin 2021). Historically, energy transitions have been complex and hardly swift. Past energy transitions have also been “energy additions” (adding energy sources over other existing options), but the coming energy transition is expected to be complete switch from a world economy which is dependent on hydrocarbons for 80% of its energy needs (Yergin 2021).

Enhanced mitigation through decarbonization of the world economy and broader action to shift development pathways towards sustainability will have distributional consequences within and between countries. The substitution of technologies and practices will fundamentally alter the nature and viability of many economic activities, shrinking some industrial sectors whilst others may emerge (Green & Gambhir 2020). There are also many positive aspects of the transition, in addition to the benefits from limiting climate change impacts. A low or zero-carbon economy could be as prosperous, or even more prosperous than a high carbon one (World Bank, Fay et al. 2015). However, it will also cause significant disruption, dislocation, costs and losses to many individuals, households, groups, and countries. This does raise complex normative and political questions about who should bear the “transition risks” (Gambhir & George et al. 2022) of such mitigation actions and how some of those risks can be addressed in policy design. Mitigation and adaptation actions are

now conceptualized as a risk transference between communities (Sovacool et al. 2015). Making low carbon transitions just, equitable and politically ‘smooth’ has been an increasing focus of research and literature in the last decade; a shift from the justice dimensions of burden sharing and climate change impacts which was dominant before.

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. Less equal societies have a preponderance towards lower trust in institutions and a lost sense of the idea of the common good (Applebaum & Pomerantsev 2021, Wilkinson & Pickett 2009). Equity and just transitions can also enable ratcheting ambitions for accelerating mitigation.

### *1.2 The “Just Transition”*

“Just transition” has at least two primary usages: First, the phrase is used to mean that the transition to a low-carbon society should be fair to the most vulnerable populations – that the new low carbon economy should not perpetuate the inequities and environmental hazards of the current fossil fuel-based economy and that the

transition provides the opportunity to counteract those impacts. The broader concept around fairness to vulnerable populations implies a grand restructuring of societal inequality (Eisenberg 2018). The second meaning of “just transition” calls for protecting workers and communities employed in the high carbon economy, those who face the undue or disproportionate burdens of mitigation action (Eisenberg 2018). Climate mitigation literature often focuses more on the second usage, defining it as a transition from a high-carbon to a low-carbon economy which is considered sufficiently equitable for the affected individuals, workers, communities, sectors, regions and countries (Jasanoff 2018; Newell and Mulvaney 2013). It is a principle of distributive economic justice, insisting that those displaced due to public-driven actions should not alone sustain their economic losses.

The term owes its origins to the US labor movement and sits at the intersection between the energy transition and energy justice bodies of literature (IPCC 2022a). In 1973, trade unionist Tony Mazzocchi collaborated with environmentalists to organize the members of ‘Oil, Chemical and Atomic Workers’ Union’ (OCAW) for the “first environmental strike” ever. Together, they protested against the health and safety issues at Shell refineries in 4 US states (Chedd 1973). Appreciating the origins of just transition leads us to conclude that it involves more than simply helping workers to adapt to changes in their industries but is about fulfilling a broader and deeper egalitarian and ecological vision (Stavis et al. 2020). This “living concept” enables us to highlight its multiple functions for workers and organized labor. Just transition is not only about creating a safety net for precarious workers in declining sectors, but

about getting workers and frontline communities to engage in the environmental debate, organizing workers in ascending green sectors and getting those still dependent on polluting industries and sectors to accept and support a green transition.

The inclusion of the term “just transition” in the Paris Agreement raised awareness of the social dimensions of the low-carbon transition (UNFCCC 2015). This has also paradoxically separated it from the frontline communities and labor unions that conceptualized it and continue to mobilize around (Stavis et al. 2020). COP-24 in Katowice, Poland was termed as the ‘Just Transitions COP’ with the signing of the Silesia Declaration (2018) and a focus on addressing job losses in the fossil fuel industry. There has been criticism that rather than providing a clear sense of how a just transition can be achieved, it actually exposed climate policy makers’ narrow understandings of just transitions, instead of dealing with the experiences of frontline communities and how they are used to justify inaction or low ambition on climate (Stavis et al. 2020). There has also been recent criticism that just transitions have been used by governments as a shield to continue and enhance fossil fuel development in the last few years (Heffron & McCauley 2022).

### *1.3 Addressing distributional implications for Just Transitions*

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).

This implies the need to incorporate distributional considerations into energy and climate policy. These considerations have long been embedded in international climate agreements through concepts such as common but differentiated responsibilities (CBDR) and intergenerational equity but are also reflected in recent proposals like the Green New Deal policies & proposals (European Commission 2020, Galvin & Healy 2020, Green New Deal 2019). 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. Such initiatives 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.

#### *1.4 Current literature*

##### 1.4.1 Overview

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 often 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.

#### 1.4.2 Knowledge gaps

Taken together, the above studies have mostly drawn general insights at the aggregate global level without addressing the regional differences in detail. Few studies do undertake comparisons of regional effects, as the IPCC Special Report put it “*very little literature has formally examined distributions under 1.5°C consistent mitigation scenarios*” (IPCC 2018).

**The first key knowledge gap** is around comparison and identification of policies and varied mitigation pathways for their distributional consequences. This limits insights on how pathway design can influence attainment of multiple national & societal development goals. Almost all works explore societal implications of different mitigation pathways, often those varying with climate goals like NDC targets, 2 or 1.5 deg C. There is no exploration of how different pathways, or approaches to the same climate goal might compare in terms of their distributional impacts.

**A second gap** pertains to the distributional impacts on different income tiers from different energy-climate policies, aside from the standard carbon price approach. When assessing the distributional impacts, it is well established that higher energy prices that may result from fossil fuel subsidy phaseouts or carbon pricing can disproportionately affect poor consumers (Dorband et al. 2019). However, knowledge gaps remain on distributional dynamics along income classes, or effects within countries in terms of changes to the energy burden. Assessment of impacts at the household level is needed to investigate attainment of sustainable development for

all. Whilst most IAM studies show poor countries or regions are more vulnerable than rich or developed regions, very few downscale the impacts to show that poor households are more vulnerable than rich households. The lack of consideration of distributional aspects skews the estimation of investments needed for SDG attainment.

**A linked third knowledge gap** relates to assessing the impacts on household energy burdens in totality, accounting for both price, income and household fuel choices in totality. Current literature has only looked at the direct energy consumption impacts (i.e. “joules”) and not the changes to share of income spent on household energy needs under different energy-climate pathways.

**Another significant fourth knowledge gap** is the limited literature acknowledging that energy-related impacts could fall along multiple dimensions and not just access or affordability, and these could be also be related to factors beyond income. The energy-climate literature has also ignored factors beyond income when assessing distributional outcomes, a fact highlighted in recent calls to address the identification and modeling of such features in energy and well-being research (Rao & Wilson 2022). Energy burdens for households may be due to a combination of multiple socioeconomic and sociopolitical factors and identities. Whilst non-IAM studies, especially those on energy poverty, health, crime etc. have explored some of these household or individual conditions, there remain wide gaps in assessing how such conditions individually drive or intermingle to create conditions limiting the ability to

cope with a rapid energy transition. IAM studies, have of course, only recently forayed into the income classifications and have no exploration of factors beyond it.

### *1.5 Research questions*

#### 1.5.1 The caboose and the engine

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. Koberle et al. (2021) showed that comparable levels of income can be attained globally by increasing carbon efficiency by a factor of five. 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 that incorporate alternative policies beyond a carbon pricing mechanism to limit these risks and achieve development objectives?

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

This can be seen through the analogy of a caboose and an engine (Sapatnekar 2020), where the social goals have hitherto been comprehended as an outcome or trailing caboose connected to the engine of energy-climate policies. Are some policies able to connect the caboose and the engine in a way that it can be powered forward? Are

there policies which can use the caboose of social goals to add power to or propel and accelerate the engine of mitigation ambition?

#### 1.5.2 Sub questions to address the overarching research question

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 approaches to achieve both climate & societal development goals together, I outline three specific research questions sought to be addressed through this dissertation:

- *What are the co-benefits and trade-offs of different 1.5°C pathways across SDG-7 goals and national energy priorities? What kinds of policies can help attain multiple national energy goals?*
- *What is the impact of different 1.5°C pathways on household energy burdens across different income tiers? What kinds of policies can support better outcomes for the most vulnerable?*
- *What are the different dimensions of energy poverty likely to be influenced by energy transitions? How do underlying socioeconomic features affect the inequities in the distributions along those dimensions?*

These questions are highly relevant to climate policy making. In seeking to answer these, this dissertation informs policy makers not just on what consequences (however unintended) may result from a rapid energy transition linked to climate change mitigation policies, but also on how such consequences can be obviated by better policies.

## *1.6 Approach & main contributions*

### 1.6.1 Methods

These are big questions which can be addressed in many ways, all with their pros and cons. The first question relates to average impacts for a given region and representative household (i.e the spatial distributional impacts), whilst the second question examines the downscaled impacts or distributional impacts by income strata. In either, one needs to examine the temporal effects as well, considering not just the short-term (~2030) effects, but also the longer-term (~2050) consequences. For these, I employ an Integrated Assessment Modeling (IAM) approach as the foundation, coupled with other analysis.

Despite the discernable limitations in existing IAMs to represent heterogeneity and distributional impacts, this dissertation uses an approach employing IAMs in combination with household survey data to answer the first 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).

For the third question, I employ empirical approaches on detailed household survey data for a case study of India. India is representative of the different dimensions of energy poverty, as well as a multitude and diversity of possible deprivations in its diverse population. It is also a significant case to consider in terms of the importance to climate change policy in the globally, and the emphasis Indian policymakers have placed on local development needs and the concept of CBDR.

### 1.6.2 Contributions

This study provides a distinctive contribution to the research in terms of its findings and policy implications - modest in its approach, but novel in the quantification of impacts and consequences on regions or income strata and revealing the multidimensional inequities and their overlapping interactions with energy-related deprivations. It does not seek to explicitly pursue model development, although some aspects would be relevant for inclusion in future advances to integrated assessment approaches.

This study demonstrates that bespoke and broad-based mitigation pathways that account for underlying local & global inequities can support simultaneous attainment of multiple national energy priorities. It also validates those pathways as the best options for addressing energy burden inequities within a region. Lastly, it uncovers the ways in which some inequities can overlap, entrap marginal communities and lie beyond income characterizations.

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 provides 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.

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 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.

Another vital contribution of this study is to bring an intersectionality framework to the energy poverty question and examine its multidimensional nature and overlaps with other horizontal and vertical inequities, both upstream (education, income, geography, social class) and downstream (gender). It is possibly the first study demonstrating empirical evidence of such a nexus, and the distinct relationships between energy poverty dimensions and other deprivations in different contexts.

The important takeaway from this study is that mitigation pathway choice and design matters for just energy transition goals and tailored pathways addressing underlying local and global inequities provide latitude for synergies and progressive impacts. It also establishes that technology solutions alone are unable to redress pre-existing inequities and should be complemented with other support policies for the vulnerable. This study 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. Without broadening the basket of policy choices, and accounting for vulnerabilities of marginal communities globally & locally, climate policy (however well-intentioned) would have the inadvertent consequence of protecting the affluent, deprivileging the vulnerable and exacerbating inequities.

### *1.7 Dissertation structure*

The rest of this dissertation tries to answer each of the research sub-questions in separate chapters.

Chapter 2 starts with a philosophical and real-world exploration of examples of multiple contradictory wants impossible to attain simultaneously. It then posits such situations in the energy-climate policy context and explores the literature around the energy trilemma and tradeoffs between national choices under mitigation policy, connecting it to recent geo-political and energy security upheavals. The chapter

considers the fact that mitigation policy could increase energy prices and lead to avoided energy consumption, bringing some below decent living thresholds. There could also be a shift in fuels used and related negative impacts for some SDGs and regions. It then examines alternative mitigation pathways using GCAM and interrogates impacts of different mitigation pathways to 1.5 deg C varying by technology choices, pace and socioeconomic dimensions on aspects of energy poverty and income inequality. After discussing a comprehensive set of scenario variations, it examines how they perform across a defined set of multiple national energy goals explicit or implicit in the SDG-7 and demonstrates how pathways focused on demand side approaches are able to achieve almost all goals across global regions. The chapter concludes with a summary of main findings and caveats to its approach.

Chapter 3 considers that mitigation policies have unequal impacts on the population within regions and more vulnerable households may be created when energy burdens increase disproportionately across income tiers. It examines the limited literature on the topic and identifies key gaps, and then employs the scenarios designed in chapter 2 with a combination of household survey data to illustrate pathways that can limit the impacts on the poorest households.

Chapter 4 explores the concept of transitional energy poverty and households which are vulnerable to it. Using a case study of India, and nationally representative household survey data, it demonstrates various distributional aspects of energy

poverty. It then explores how underlying systemic factors could drive energy poverty and what happens when inequities overlap or intersect. The results section leads to a discussion on the consideration of intersecting identities within populations, the need to see energy poverty as a symptom of other inequities and targeting benefits to account for non-financial aspects. It concludes with implications for improving representation in IAMs beyond income characteristics.

Each chapter separately explains the models and methods, caveats and limitations, and is accompanied by an extensive body of supplementary information in separate appendices. The last chapter 5 summarizes the broad findings and highlights main contributions from each of the previous three and deliberates on the policy implications of the results. It also suggests directions for future research.

## Chapter 2: Mitigation Pathways to Attain Multiple National Energy Goals

### 2.1 Introduction

#### 2.1.1 National energy priorities

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, mainly in the Global South, 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). In contrast, the discourse around energy poverty in the Global North has focused on energy poverty in the context of affordability (Drehbol et al. 2019, Graff et al. 2021) or energy security (Cherp & Jewell 2014, Rodriguez-Fernandez 2022). This conundrum, a challenge of achieving simultaneous improvements in energy access, affordability, and sustainability, has become one of the most critical issues facing policy-makers, industry leaders, and academics. It is particularly complex due to the intricate relationships and trade-offs between these dimensions, in different regional contexts. The traditional approach to addressing this challenge has been to focus on one or two dimensions at the expense of the others, resulting in unsustainable outcomes. However, recent efforts to decarbonize the energy system, such as climate mitigation policies and carbon pricing, have further complicated the

challenge, making it even more daunting to achieve multiple dimensions simultaneously.

### 2.2.2 *Reductio ad absurdum*

The difficulty of choices between multiple, seemingly unfavorable or unacceptable, options has been an aspect considered in philosophy and religion, from where it moved into economics and politics, and more recently into business and technology fields. *Reductio (or argumentum) ad absurdum* is the form of argument that attempts to establish a claim by showing that the opposite scenario would lead to absurdity or contradiction (Merriam-Webster. This concept of ‘proof by contradiction’ or ‘argument to absurdity’ traces back to ancient Greek philosophy and has been a staple of mathematical and philosophical reasoning and debate.

The ancient Greek philosopher Epicurus was amongst the first to promote the idea of justice as a social contract. The *Epicurian Paradox*, attributed to him by David Hume, questioned the nature of God and the problem of evil and is one of the ancient examples of a trilemma with contradictory choices (Hume 1779). C.S. Lewis’ formulation on the divinity of Jesus is another example from religion where only one of the three possibilities could be correct – Jesus as “*mad, bad, or God*” (Davis 2009; Lewis 1952). In the 2<sup>nd</sup> century AD, the Mahayana Buddhist philosopher Nagarjuna discussed the trilemma between cause and effect (Garfield 1995).

The Agrippan trilemma (reported by Sextus as comprising five “modes” and not three), and its later formulation by the German philosopher Hans Albert as the Münchhausen trilemma, delves on the theoretical impossibility of proving any truth, even in the fields of logic and mathematics, without appealing to accepted assumptions. A decision between multiple unsatisfying options is, therefore, unsolvable and the subject has to work with available knowledge, conjecture and criticism (Franks 2005; Albert 1985).

In law and politics, the feature of entrapment between choices was termed as a “cruel trilemma” and a precursor to the right against self-incrimination or more commonly known as the Fifth Amendment Right in the American Constitution (Rubinfeld 2005). The more recent ‘Brexit’ choices relating to the Northern Ireland Protocol and British participation in the EU Single Market, or Customs Union or a border in the Irish Sea has also been termed as the “Brexit trilemma” (Springford 2018). Keynes (1936), in economics, anticipated an uneasy choice between labor rights, full employment and stable prices. In business and project management, Arthur C. Clarke explained the impossible choices between quality, cost and speed of delivery (Clarke 1990). It is possible to envision a conflict along multiple dimensions in the energy-climate landscape, with nations having to choose and manage between multiple trade-offs.

### 2.1.3 The impossible energy trinity

The global energy trilemma, the challenge of achieving simultaneous improvements in energy access, affordability, and sustainability, has become one of the most critical issues facing policy-makers, industry leaders, and academics. The energy trilemma is particularly complex due to the intricate relationships and trade-offs between these dimensions. The traditional approach to addressing this challenge has been to focus on one or two dimensions at the expense of the others, resulting in unsustainable or unsatisfactory outcomes.

Other conceptualizations of this “trilemma” include energy security as a crucial dimension, and the Russia-Ukraine conflict has underscored the challenges associated with balancing the competing demands of security, affordability, and sustainability (Osička & Černoch 2022). The conflict has highlighted the vulnerability of Europe's energy supply, as Russia remains a major supplier of oil and gas to the continent. This has raised concerns about the potential for energy shortages and price spikes, as well as the need for Europe to reduce its dependence on Russian energy sources.

Moreover, the conflict has brought into focus the complex interplay between energy and geopolitics, with energy resources and infrastructure often being used as tools of political leverage, such as the example of the Nord Stream pipeline with Germany (Goldthau 2016; Barnes 2017; Misik 2022). This has led to renewed calls for energy diversification and investment in alternative energy sources, as well as greater collaboration among energy-producing and consuming nations to promote energy security and stability. While efforts to reduce Europe's dependence on Russian energy

sources could enhance energy security, they may also come at a cost to affordability and sustainability (Žuk & Žuk 2022).

When considering energy-climate policies, such as carbon pricing or emissions reduction targets, the trade-offs between these dimensions become even more pronounced. For example, policies that prioritize sustainability by incentivizing the use of renewable energy sources can increase energy costs and reduce affordability, particularly in the short term. Similarly, policies aimed at improving energy access and affordability in the Global South, such as subsidies for fossil fuels or electricity, can undermine efforts to reduce greenhouse gas emissions and achieve climate goals.

This essay aims to empirically investigate this conflict between seemingly unmanageable and intransigent energy goals, centering it around the explicit and implicit aspects in the UN Sustainable Development Goals. It focuses on the trade-offs and synergies between energy access, affordability, security, efficiency and sustainability under climate mitigation policy. Using empirical evidence from a detailed energy-climate model accounting for multi-sectoral interactions, it will examine the extent to which these dimensions can be improved together, and the conditions under which this is feasible. The results will provide recommendations for policymakers, industry leaders, and academics on how to address the interlinkages in a more comprehensive and sustainable manner under climate mitigation policies or carbon prices.

## 2.2 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 through 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).

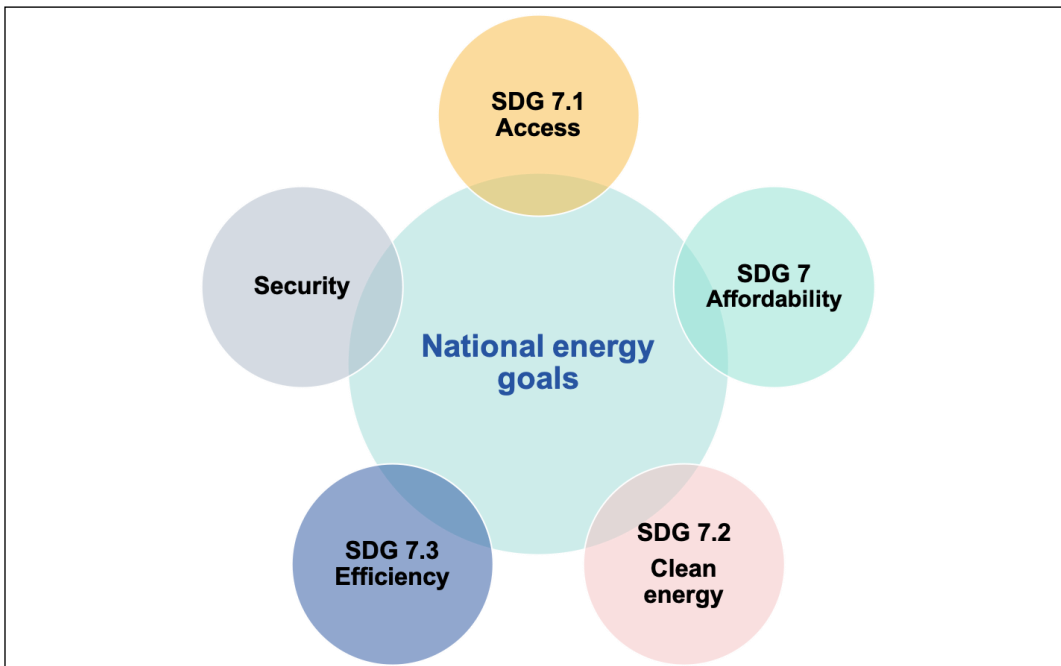
Projections of household energy use have been made assuming attaining higher living standards in developing countries (van Ruijven et al. 2011, Daioglou et al. 2012, Krey et al. 2012), or aspects of curtailment of consumption and income (Umit et al. 2019). Streimkiene et al. (2019) provides a comprehensive review of energy poverty impacts of climate policies in the EU. Guan et al. (2023) recently applied a multi-region Input-Output modeling approach to link the household energy affordability question to the energy security issues resulting from the Russia-Ukraine conflict, showing how cost of living pressures could push millions into impoverishment.

Further, while SDG-7 attainment has been a focus, it has scarcely examined 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.

### 2.3 Approach

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. This study, therefore, considers energy security to be an intrinsic, inseparable and unstated dimension of SDG-7 as in Iyer et

al. (2018) and Jewell et al. (2016). This analysis is limited 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, this study consider 5 national energy priorities to be attained by each pathway (Figure 2.1) and assess the effects for multiple global regions.



*Fig. 2.1: The 5 national energy priorities considered in this study, based on stated and implicit SDG-7 goals*

Integrated assessment models (IAMs) have played a key role in examining the energy trilemma, energy trinity, and related constructs in the context of climate policy. These models have been used to explore the complex trade-offs and synergies between different dimensions of energy and climate policies, including energy access, affordability, sustainability, and security.

While IAMs have considered synergies and trade-offs for UN SDGs, there has been less emphasis on the intra-SDG trade-offs and synergies within the energy trilemma and energy trinity constructs. While many SDGs have multiple dimensions with trade-offs, such as the goal of sustainable cities and communities, which must balance environmental sustainability, economic growth, and social equity, there has been less emphasis on the complex trade-offs and synergies within the energy trilemma and energy trinity constructs.

### 2.3.1 Model description

The alternative energy-climate policy options are represented through scenarios in this study, employing 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<sub>2</sub> 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<sub>2</sub>/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<sub>2</sub> 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. The floor area assumptions vary by regions, accounting for income elasticity and satiation levels (appendix A.1).

### 2.3.2 Scenarios modeled

One way to abstract from impacts of climate change in mitigation pathways is to explore sets of scenarios that achieve similar cumulative emissions, since they would likely have similar climate impacts. Such temperature-clustered scenarios could differ in terms of how they achieve their climate goal (timing, technology and instrument choices), and could therefore provide insights into corresponding costs and how they are distributed within society – across and within regions.

This study models a broad array of 17 pathways (Table 2.1) to the end-of-century climate goal of 1.5°C ( $\pm 2\%$ ), which vary by pace of transition (the global net zero CO<sub>2</sub> 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 (Appendix A.1).

**Table 2.1:** *List of scenarios modelled in this study*

<b>Scenario set</b>	<b>Criterion</b>	<b>Pathway name</b>	<b>Short description</b>
<b>I</b>	<b>Reference</b>	REF	The ‘business as usual’ or ‘no new policy’ scenario, the standard SSP-2 implementation in GCAM including Covid-19 GDP impacts
<b>II</b>	<b>Pace of transition</b>	NZ2040	Achieving global net zero CO <sub>2</sub> emissions in 2040
		NZ2050	Achieving global net zero CO <sub>2</sub> emissions in 2050
		NZ2060	Achieving global net zero CO <sub>2</sub> emissions in 2060
<b>III</b>	<b>Technology choices (generally, supply side changes)</b>	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 <sub>2</sub> )
<b>IV</b>	<b>Demand side changes</b>	ELE	Increased preference to electrification in buildings, industry & transport

		NoTrBio	Complete ban on use of traditional biomass in residential services
		BEH	Behavior changes & societal transformation (dietary shifts, demand reduction, transport behavior, smaller houses) (George et al. 2021)
		COMPR.	A representation of comprehensive energy policy using an “all of” approach. This 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, Fuhrman et al. 2023)
<b>V</b>	<b>Regional effort sharing</b>	C-OPT.	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
		SOVER.	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
		GR.FATH.	Based on the Grandfathering Principle, future emission rights & responsibilities based on 2015 levels
		HIST.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 scenarios modeled here are based on SSP-2 and involve the same trends except for those involving demand side measures. The floor space satiation levels are reduced across all high- & middle-income regions by 10-20%, limiting any increase in per capita residential floor space in those regions. We leave the floor space levels unchanged for low income regions, allowing for continued increase in energy services. The satiation levels for the low-income regions are higher than the decent living energy thresholds applied in Grubler et al. (2018).

The demand side measures modeled in the above pathways involve no cost to the system. This can be considered generally true for aspects such as ride sharing, meat or dairy consumption reductions, etc. although there would be an associated well-being cost which models are incapable of accounting for. Some other demand side options like efficiency increases beyond the SSP-2 ranges would involve higher spending on research, development and marketing of such products, and such changes to budgetary allocations by governments and private actors are also not explicitly modelled. Some dimensions of behaviour change including higher share of public transport or electric vehicles does involve increased government spending on providing infrastructure support by means of transfers to local governments and support for charging networks etc. These budgetary allocations or “within-GDP” changes are not accounted for in the policy costs of these actions and it is generally assumed that such spending reallocations between different sectors of the economy are balanced. As seen from the case of the recent Inflation Reduction Act in the US,

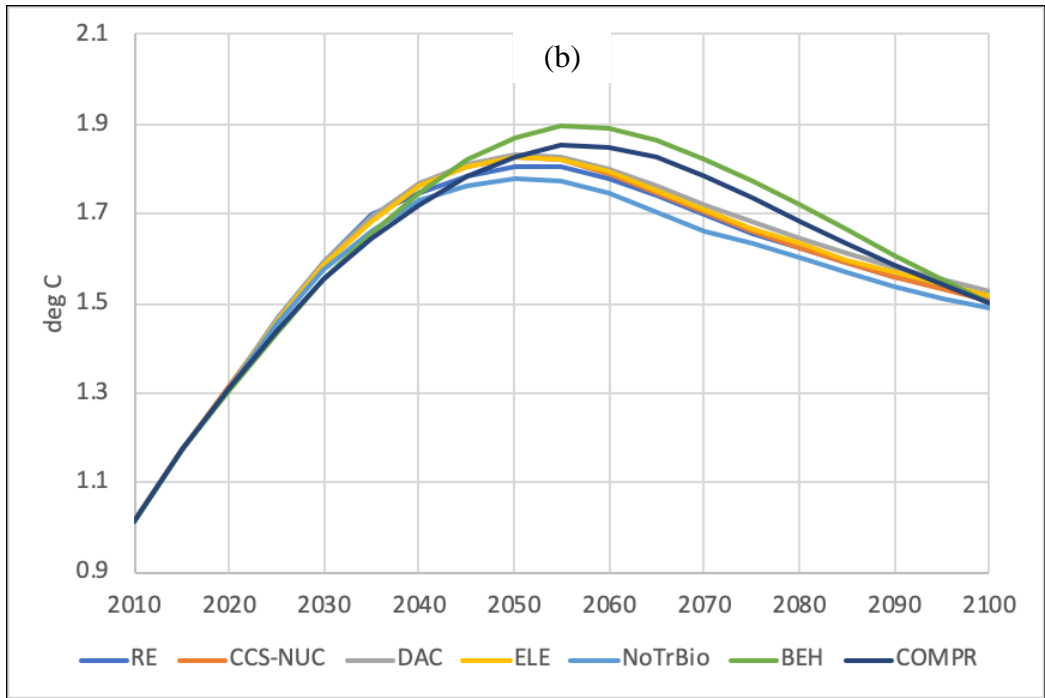
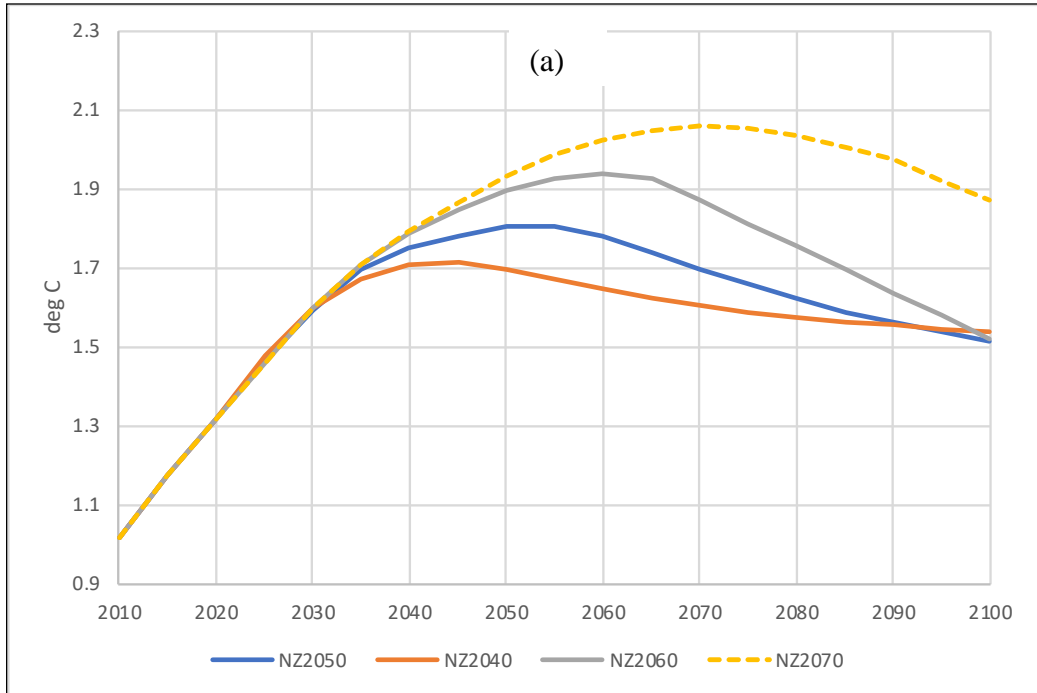
spending decisions and budget allocations for increased uptake of cleaner and more efficient options can come through different budgetary support mechanisms and modelling each would be beyond the scope of this analysis. There could also be demand side options which are simply cheaper to adopt for businesses, but legacy technology limits adoption. An example of this is the HFC reduction component based on the Kigali Amendment where industry bodies have mostly supported the changes since they enable better market outcomes, while also supporting cleaner technology adoption.

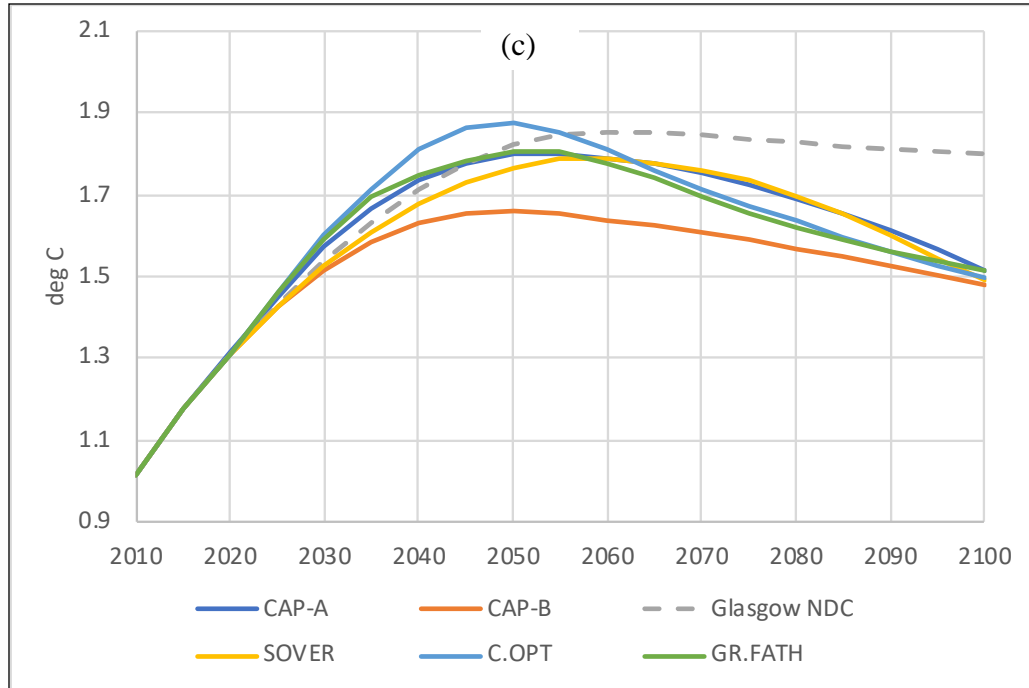
The regional mitigation effort sharing principles were adapted from van den Berg et al. (2019), as far as they relate to capability, grandfathering rule, sovereignty & historical responsibility. It is important to note here that relative to grandfathering, the ‘ability to pay’ or ‘capability’ pathways 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 (see IETA 2021, for example) 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.

The mitigation scenarios listed in Table 2.1 were modeled in GCAM and were all able to attain the 1.5°C goal in 2100 (Fig. 2.2 a-c).





**Fig. 2.2:** 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<sub>2</sub> emissions attained in 2070 failed 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.

### 2.3.3 Choice of metrics

For each mitigation pathway, this study examines the relative impacts for different regions across the 4 dimensions of SDG-7 targets (access, affordability, clean energy, energy efficiency).

Whilst several metrics have been used in the literature for each of these energy goals, this study applies the set of indicators listed in Table 2.2. These indicators, although not extensive, are broadly representative of the central dimensions sought to be achieved under each goal. It analyzes 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 (“REF” 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 2.2: National energy goals and corresponding metrics*

<b>National energy goal</b>	<b>Metric/ Indicator chosen for this study</b>
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, much 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 metrics of energy access (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.

This study employs 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. This study does not employ these thresholds here since the limits are dependent on regional context (Hererro 2017).

The quantum of clean energy is measured based on the share of renewable energy sources in the electricity mix. The analysis is restricted 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, the specific definition in SDG 7.3 which relates to energy intensity of GDP has been adopted, 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.

The share of imports as a metric for energy security has been included 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, this metric is not just reasonable, but also warranted.

## 2.4 Results

We demonstrate and discuss the results for the 4 major regions (USA, EU-15, China & India) in this section (Fig. 2.3 a-d) and supplement these observations with additional results for other developing and underdeveloped regions of interest in the SI (Appendix A.2 shows results for South Africa, Western, Eastern & Sub-Saharan Africa, Indonesia & Brazil).

Across any 1.5°C mitigation scenario varying merely by pace (Fig. 2.3(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 REF 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 are 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 A.3).

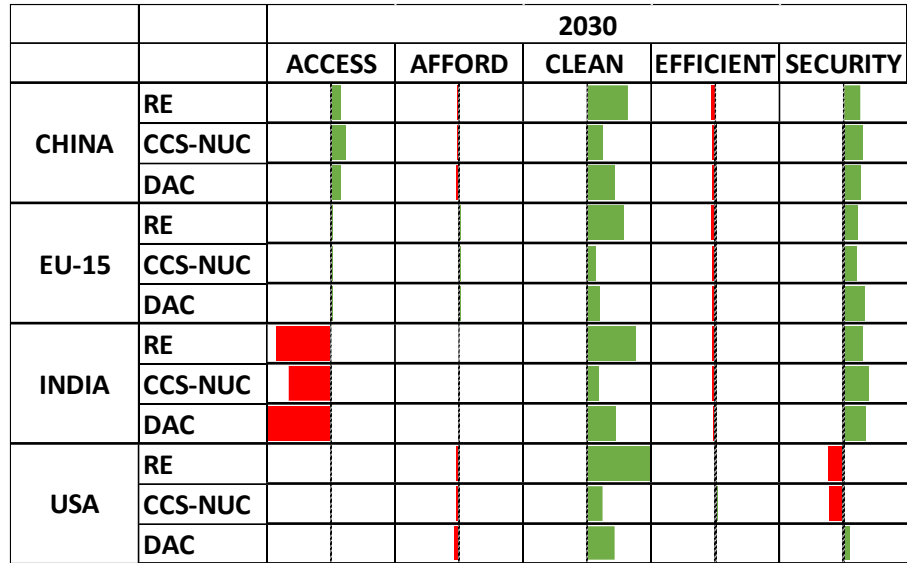
		2030				
		ACCESS	AFFORD	CLEAN	EFFICIENT	IMPORT
CHINA	NZ2040					
	NZ2050					
	NZ2060					
EU-15	NZ2040					
	NZ2050					
	NZ2060					
INDIA	NZ2040					
	NZ2050					
	NZ2060					
USA	NZ2040					
	NZ2050					
	NZ2060					

**Fig. 2.3(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 CO<sub>2</sub> emission year for key regions. The synergies and trade-offs are measured ‘relative to reference’, as ratio of the metrics (from table 2.2) in the given scenario to same metrics in the REF scenario

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. 2.3(b)).

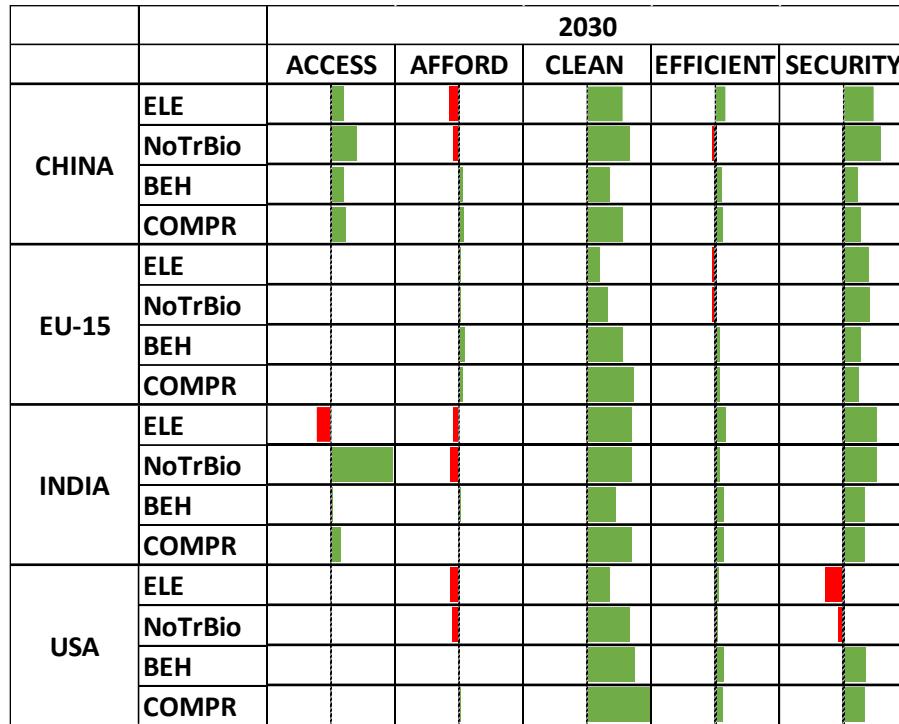
In the long term, some of these pathways do improve access levels in China, but not in other developing regions. On the other hand, pathways which promote electrification or eliminate the use of solid fuels like traditional biomass, significantly improve the access related metric across all region. The 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 can demonstrate synergies across all dimensions for all regions.



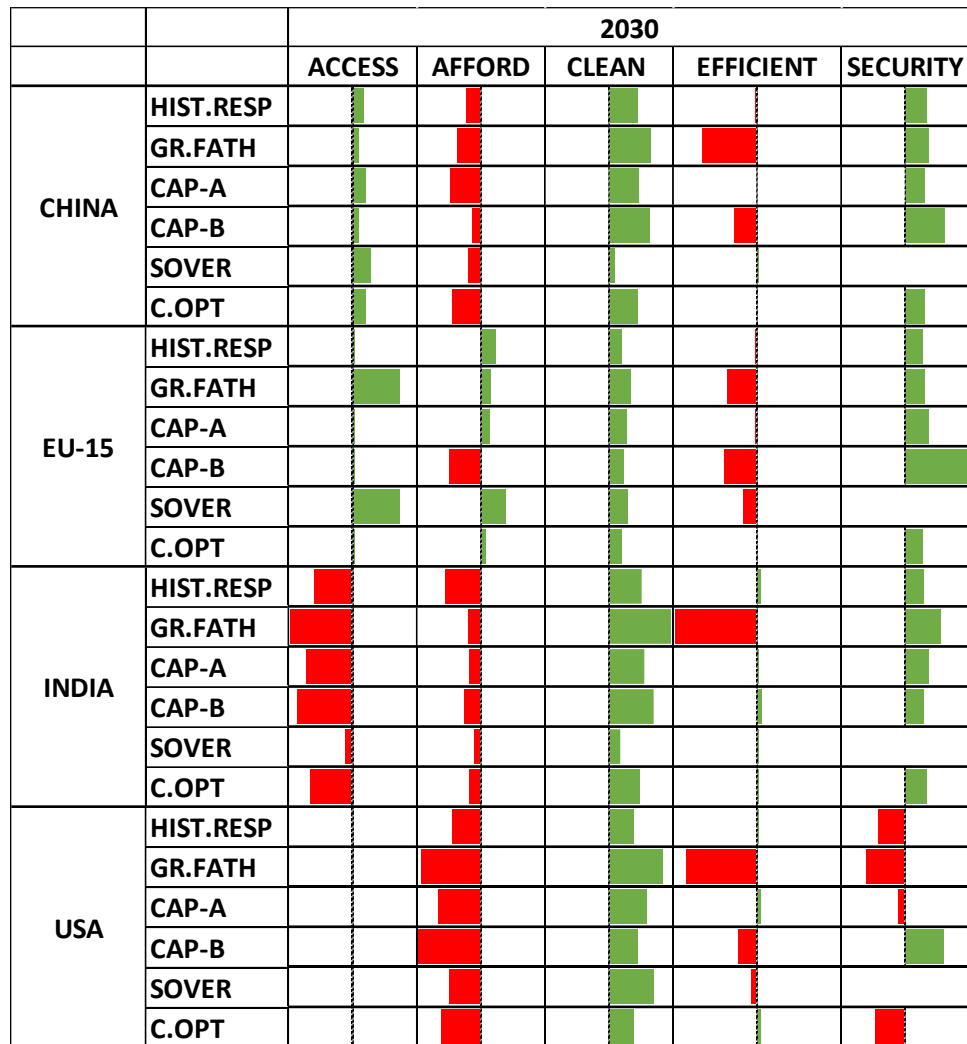
**Fig. 2.3(b):** *Magnitude of synergies (green bars) and trade-offs (red bars), relative to reference, across national energy goals in the near term (2030) for pathways varying by supply side technology choices for key regions*

For pathways based on demand side changes, we observe synergies across all dimensions, especially for the Global South (Fig. 2.3 c). The near-term co-benefits are strengthened in the long term as well (Appendix A.3).



**Fig. 2.3(c):** *Magnitude of synergies (green bars) and trade-offs (red bars), relative to reference, across national energy goals in the near term (2030) for pathways varying by demand side mitigation options for key regions*

The final set of pathways based on regional effort sharing also shows losses relative to REF for developing regions, especially in pathways applying principles such as grandfathering (Fig. 2.3 d).



**Fig. 2.3(d):** *Magnitude of synergies (green bars) and trade-offs (red bars), relative to reference, for pathways across national energy goals in the near term (2030) varying by regional effort sharing principles employed*

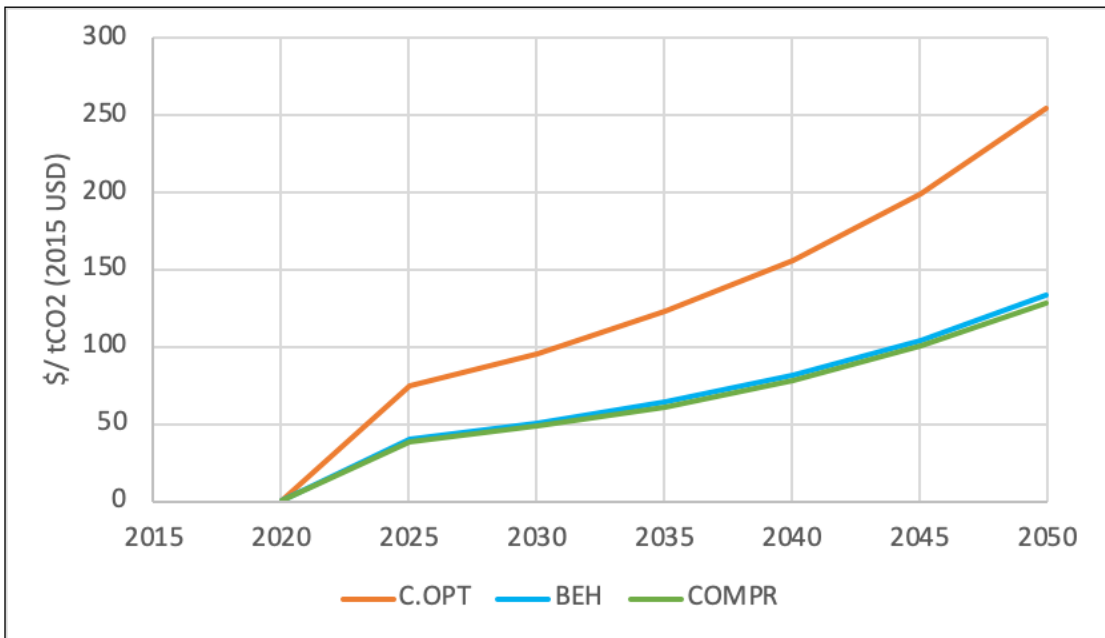
While financial transfers based on historical responsibility alleviate some of these compromises, the increased consumption levels lead to household affordability trade-offs. The unfairness of the grandfathering principle is matched by the results for the Global North when stringent pathways involving financial transfers or expedited net zero commitments are imposed. Self-determined pathways like the NDCs (represented by SOVER.) do have relatively minor effects for India due to low

ambition in the first commitment period, but the increased mitigation ambition later in the century also increases the strength of observable trade-offs. Pathways emphasizing shift in mitigation burdens based on development or income levels (CAP-A & B) levy significant affordability trade-offs for the Global North regions due to the rapid phaseout of fossil fuels and linked higher carbon prices in those regions. Allowing for financial transfers between regions to compensate for the historical responsibility of emissions and climate impacts does reduce some of the access related trade-offs in the Global South. However, this mechanism by itself is insufficient to improve access levels in most cases.

These general results and trends also hold for other major regions shown in the SI (Appendix A.2). 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.

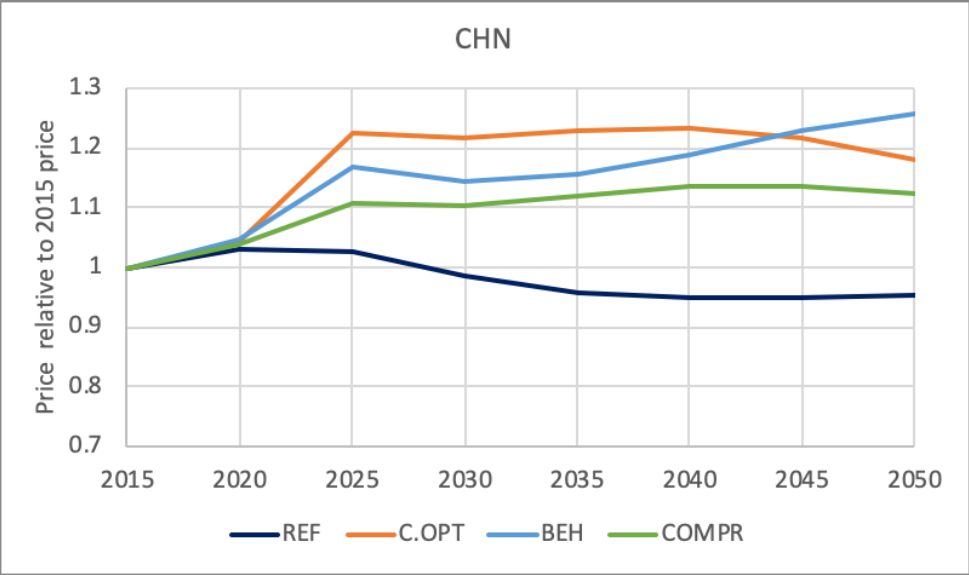
## 2.5 Discussion

Depending on the technology choices and marginal cost of mitigation varying between regions, the global (and regional) carbon prices vary across the scenarios modeled. An example of the global (shadow) carbon price and its significant variation across scenarios can be seen between the cost optimal pathway to 1.5C, which has about \$250/tCO<sub>2</sub>, relative to prices of less than \$150 for pathways employing behavioral and demand side shifts (Fig. 2.4).

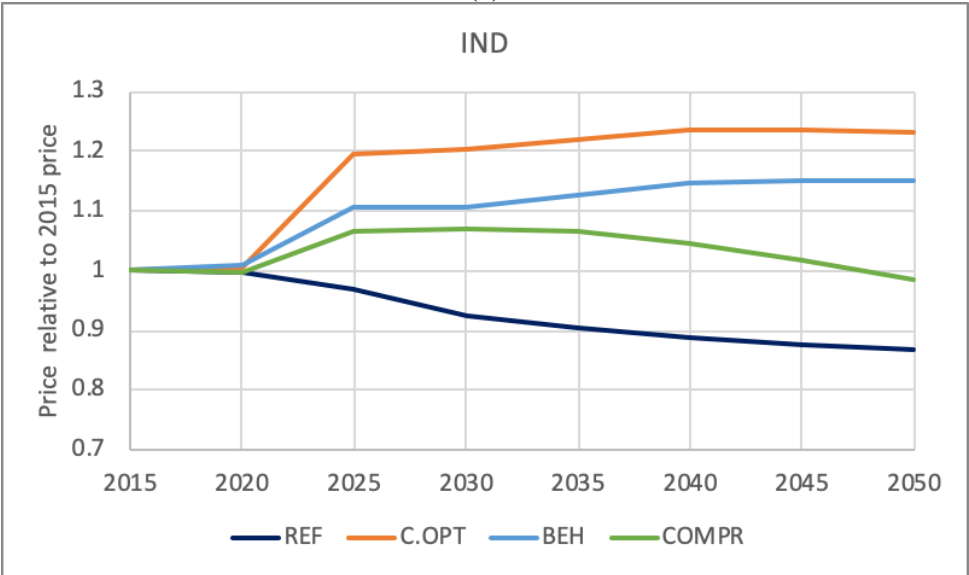


*Fig. 2.4: Global carbon price variation between key scenarios modeled*

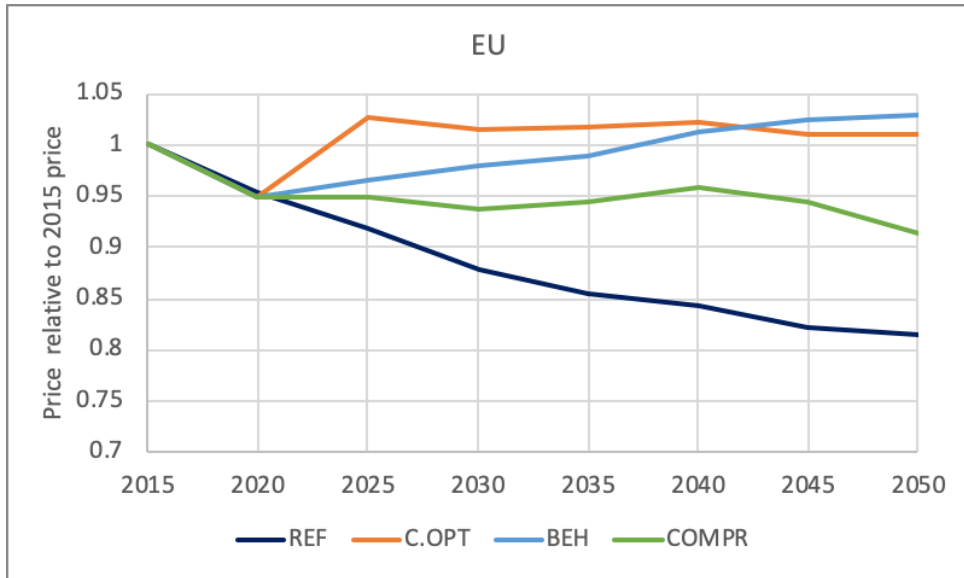
The shadow carbon price gets reflected in the prices of carbonaceous fossil fuels across regions. A representative trend of these variations for household electricity in different regions is shown the panel (Fig. 2.5 a- d). Mitigation scenarios always have a higher price than the REF case. It is interesting to note here that pathways involving demand side shifts (BEH & COMPR) tended to have lower energy prices relative to cost optimal pathways or those dominated by other technologies. After 2040-2045, with rising demand for electrification and phaseout of fossil fuels from other sectors driving demand for electricity, we find increase in prices. However, the weighted average costs of all fuels for residential services across regions remains lower than the C.OPT scenario (Fig. 2.6 a-d).



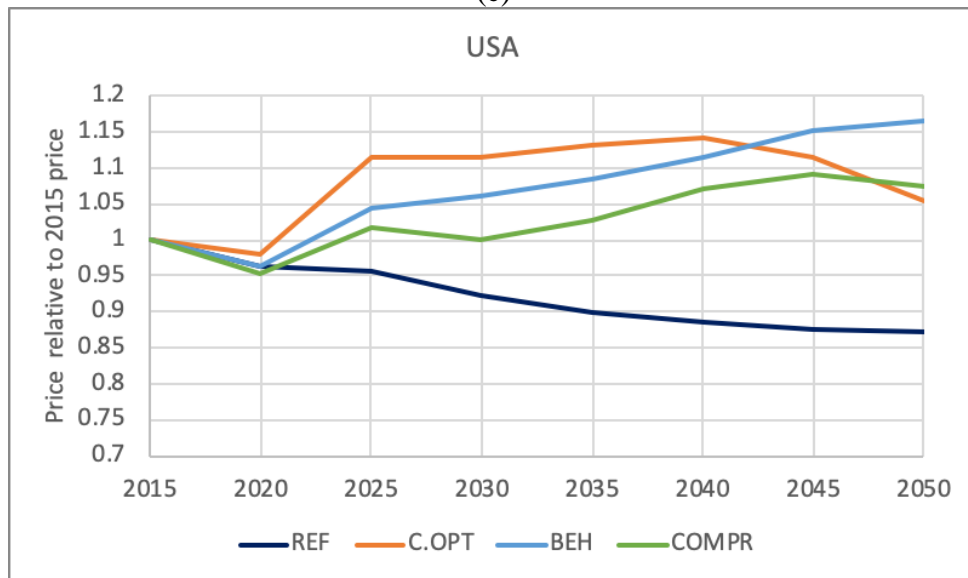
(a)



(b)

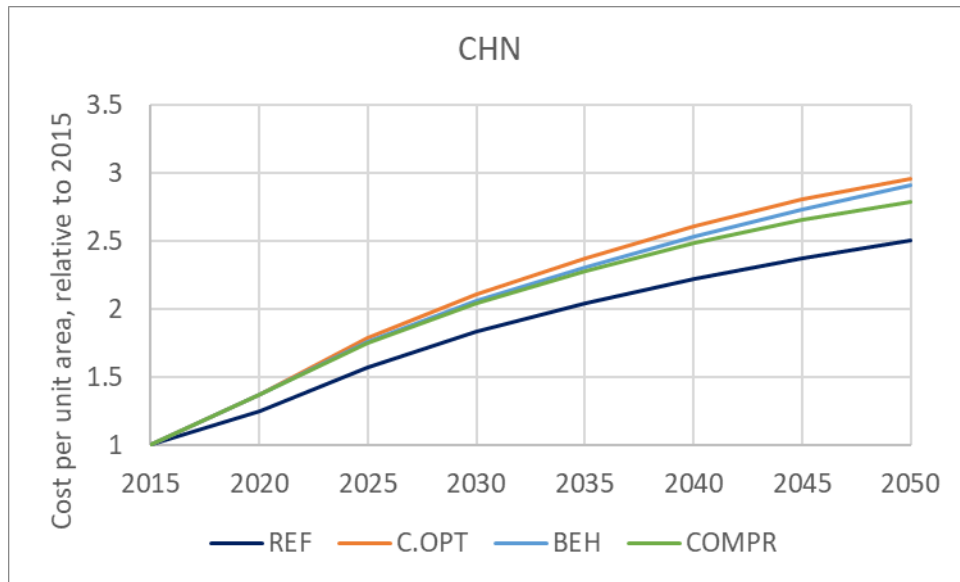


(c)

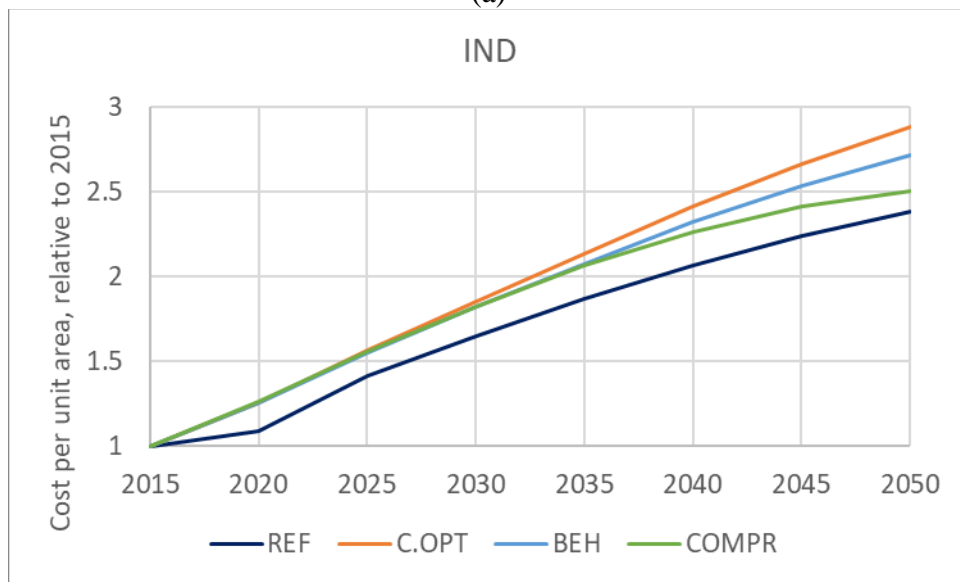


(d)

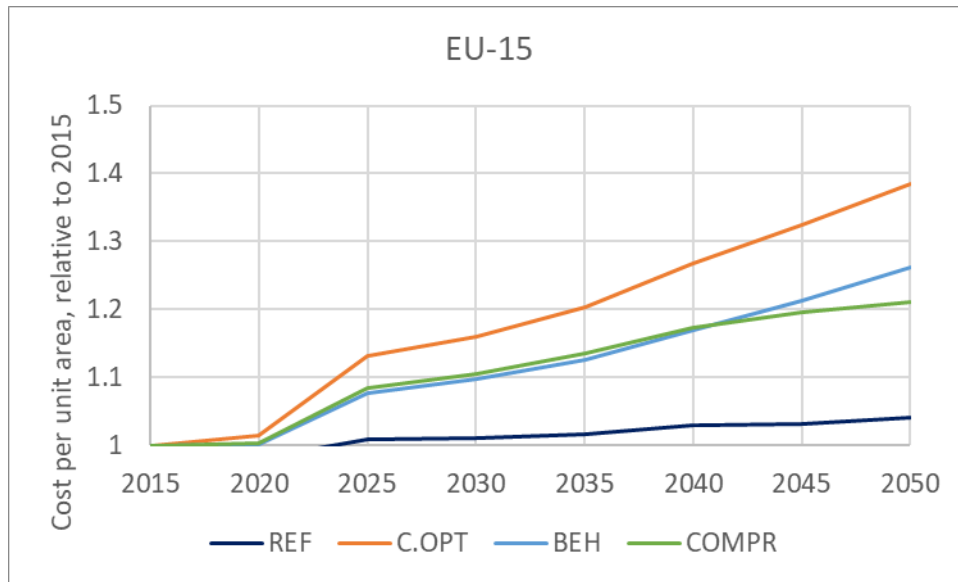
**Fig. 2.5 (a-d):** Electricity prices to residential sector across key scenarios, for the Global South (a- China, b – India) and the Global North regions (c- EU15, d-USA)



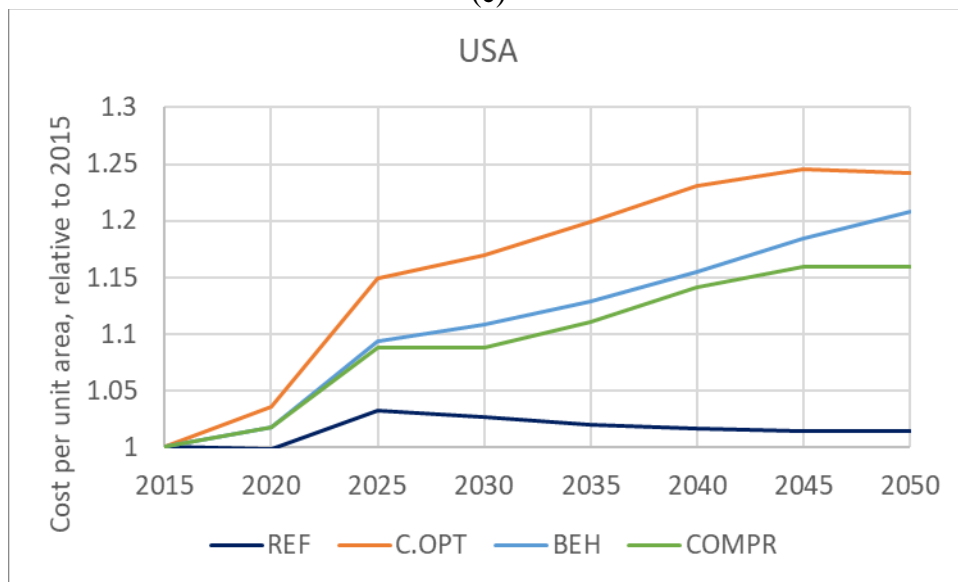
(a)



(b)



(c)

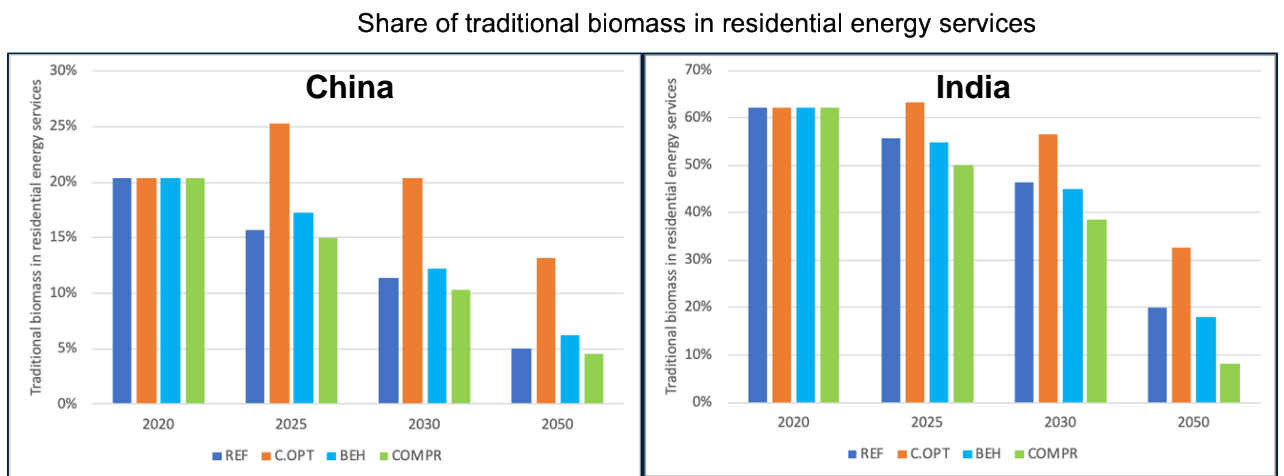


(d)

**Fig. 2.6 (a-d):** Weighted average energy services prices per unit area, to residential sector across key scenarios, for the Global South (a- China, b – India) and the Global North regions (c- EU15, d-USA)

With relative changes to fuel prices, households choose between options in each scenario and time period depending on income & price elasticities in the model. A critical point to note here is that high fuel prices affect energy access in regions of the

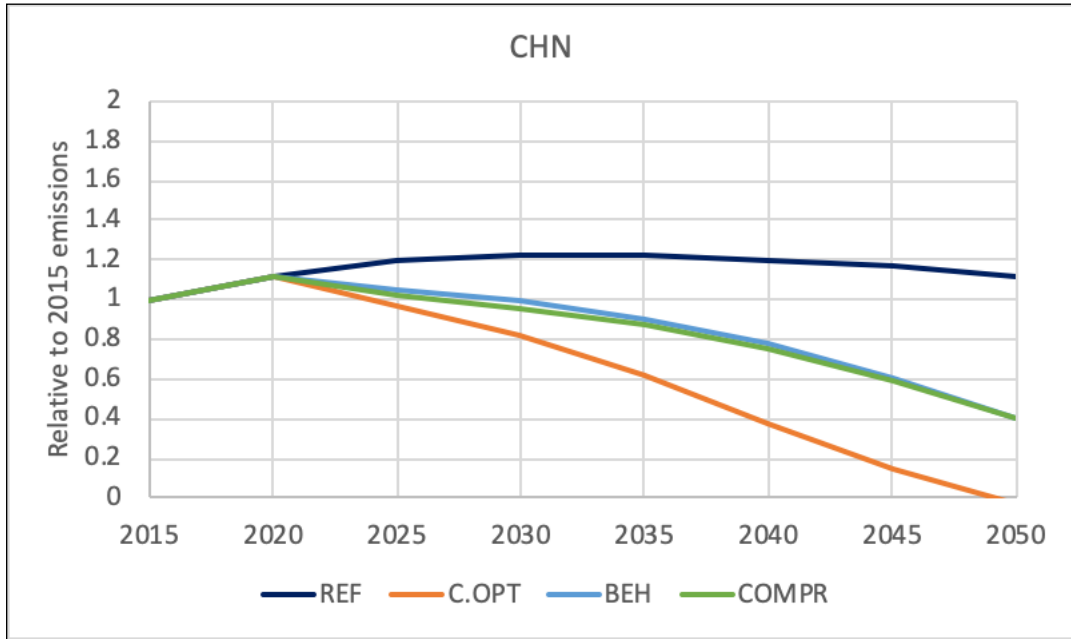
Global South, driving up the share of residential energy consumption from cheaper traditional biomass sources. This is especially notable in the near-term spike in share of traditional biomass in both China & India in the C.OPT pathway. However, demand side mitigation options involving lower carbon prices overall, allow for these regions to continue their trend of reduction in traditional biomass use, and even achieve reductions beyond the REF scenario (Fig. 2.7). We do not see such effects in the Global North, however, given the almost negligible amounts of traditional biomass use in residential sector.



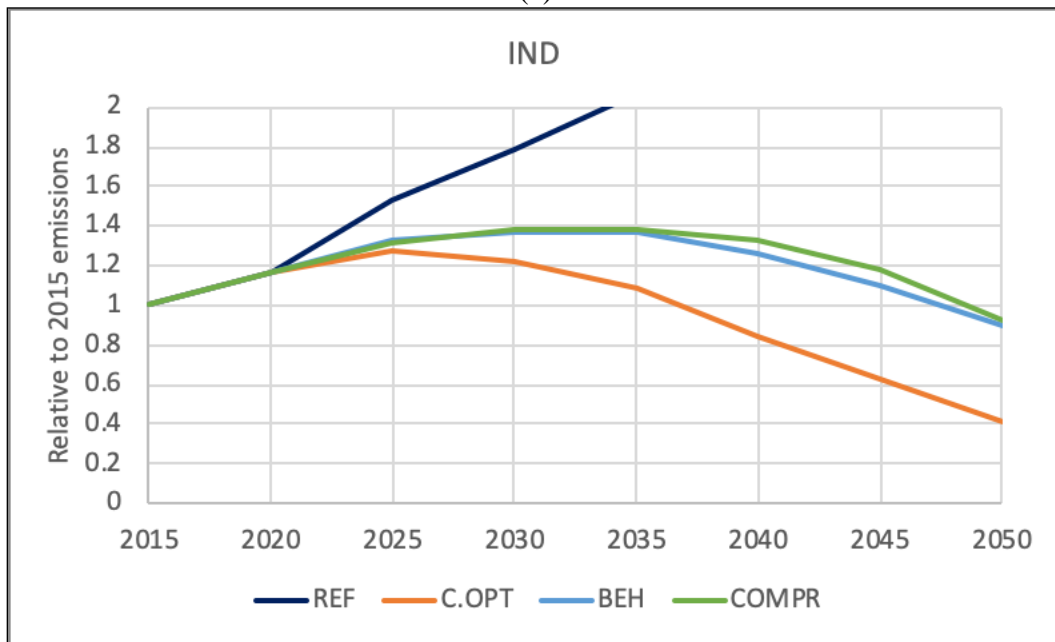
**Fig. 2.7:** *Share of traditional biomass (0-100%) in residential final energy consumption in China & India across scenarios*

Scenarios which involve significant behavioral and/or demand side mitigation policies also redistribute the global mitigation burden, reducing the consumption related emissions of the more affluent Global North. Another chunk of significant GHG reductions is effected through non-CO<sub>2</sub> gases, especially those related to meat consumption and use of HFCs regulated under the Kigali Amendment. These changes

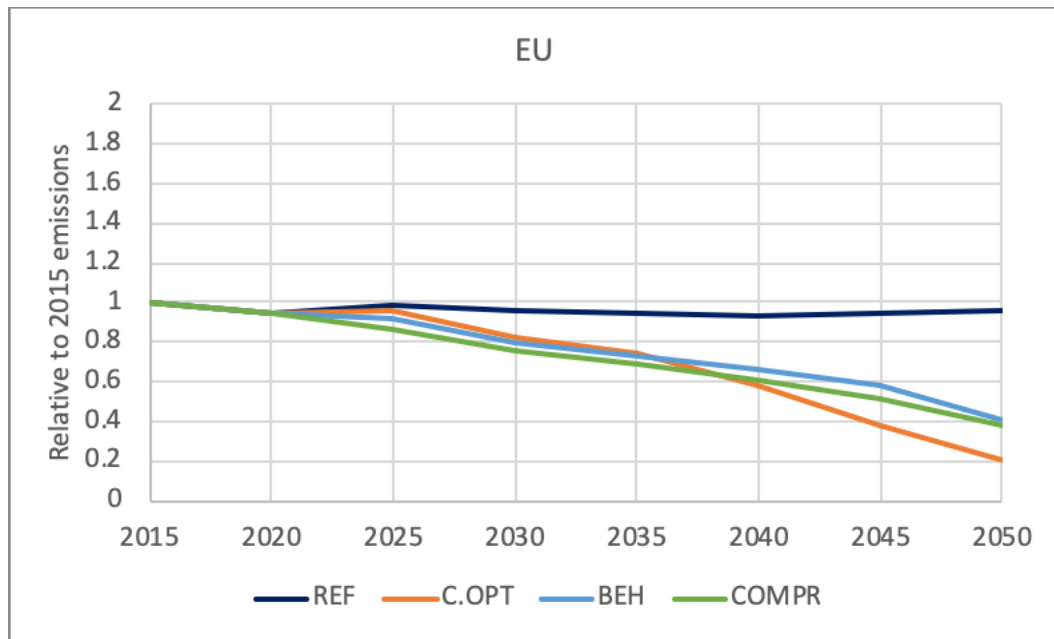
rearrange the CO2 emissions reduced for the 1.5C carbon budget, and relax the emission constraints on the Global South.



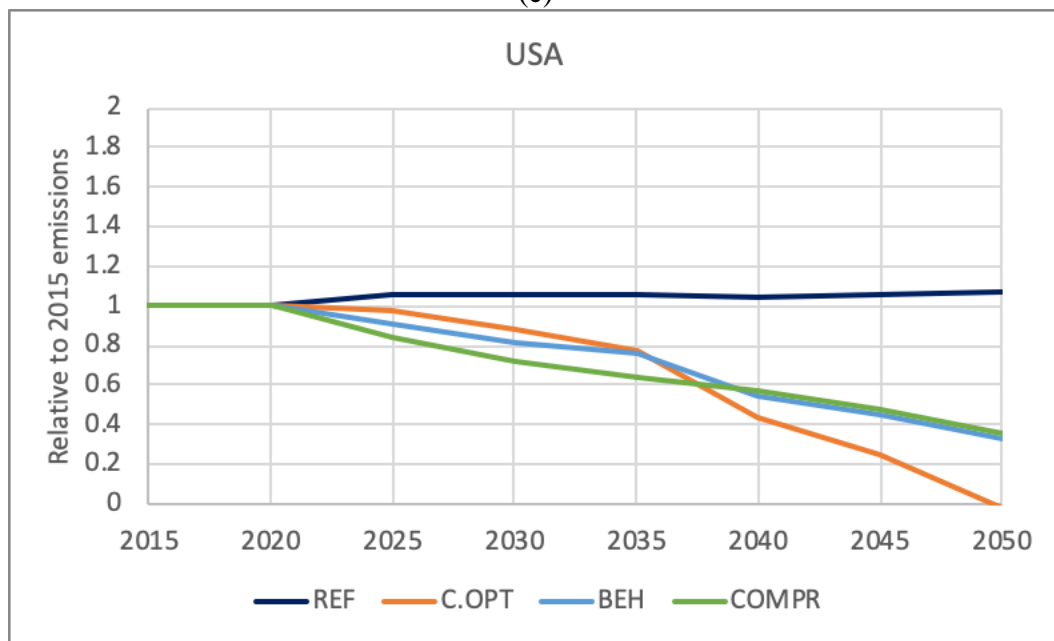
(a)



(b)



(c)



(d)

**Fig. 2.8 (a-d):** Net CO<sub>2</sub> emissions in different global regions relative to 2015 levels in key scenarios

With higher mitigation now possible in the Global North (Fig. 2.8 c, d), a “carbon space” is created for regions like China & India (Fig. 2.8 a, b) resulting in BEH & COMPR scenarios having higher CO<sub>2</sub> emissions for those regions. It is notable in the

case of India when the new constraint allows it to continue to a peak emissions level till 2030-35 (albeit still significantly lower than the REF case in terms of absolute emissions).

The shift in peak year for BEH & COMPR relative to CO pathways is observed across other developing regions as well (Table 2.3), with most regions seeing an additional carbon space being available for about 10-15 years.

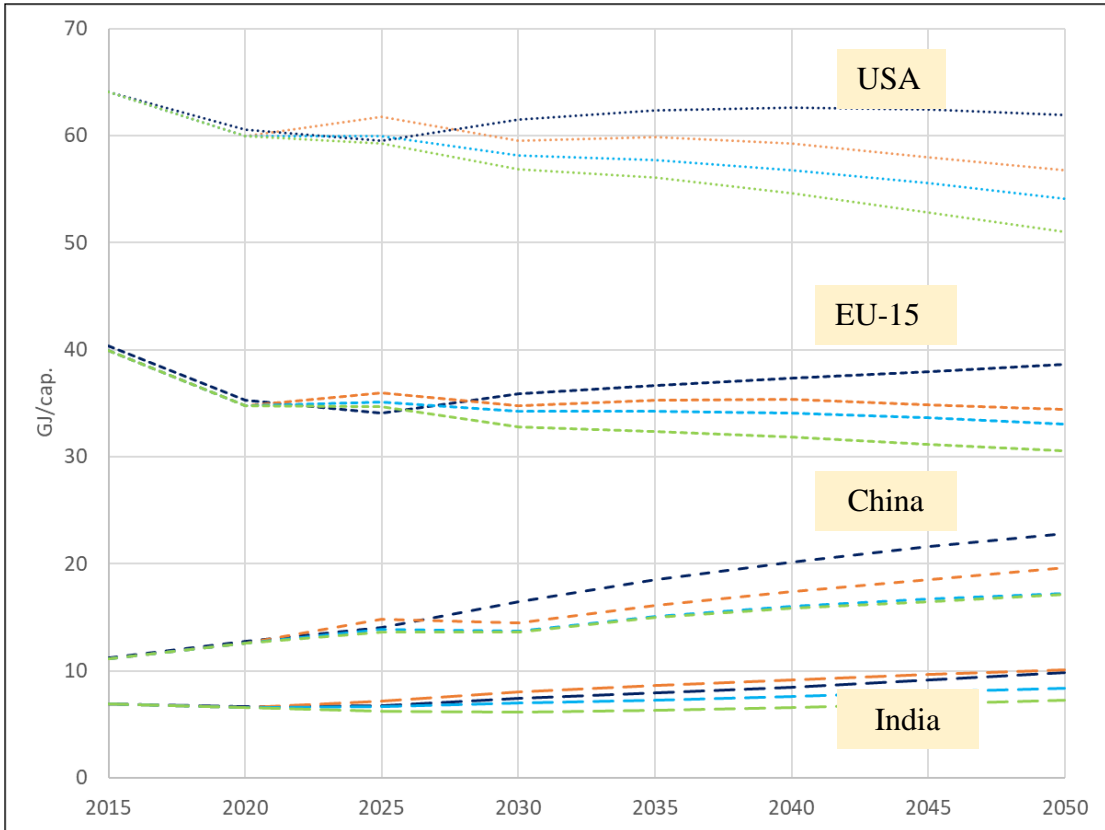
*Table 2.3: Shift in peak year across scenarios*

Region/ Scenario	<b>C.OPT</b>	<b>BEH</b>	<b>COMPR</b>
Africa_Eastern	2015	2025	2015
Africa_Northern	2020	2030	2035
Africa_Southern	2015	2035	2030
Africa_Western	2015	2030	2030
Brazil	2015	2015	2015
China	2020	2020	2020
India	2020	2030	2035
Indonesia	2020	2035	2035
Mexico	2020	2020	2020
Middle East	2020	2025	2020

This “carbon space” balances the mitigation portfolio between the Global North & South, allowing improved access to cleaner energy services and improved human well-being in the regions which need it the most. This is a key reason why demand

side mitigation options enable the possibility of attaining social & mitigation goals together, at a much lower cost. This explains the results we see in figs. 2.3 (c) and 2.7, with improved access to energy services, improved affordability, and synergies across all national energy goals attained in some pathways.

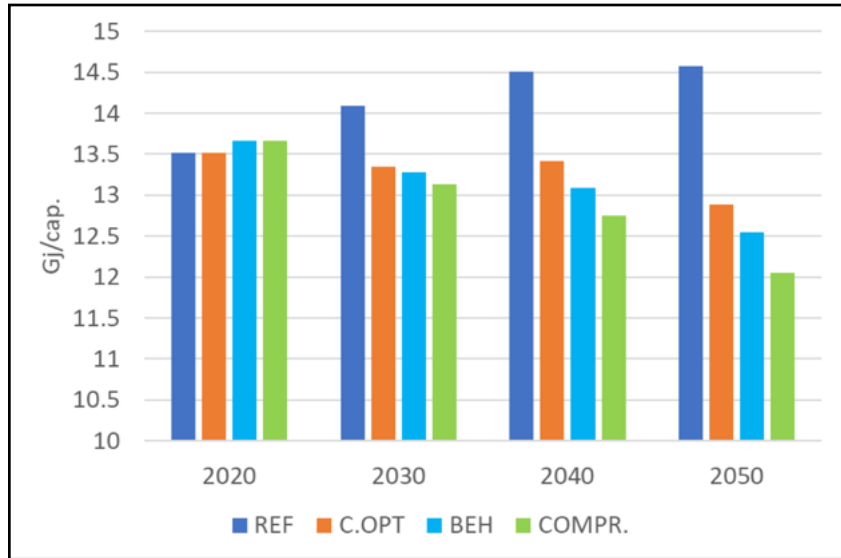
Demand side mitigation also reduces the overall residential energy service consumption significantly in the Global North, indicating the reduction in “affluent” or “luxury” emissions. It must be noted here that these reductions are without major impact on comfort levels in regions which consume services at 3-4 times the global average. In contrast, BEH & COMPR scenarios allow for notably smaller percentage reductions for the Global South, indicating some degree of increased convergence in energy services might be attainable without compromise on climate goals (Fig. 2.9). Addressing such global inequity is important for enhancing mitigation ambition in many regions.



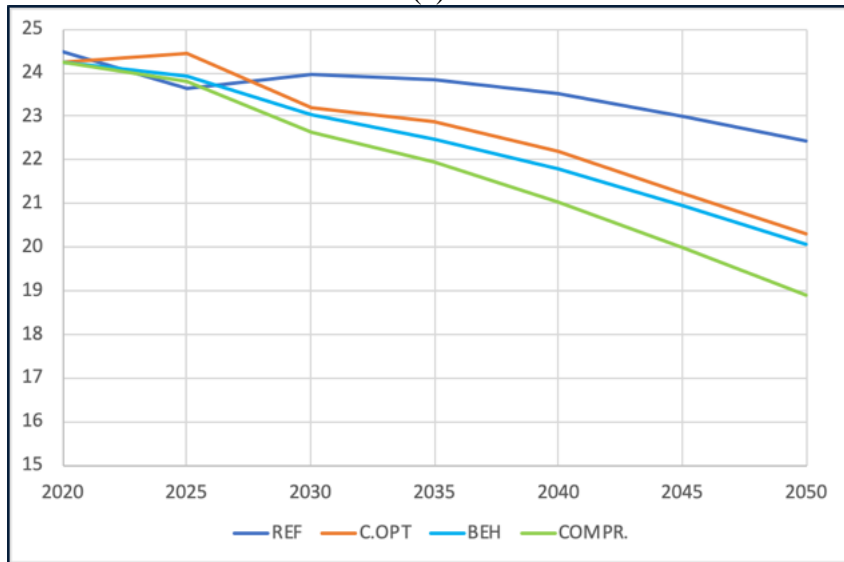
**Fig. 2.9:** Residential energy service output across scenarios for different regions and gradual convergence

We observe greater convergence of energy service levels across regions, as measured by the root mean square of differences or error (RMSE) between average residential energy service levels across regions and the global average (Fig. 2.10, panel a). A lower RMSE indicates less dispersion from the central value and reduced inequality. These results are also validated in terms of the standard deviation of the mean residential energy consumption across regions from the global mean (Fig. 2.10 panel b). Whilst the convergence seen here is rather small, it does indicate the possibilities around BEH & COMPR pathways where demand reduction is a means to reducing

global inequities in energy consumption & energy services. The demand side reductions are moderate compared to the ranges in IPCC AR6 scenario ensembles, and there remains scope for much greater degree of convergence in service levels with strengthened assumptions on demand reduction.



(a)



(b)

**Fig. 2.10:** RMS of deviations of regional average residential energy service levels against global average (panel a) and standard deviation of differences between regional and global average residential service levels (panel b)

## 2.6 Conclusions

### 2.6.1 Key findings

Based on the results showcased in the previous section, this study finds that climate change mitigation 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, it 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.

Another aspect to note here is the reduction in non-CO<sub>2</sub> emissions in pathways like BEH & COMPR from diet shifts and HFC (Hydro-fluoro carbon) emission reductions. The enhanced action on non-CO<sub>2</sub> 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 countries in the Global North seek to implicitly argue for and follow it. We show that such a principle is extremely unfair for the

regions which have very limited carbon footprints and fall well below the global average in terms of energy services consumed. 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.

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. Such pathway design, incorporating the distribution of capability, responsibility and equity, can enhance participation in international mitigation efforts and enhance global mitigation ambition.

#### 2.6.2 Limitations

However, a few caveats must be noted. Different trade modeling paradigms could lead to different estimates of imports/exports even in the same set of scenarios and the framework within GCAM could affect those results related to the “energy security” characterization here. Second, this study only examines fossil fuel imports and exports in the indicator of energy security. Trade in other fuels (e.g., bioenergy), technologies (e.g. solar cells, batteries and key metals) may be much more important in the future from the point of view of security of the national energy

supply chain. Likewise, this study looks at only the sovereignty perspective of energy security and other perspectives of energy security such as diversity of supply; reliability of supply may very well be important.

Limitations also exist with the IAM approach used here, the limited consideration of energy use in households to electricity, cooking and excluding transport and other services which may also constitute a share of household energy spending. There is also a limitation with the modeling of household decisions on energy use versus other priorities in the IAM and the lack of consideration of appliance ownership. However, these risks are largely mitigated by the consistent framework adopted here. Further, since the question explores only relative effects between pathways, the risks should not be debilitating, and the overall conclusions should hold good.

Despite these risks, the question formulated, and approach proposed is still able to provide generalizable and policy relevant insights, which is the goal of this study.

## Chapter 3: Mitigation Pathways to Attain Progressive Energy Burden Outcomes for the Poorest

### 3.1 Introduction

#### 3.1.1 Inequity and climate policy

Whilst the decarbonization of the global economy could bring immense benefits at the aggregate level and specifically to many individuals and groups, it may also be disruptive and costly for some, at least in the short term. Vulnerable sections would face those inequities which could evolve into further inequalities, unless addressed by the policy process. The ‘Yellow Vests’ protests in France expressed, among other things, a growing sense of anger at the fact that the country’s increasingly cash-strapped and precarious working and lower-middle class, was unjustly being made to pay for the energy transition. The climate justice issue is increasingly being framed as one that cuts across national borders. The tension is more and more between a minority of super-rich individuals with high-carbon lifestyles, and a mass of poor people who are least responsible for the climate crisis but suffer the most from its effects and are disproportionately made to pay for climate mitigation and adaptation measures. It is also possible that climate policies may drive further inequality through elite capture.

Income inequality has received increasing attention in the media and popular literature recently, with bestsellers like *Capital in the 21<sup>st</sup> Century* and *The World*

Inequality Reports prominent examples (Piketty 2018, Chancel et al. 2022). Income inequality has also been shown to be driver of mass protest movements, uprisings and political insurgencies in the last 15 years (Ortiz et al. 2022a, 2022b). There has also been an examination of how the climate and environmental crises, and efforts to address them, are accentuating inequalities between the rich and poor. Examples include works that question the incentives and privileges provided to the rich as part of California's climate policy, calling it a version of 'Green Jim Crow' enactment (Hernandez 2021) or how disproportionate subsidization of the high carbon lifestyles and energy-related services for some classes represents a 'clean tech privilege' in Washington (Boucher & Merida 2022).

Climate policies can affect income inequality through multiple pathways, including skewed benefits of subsidy or incentivization programs, limiting employment opportunities for certain populations and regions, stranded assets and job losses in certain sectors, lost investments and pension funds, changes to property values and use due to zoning regulations, lost subsidy programs, the higher cost of energy and food, reduction in public funded programs and downstream effects on healthcare & education in vulnerable communities etc. There are recent modeling studies on how income inequality could increase with climate change (Jakob & Stekel 2014, Hsiang et al. 2017, Diffenbaugh & Burke 2019) and how addressing income inequality could even be a means to limit climate change impacts (Rao & Min 2019).

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).

### 3.1.2 Research objective

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). Taken together, the above studies have mostly drawn general insights at the aggregate global level without addressing regional differences in detail. However, knowledge gaps remain on distributional dynamics along income classes, or effects within countries in terms of changes to the energy burden. Assessment of impacts at the household level is needed to investigate attainment of sustainable development for all.

In chapter 2, it was shown that 1.5C pathways emphasizing judicious effort sharing and demand side shifts enable attainment of multiple national energy goals. Such pathways do enable more equitable global impacts of mitigation. However, the within-region distribution of impacts of mitigation policy still remains unexplored for

those pathways. Do the findings hold true for the most vulnerable and poorest within the Global South, or even the North?

In this chapter 2, we build on the modelling in chapter 2 to downscale the impacts on energy consumption by income strata and extend it to consider the household energy burden within those strata and argue that it is a better representation of the actual distributional impacts felt by the vulnerable.

### 3.2 Current Literature

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, Klinsky & 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.

### 3.3 Methodology

Since the average household effect in a region would rarely represent the actual distributional effects, this study explores 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 USA, it uses 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, it employs the nationally representative and detailed India Human Development Survey or IHDS-II (Desai & Reeve 2018). While the use of survey data from almost a decade ago is a possible limitation, 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, this study showcases the differences in access and affordability for households in different income deciles. For this, it uses 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). The log-normal distribution has been the most commonly used and established (Souma 2001, Darvas 2019, Sahasranaman

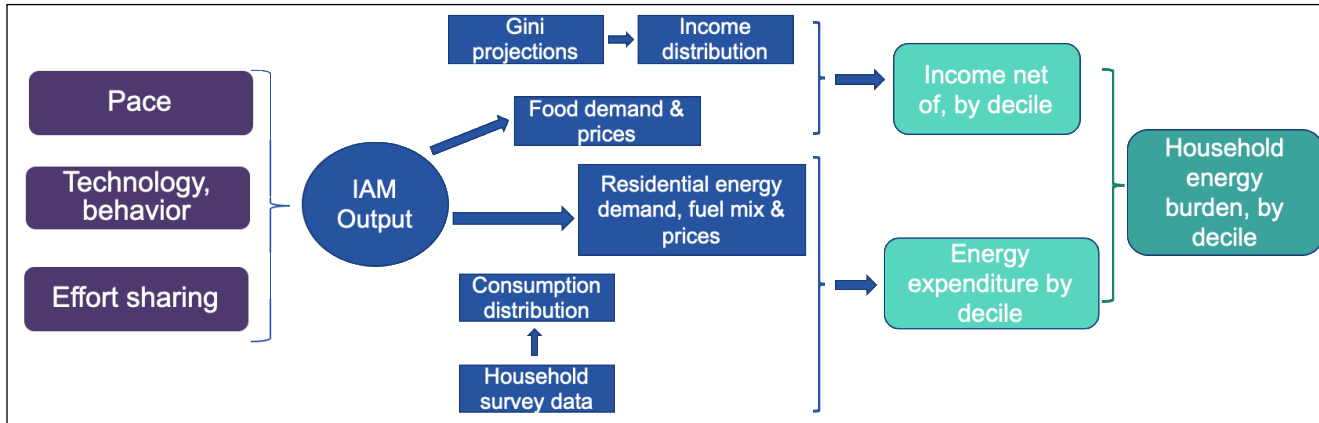
& Kumar 2020, Sahasranaman & Jenkins 2021). Some recent research has also showcased limitations of the log-normal approach (Narayan et al. 2023). These limitations on data & computational aspects are unlikely to affect the major findings since the directional trends would remain similar.

The decile level income projections are computed from the Gini projections and ‘net income’ for a household in each decile is computed after accounting for the food expenditures. 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.

For the numerator in eqn. E.1, the output fuel mix for the residential sector in a region is distributed based on the consumption demand by deciles obtained from the household survey data. Thus, the household energy expenditure by each income decile is computed. The outcome variable of interest here is the household energy burden, computed as:

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

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 REF scenario.

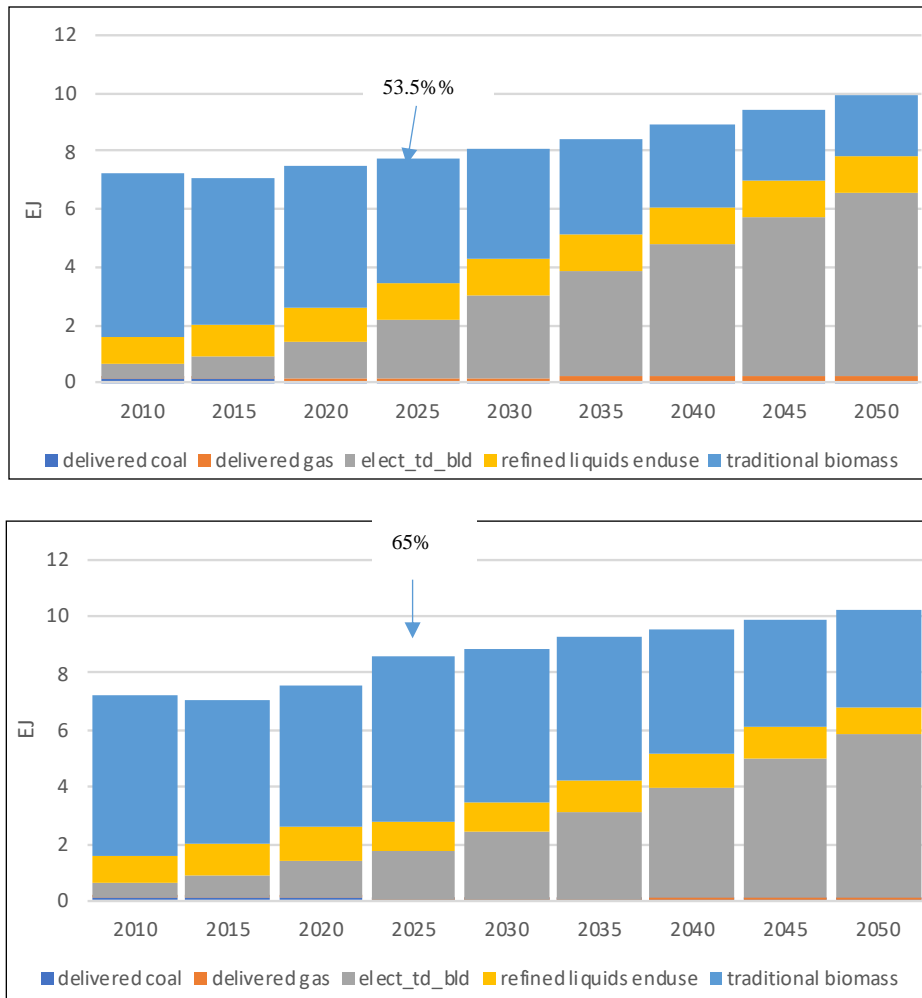


*Fig. 3.1: Flowchart of approach from downscaling scenario results in combination with income distribution and household survey trends*

### 3.4 Results

Given the varied climate policy assumptions and regional burden shares, each scenario has differing trends in residential fuel prices and consumption levels, which would lead to divergent trends in consumption and spending levels for households in different income tiers. 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. 3.2)

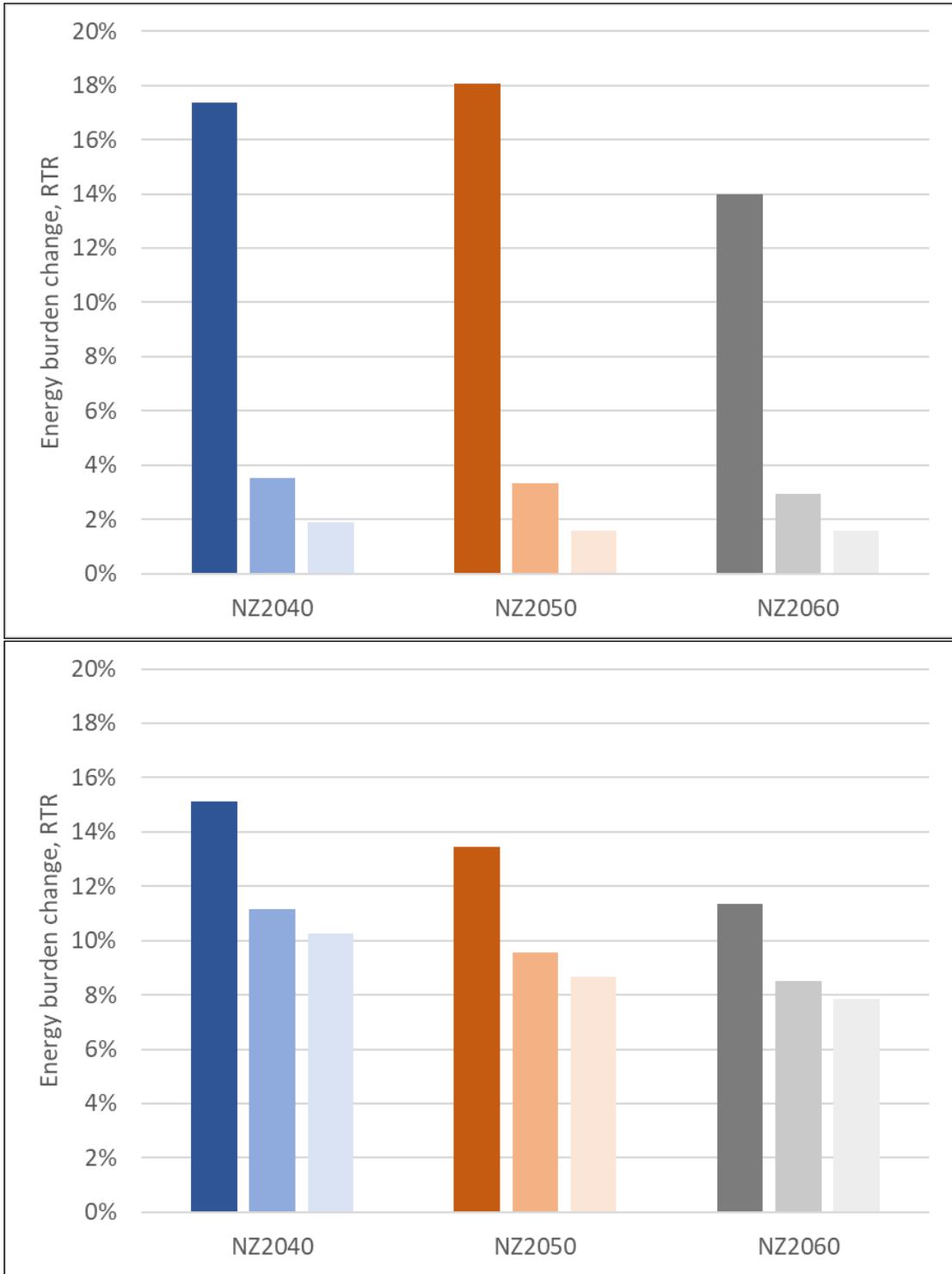


**Fig. 3.2 (a-b):** The top panel (a) shows the residential energy fuel consumption in India for the reference scenario while the bottom panel (b) represents the same for the cost optimal mitigation pathway to 1.5 deg. C. The arrows indicate the share of traditional biomass in total residential energy 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.

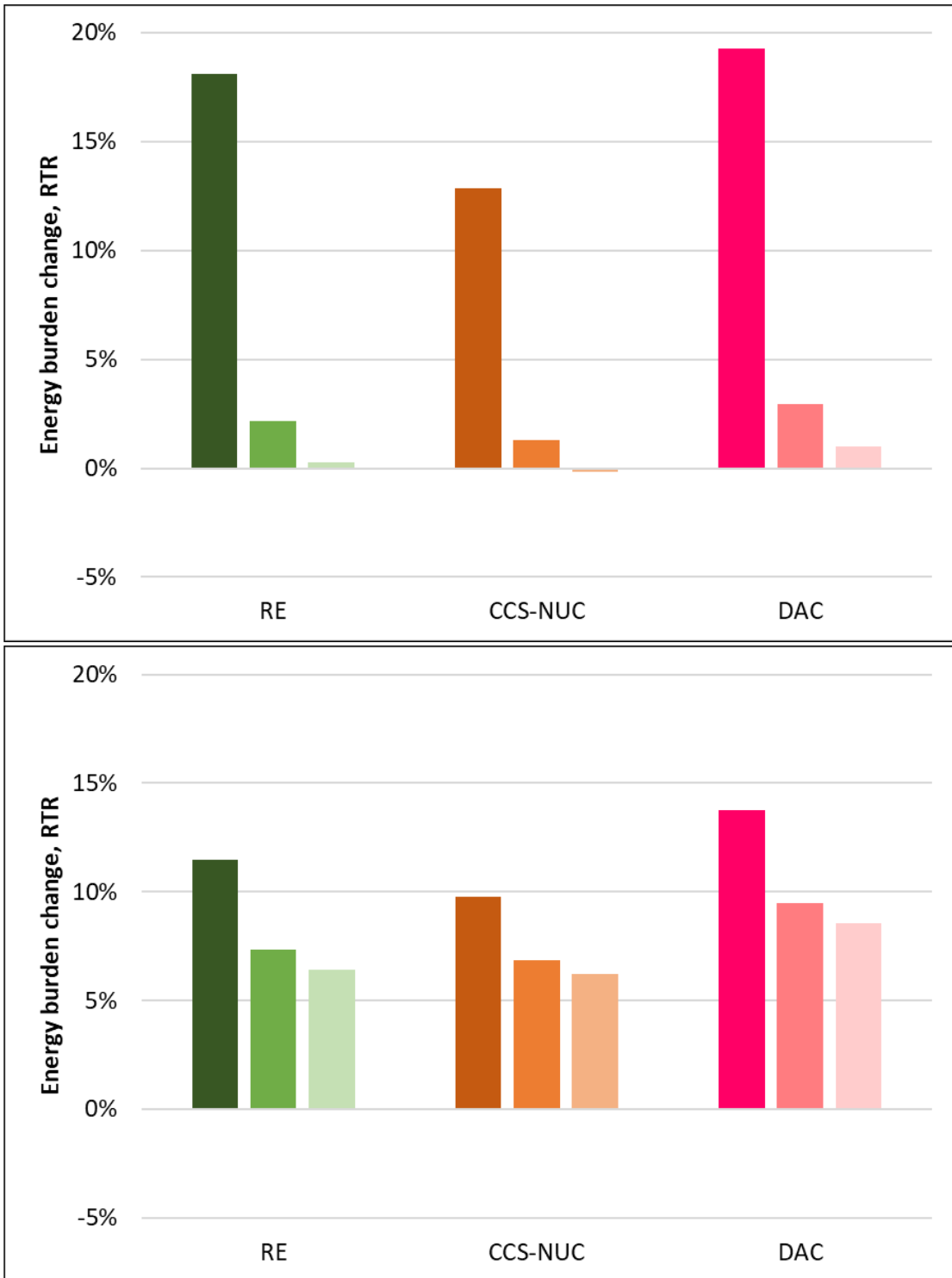
The set of results shown here (Fig 3.3 – 3.6) are for the changes in household energy burdens for the poorest decile (D1), the middle decile (D5) and the richest decile (D10) in India & USA in each scenario. The results for variation in transition pace

(Fig. 3.3 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 higher change in energy burden (~18%) compared to the US (~14%). Further, there is significant variation in the impacts across income tiers in India, with insignificant impacts for the richest decile (<2%), compared to the poorest households which face an increase in energy burden between 14-18%. In contrast, the impacts, though still regressive in character, are relatively more balanced in the US (smaller range of 9-15%). This is due to the higher income levels, as well as higher but more even energy consumption in the US, leading to increased expenditure.

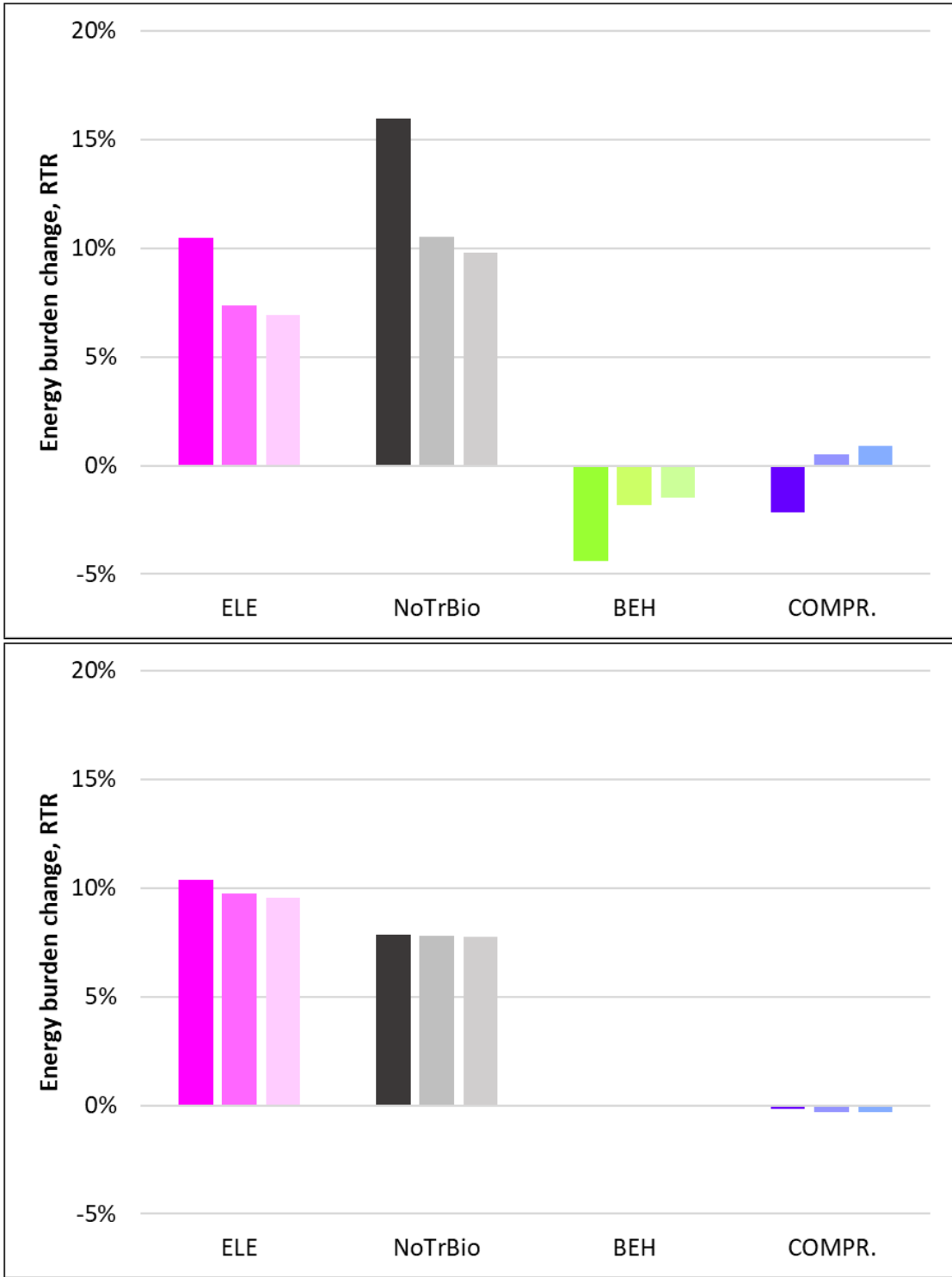
Supply-side technology-based pathways also show similarly regressive impacts in both regions (Fig. 3.4 a-b), but we notice increased household expenditure in the middle and top deciles in scenarios implementing electrification or eliminating traditional biomass fuel usage (Fig. 3.5 a-b). The higher demand 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. 3.3 (a-b):** Short term impacts of pathways varying by pace of transition on household energy burden changes for the poorest, middle & richest decile in the top panel (a) India and bottom panel (b) USA. Energy burden changes are measured as percentage relative to reference (RTR) i.e. against the REF scenario



**Fig. 3.4 (a-b):** Short term impacts of pathways varying by supply side technology choices on household energy burden changes for the poorest, middle & richest decile in the top panel (a) India and bottom panel (b) USA.

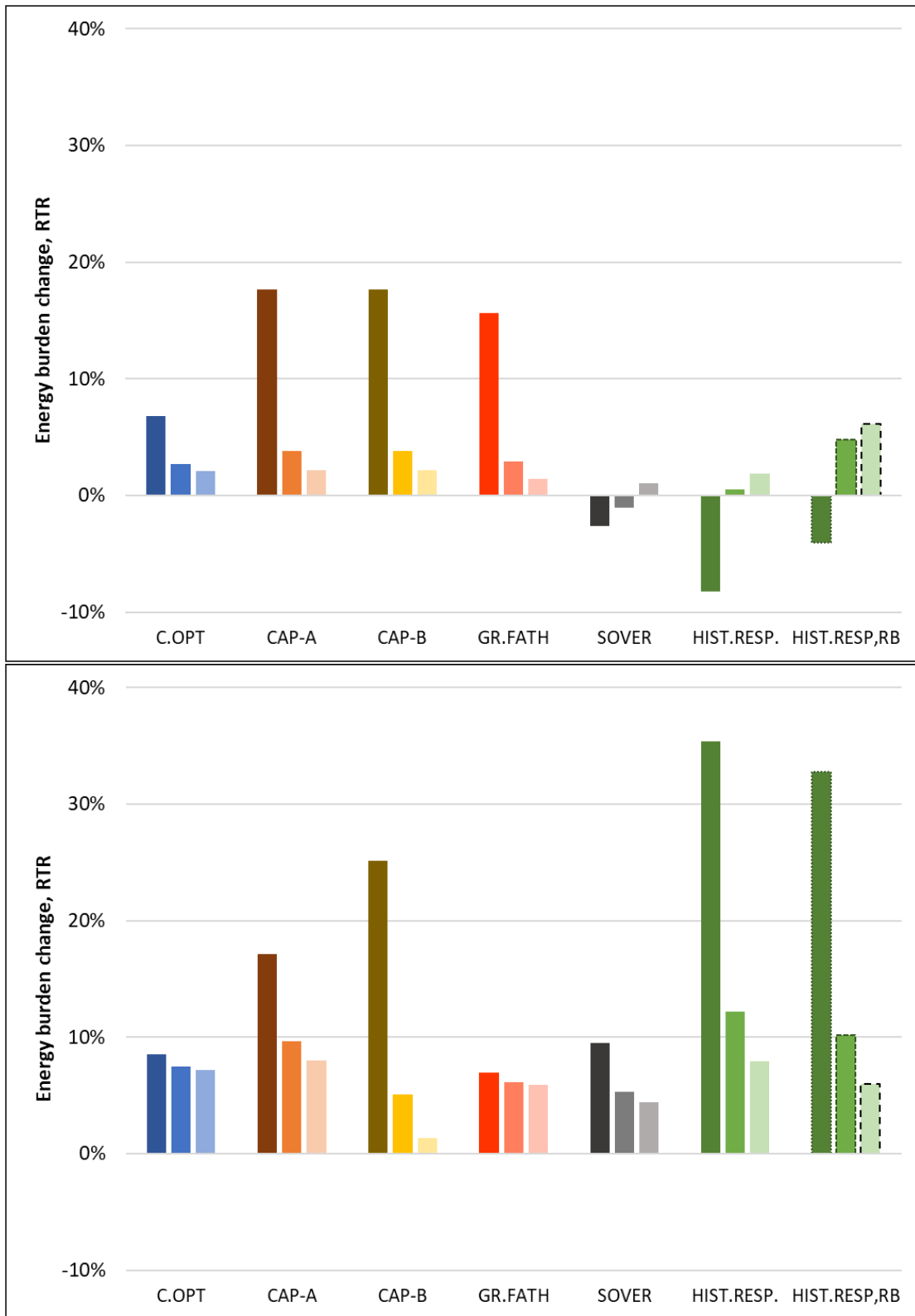


**Fig. 3.5 (a-b):** Short term impacts of pathways varying by demand side technology choices on household energy burden changes for the poorest, middle & richest decile in the top panel (a) India and bottom panel (b) USA.

The noticeable finding here is that BEH & COMPR pathways impose lower energy burdens on the poorest deciles compared to the other deciles (Fig. 3.5 a, b), and in some cases reversing the regressive impacts from carbon pricing coupled with underlying inequity. This is especially true for India, but the impacts in the US also suggest no increase in residential burdens compared to the existing distribution.

For the set of pathways varying by effort sharing principles (Fig. 3.6 a-b), cost optimal pathways (C.OPT scenario) in IAMs lead to increased burdens on the poorest countries, as well as the poorest households within those countries. The regressive within-region impact is, again, more prominent for India. In contrast, pathways forcing an immediate net zero goal on the US based on its capability also have disproportionate impacts on the poorest. CAP-B which imposes an immediate net zero goal rapidly increases the energy burdens for poorest deciles in the US. Even then, the impacts are only slightly higher than those for India where CAP-A and CAP-B impose a net zero year around 2065-2075.

In pathways where the grandfathering principle is employed (GR.FATH), regressive effects across & within regions remains, with such a pathway relaxing the burdens for the poorest in the US even compared to the C.OPT scenario.



**Fig. 3.6 (a-b):** Short term impacts of pathways varying by global effort sharing approaches on household energy burden changes for the poorest, middle & richest decile in the top panel (a) India and bottom panel (b) 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 (HIST.RESP), which would predominantly hurt the poorest populations since the transfer shares are equally distributed amongst the US population.

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. An additional pathway (HIST.RESP, RB) is also modelled here as part of sensitivity analysis. It shows the impacts when the rebound effect is also taken into account, with households in India changing their consumption behaviour upon receipt of higher net incomes after financial transfers. The effect reduces the positive gains to some extent, but progressive outcomes remain. The impact on the US is relatively insignificant relative to the “no rebound” case.

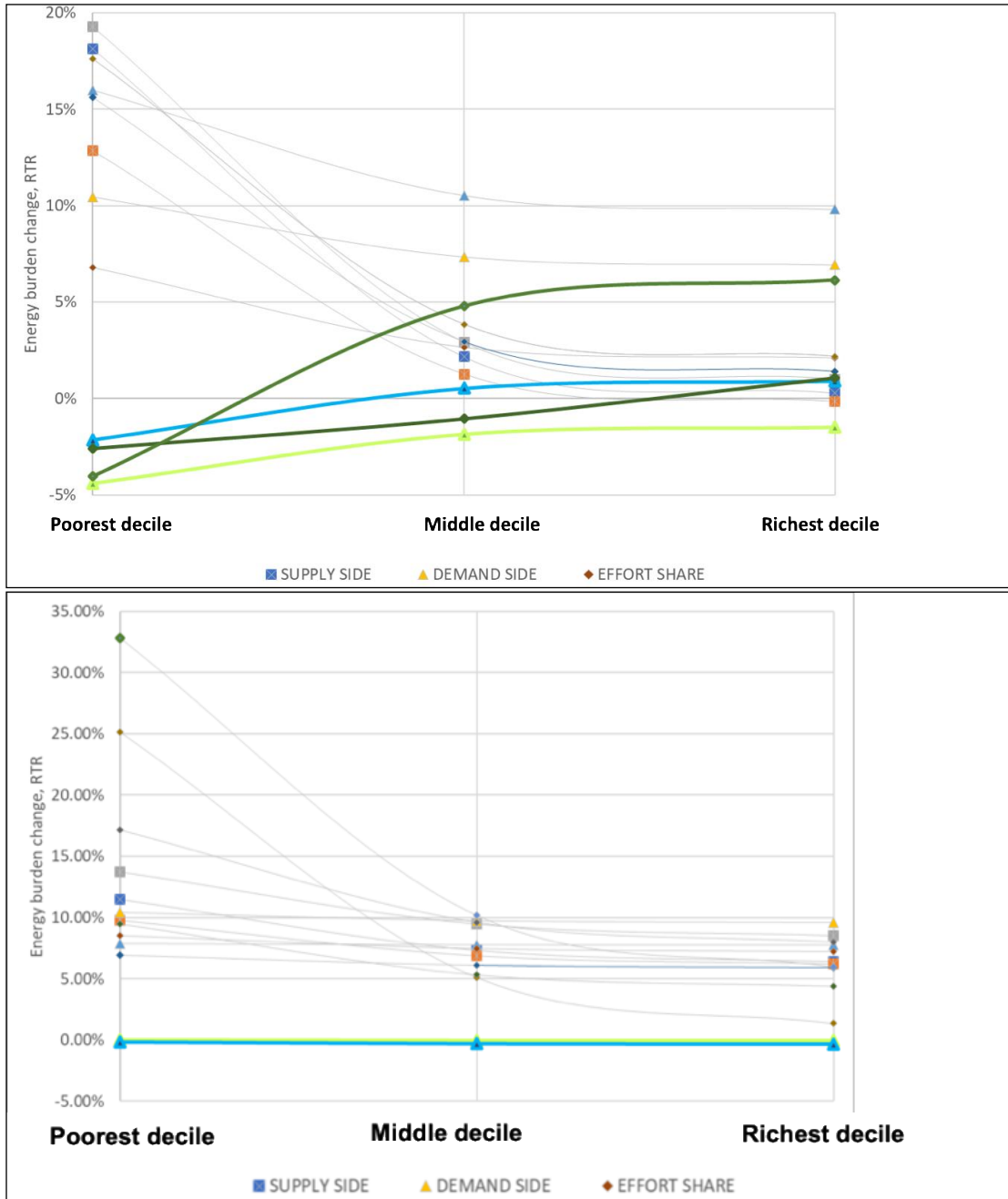
Apart from the short-term (2030) impacts on household energy burden, the long-term trends are also showcased in Appendix B.1 for both regions and all pathways. The results are generally along the same trend, although far higher increases in burdens result across pathways due to much higher food prices and reduction in net incomes.

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 (Appendix B.2 for India using MESSAGE-Access model, and Appendix B.3 for the US employing income elasticities by decile).

### 3.5 Discussion

The demand side mitigation pathways show progressive impacts for the bottom deciles. The reduction in demand and increased space for mitigation by reduction in non-CO<sub>2</sub> emissions enables the poorest sections to increase consumption levels and be better off in both the short and long term. While both BEH & COMPR pathways show progressive impacts across India & US, the effects are slightly muffled for the COMPR scenario due to the additional technology factors enforced. Fig. 3.7 summarizes the implications of all technology, effort sharing & demand side pathways. It is found 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.



**Fig. 3.7 (a-b):** Summary of 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.*

Supporting the results from chapter 2, it is 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<sub>2</sub> emissions in pathways like BEH & COMPR from diet shifts and HFC (Hydro-fluoro carbon) emission reductions. The enhanced action on non-CO<sub>2</sub> emissions creates development space for vulnerable regions and the poorest sections within those regions and could enable them to limit regressive impacts. These findings are along the lines of other literature that demonstrated demand side approaches as avenues for well-being outcomes (Creutzig et al. 2022).

Global effort sharing is shown to have different local effects by region.

‘Grandfathering’ as an allocation principle privileges historically high-emitting region. 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.

### 3.6 Conclusion

#### 3.6.1 Key findings

In summary, one of the main results of this work is that the mitigation pathway choice and design matters and that bespoke pathways can bring about progressive impacts within regions. 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<sub>2</sub> 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.

### 3.6.2 Limitations

There are a number of caveats with the 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 also do not account for the costs of demand side shifts, such as higher efficiency or increased access to public transport and electric vehicles or better recycling and reuse options being made readily accessible. There would be an associated cost towards public infrastructure and research spending which we assume to be balanced amongst the different budgetary mechanisms across sectors. There could be a regressive effect if the costs of such improvements to infrastructure are ultimately based on higher taxation across all income strata. The benefits seen to accrue to poorest deciles would then be cancelled by some of the tax increases they may face. This is also dependent on regional tax structures and how the increases in spending may come from reallocations within existing budgets by reduction in other sectors (example, military) or from different component taxes such as fuels, primary

goods & services etc. all of which have different effects by income strata. Similarly, there is also a “well-being” cost for some of the demand reductions of certain classes, and the psychological dimensions have not been accounted for. Reduction to certain “affluence” goods consumption may affect different populations differently based on their development and aspiration levels and a change to societal thinking around utility of increased consumption beyond certain subsistence and comfort levels needs more study. While measures such as “decent living energy” (Rao et al. 2018) do suggest a general structure, the acceptability of such levels amongst different populations remains underexplored and beyond the scope of this analysis.

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 appendices B.2 & B.3). 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, important for policy formulation.

## Chapter 4: Intersecting Vertical & Horizontal Inequities

### Influencing Energy Poverty

#### 4.1 In a nutshell

##### 4.1 Abstract

Energy poverty indicates difficulty in securing levels of decent living energy services. This study examines the intersectional dimensions of energy access, with a focus on social class, geography, income, education and gender. Using a nationally representative household survey from India, it demonstrates how overlapping inequities along these dimensions leads to significant disparities in reliable access, affordable use and clean and efficient energy service delivery. Additionally, it finds that these effects differ by the type of energy service. Such systemic inequities extend beyond income poverty and disproportionately affect households with multiple deprivations, whereas households without any of the underlying structural inequities are always considerably better off than the national average.

These findings have important implications for policy, as they suggest that interventions aimed at improving energy access in India must take into account the intersecting identities and experiences of different social groups. Targeted policies and programs that address the specific barriers faced by disadvantaged communities are suggested in order to promote greater energy access and equity in India. Rapid

energy transitions linked to climate mitigation need to consider these intersectional effects which may amplify the vulnerabilities. There are broader implications for inclusive and people-centered energy-climate policies, policy stability or raising ambition.

#### 4.1.2 Significance

Empirical analyses on the different factors explaining energy poverty has tended to be limited in scope, focusing on the extent to which each factor explains a single, often binary, outcome. This can obscure important ways in which such factors could overlap and relate to different dimensions of energy poverty and risks misidentification of vulnerable subgroups. This study finds that intersectional effects around income, class, education, geography and gender can strongly explain and link multifaceted energy poverty outcomes. In addition to statistical evidence for intersectionality, it adds nuance to the understanding of multidimensional energy poverty as a symptom of underlying inequities and argues that the story of economic conditions cannot be fully separated from other deprivations.

### 4.2 Understanding multidimensional energy poverty

#### 4.2.1 Introduction

Energy poverty is a complex and multifaceted phenomenon that continues to pose significant challenges for millions of individuals worldwide, particularly in the Global South. Characterized by a lack of access to affordable and reliable energy

services, it encompasses various dimensions, including access, reliability, affordability, and quality of services. While energy poverty's consequences are manifold, its adverse effects on human well-being are particularly pronounced. Inadequate access to modern and reliable energy services has been linked to a host of adverse health outcomes, including respiratory illnesses, as well as negative impacts on education, economic opportunity, and gender equality (Pachauri & Spreng 2011; Pachauri & Rao 2013; Pan et al. 2021; Banerjee et al. 2021; Apergis et al. 2022; Skaria et al. 2021).

Despite considerable progress in measuring and addressing energy poverty (refer Appendix C for a more detailed literature survey) and the rich literature on linking energy poverty to underlying factors, several questions remain unexplored, including the interplay between energy poverty and social exclusion and the implications of energy transitions on marginalized communities. Energy poverty is a unique deprivation and its links to other deprivations needs study (Khan 2019). Very less is known about the joint relationships of different deprivations and their links to energy impoverishment. Drawing on the energy poverty & intersectionality literature, we address a conceptual gap on the underlying social structures and their influence on different aspects of household energy vulnerability. The misrecognition of energy poverty leads to marginalization (Simcock et al. 2021).

The intersection between energy poverty and climate change mitigation and adaptation has emerged as a salient issue of global significance. The energy sector is

the largest source of greenhouse gas emissions, and efforts to mitigate climate change will inevitably impact energy access and affordability, especially for the poor. Merely greening energy systems may not make them any fairer, inclusive or just (Johnson et al. 2020). Furthermore, existing climate policies may have unintended consequences for the energy poor, such as higher energy prices or a loss of access to traditional energy sources. Households will experience problems when external conditions can suddenly change due to rapid energy transitions that demand coping capacity. There is a need to assess intersectionality and compounded vulnerability in climate change (Versey 2021). Effects of climate change are mediated through social, cultural & economic structures and processes and the unequal power relations, in addition to geographic and economic factors are important in exploring climate related injustices (Kaijser & Kronsell 2014). Energy transitions should take justice dimensions into consideration to ensure that policies and programs recognize the differing needs and impacts for different groups, and do not exacerbate existing inequalities, and stimulate greater support for climate policy (Fell et al. 2022).

This paper proposes an intersectional framework of analysis, seeking to inform more nuanced and inclusive energy policies that prioritize the needs of marginalized communities, particularly those most vulnerable to the adverse effects of rapid energy transitions. Intersectionality is an important concept in understanding and addressing the complex and overlapping forms of inequality and discrimination that individuals and communities can face. Energy poverty, which is defined as the lack of access to

modern energy services, can be influenced by various intersecting factors such as income, gender, race, and location.

#### 4.2.2 The Intersectionality framework

Intersectionality originates in the work of Kimberle Crenshaw (1989) who showed how interactions of race & gender frustrated Black women's access to the American labor movement. The term's presence in academia is relatively new, it has been popular in social justice communities for more than a century (Yale 2022).

Intersectionality is a way to examine issues to understand how different social identity characteristics interact with each other and prevailing power structures to create and reinforce power, privilege, disadvantage and discrimination (Jacobson 2022). A more detailed treatment of intersectionality can be found in Appendix D.1.

Studies focusing on a single variable or deprivation are valuable for illuminating power relations, but often fail to consider how inequities are intertwined with and reinforced by other structures of discrimination. Apart from the vertical inequality factors like income, horizontal inequities result from overt discrimination, exclusivity of public goods and unequal access to resources, which may be political, social or economic. Such inequities persist due to limited mobility between groups.

Entire communities may fall through the cracks if vulnerability is analyzed on one-dimensional horizontal or vertical inequity attributes, solely on race or income status alone. Intersectionality offers a framework for considering household's overlapping identities and experiences in order to understand the complexity of deprivations they

face. An intersectional lens can provide a more comprehensive representation of multiple factors that can shape impacts.

It has been proposed that intersectionality can be used to generate critical & constructive insights, generating alternate knowledge on power relations and institutional practices crucial for the formation of effective & legitimate climate policy (Kaijser & Kronsell 2014). Previous attempts at applying intersectionality empirically include Winker & Degele (2011) on the reciprocities between gender, race & class. Other applications of intersectional analysis relate to feminist studies and climate change (Lykke 2010), health inequalities (Bauer & Schein 2019; Bastos et al. 2018; Harari & Lee 2021), criminology (Potter 2013), disadvantages to employment and internet access during the pandemic (Moen et al. 2020; Chen et al. 2022), food insecurity (William-Forsen 2011; Patterson et al. 2020), political behavior and representation in different countries (Harell 2017; Ralph-Morrow et al. 2021; Junn 2017), and even the inequities in the US scientific workforce (Kozlowski et al. 2022).

Theoretical explorations of intersectionality in the energy poverty context have emerged recently (Mejia-Montero 2023; Waitt 2022; Middlemiss 2020, 2022). Jessel et al. (2019) review the interlinkages between energy insecurity, health and other hardships. Other work often in the Global North, though not framed in the intersectionality context, does indicate interactions beyond income that affect energy insecurity for African-American households in the US (Dogan et al. 2022; Graff et al.

2021), the coupled effects of gender and ethnicity in South Africa (Ngarava et al. 2022), gender related energy poverty in the UK (Robinson et al. 2019), and interactions between income, housing quality and energy poverty in Mumbai (Sharma et al. 2019). More commonly the literature delves on the degree of relative influence of singular socioeconomic factors explaining energy poverty, especially in the Global South (Khandker et al. 2012; Srivastava et al. 2012; Abbas et al. 2020; Mani et al. 2020; Gupta et al. 2020), and not delving into the interactions.

Thus, we find that while energy research has been far from blind in consideration of underlying horizontal inequality dimensions, and how their distributional impacts might have disproportionate outcomes for some groups. However, the extent of consideration of different dimensions of energy poverty dimensions and overlapping identities is often not fully considered or remains implicit. Empirical evidence of intersectionality is almost absent, and inherently relates to race and income dimensions in the Global North. Further, energy insecurity or expenditure dimensions in the North are only one facet of the multidimensional nature of energy poverty across the world. There has been no exploration of how these different dimensions can be influenced by the interaction of underlying inequities. Understanding these missing pieces is important to analyze the compounded vulnerability to a rapid energy transition.

#### 4.2.3 Methods

This study explores intersectionality in the energy poverty context using an example of India. Despite considerable progress in expanding electricity access, roughly 240 million people in India still lack access to electricity, with rural communities disproportionately affected. Access to clean cooking fuels is also a significant issue in India, with an estimated 840 million people relying on traditional biomass for cooking, leading to indoor air pollution and other health issues.

To account for the multiple dimensions of energy poverty along access (reliability of supply), affordability (share of income spent on household energy services) and services (ownership of appliances or means to efficiently and cleanly convert energy to useful forms), we use the Alternative Framework (Pachauri & Rao 2020; Pelz et al. 2021, see Appendix D.3 for details). While multiple other metrics exist in the literature, this Framework allows for easy characterization of key dimensions of energy poverty including separation of services and fuels, household conditions and supply conditions, and the ability to use publicly available household surveys across the world.

The data for this analysis is based on the nationally representative Indian Human Development Survey (IHDS)- Round II which covered over 45000 households in 2011-12 (Desai et al. 2018). It remains the most comprehensive, open source data set available as of now. Though more recent surveys like ACCESS have greater detail but lack national representation, covering only 6 states (Mani S. et al. 2018). The

IHDS results and inferences is supported by analysis of income deciles using the National Sample Survey (NSS) Round-66 from the same time period.

The first step of analysis involves applying the Framework to both categories of fuels (electricity and cooking fuels) and analyzing regional variations between states and how certain dimensions are more evident in some regions. It is found that significant proportion of households in the intermediate tiers who may have access to energy but are at the margins when it comes to reliability, affordability or services derived and remain vulnerable in a rapid energy transition. The results along 3 dimensions of access, affordability and service provision are shown separately for electricity and cooking fuels in Figure 4.1.

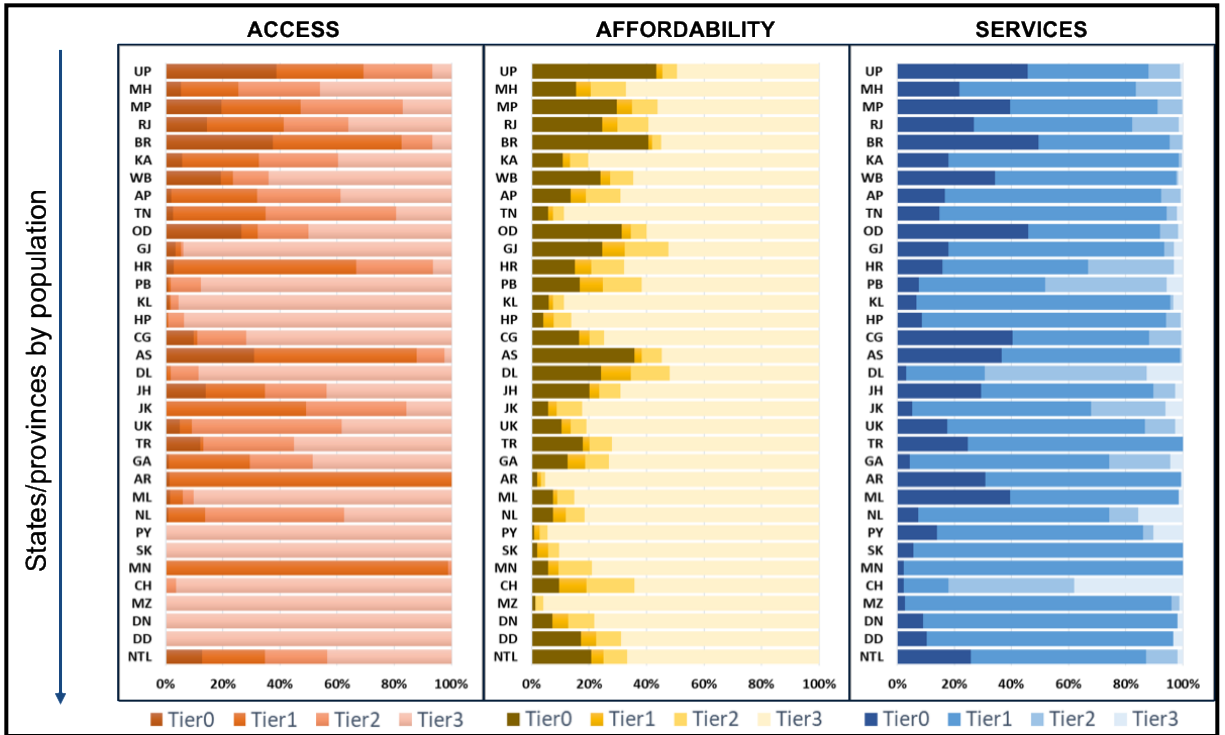
### 4.3 Results

#### 4.3.1 Distributional aspects of energy poverty in India

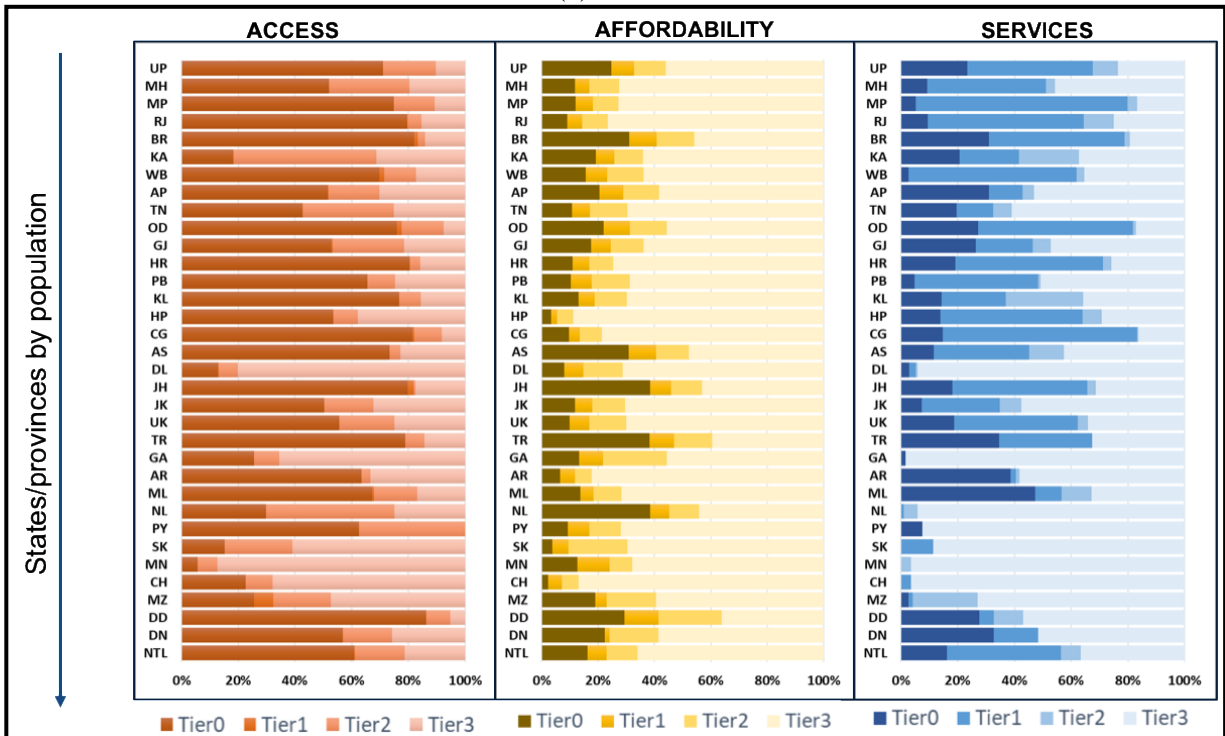
The states with the greatest share of households impoverished on the access or reliable electricity dimension also the same for affordability and services. This indicates extreme energy poverty vulnerabilities are likely for some regions. For cooking fuels, the outcomes are more complicated. Affordability and appliance ownership trends seem to be completely de-linked from clean cooking fuel access. Increased access does not necessarily imply any effects on affordability since affordability is skewed by use of cheaper traditional biomass options. The service/appliance ownership outcomes are also different since although households may own

a Tier 3 appliance (LPG cookstove), there would be significant levels of fuel stacking. We find evidence of the use of a combination of fuel sources often dominated by firewood and cow dung cakes (Appendix D, fig. D.10). Even the richest income deciles employ fuel stacking, indicating affordability challenges, apart from cultural aspects related to cooking fuel choices.

While there are significant regional differences, even at the national level, we find high levels of inequality in energy services by income strata (Appendix D.5, D.7). The results indicate the lack of a strong link between income levels and energy use in India. While electricity access & affordability improve significantly with income tiers, appliance ownership is still limited except for the 95<sup>th</sup> or 99<sup>th</sup> percentile households which are able to access multiple appliances providing for a decent standard of living. The relationship is further askew for cooking fuels, where appliance ownership does improve with income, but access gains are limited and affordability concerns remain even for the highest quantiles (Fig. D.7).



(a)



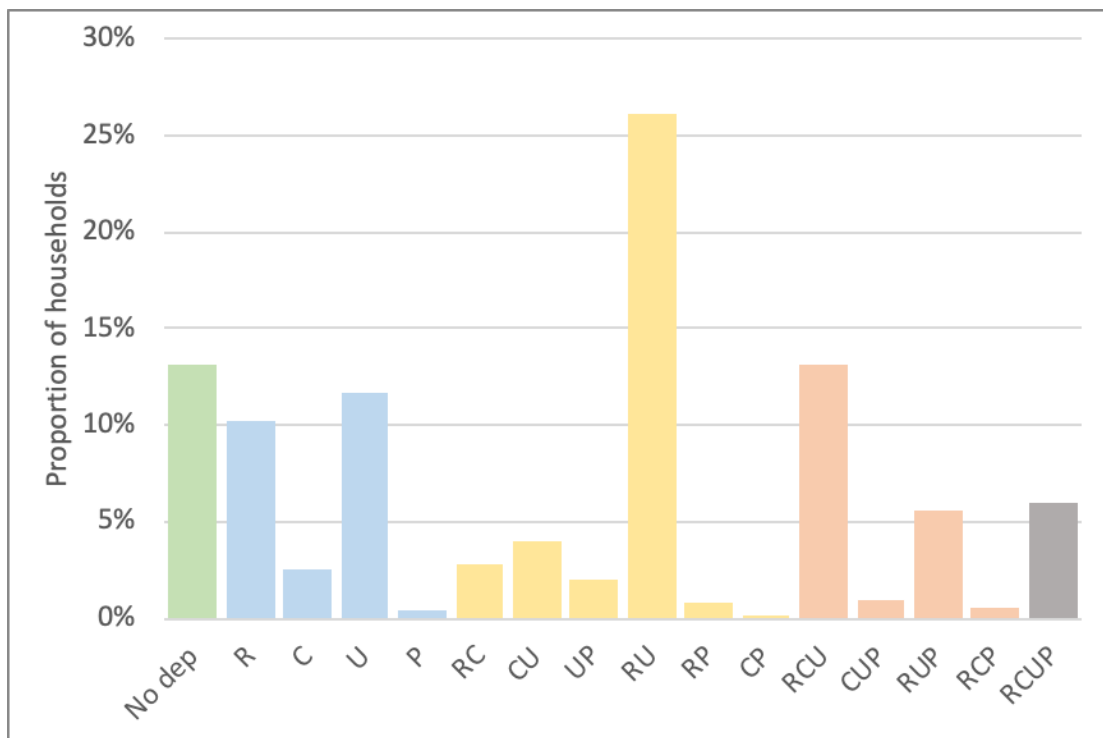
(b)

**Fig. 4.1:** Indian states arranged in descending order of share of households in the impoverished tier on energy access, with corresponding outcomes on affordability and services. Panel (a) shows outcomes for electricity and panel (b) cooking fuels. NTL indicates the national average.

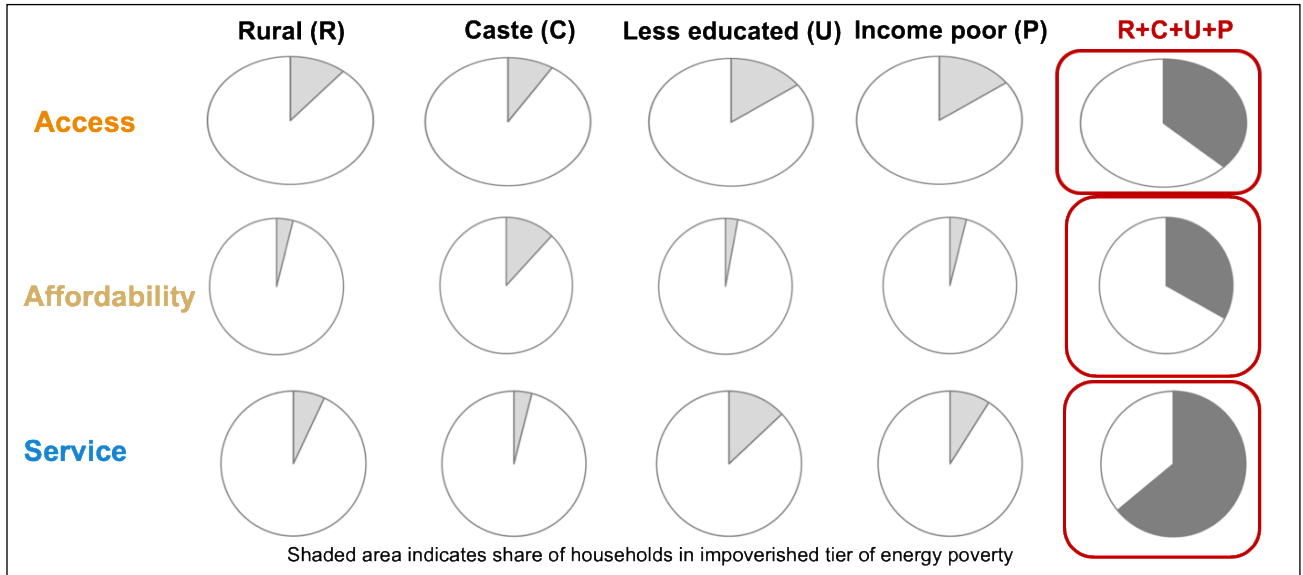
The energy Gini index has often been used to characterize the distribution of energy poverty using consumption (Jacobson et al. 2005). The Lorenz curve for electricity (Appendix, D.6) reveals high levels of inequality in consumption with a Gini of 0.43. For comparison, the Ginis for USA, Norway, Kenya & Thailand are 0.37, 0.19, 0.87 and 0.61 respectively (Jacobson, Millman & Kammen 2005). Since the Gini index has been known to conceal the impacts on the most vulnerable, we also examine the 90/10 ratio showing that the top decile of households consumes about 49.83 times that of the bottom decile household. Similarly, the Palma ratio which computes the ratio of energy consumption by the top 10 percentiles against the bottom 40<sup>th</sup> percentile (Palma & Stiglitz 2016), shows significant distributional variation in consumption with a value of 0.44.

Albeit an imperfect metric in the context of solid fuels with lower efficiencies, we compute similar coefficients for cooking fuels using the Lorenz curve in Appendix D.8 revealing Gini = 0.496, 90/10 ratio of 64 and Palma ratio = 0.31. For a more balance comparison considering households which use LPG as the primary fuel, the inequality reduces with Gini = 0.234 and a 90/10 ratio of 28. This is due to the higher efficiency of LPG and more even distribution of cooking needs across households. However, we still find a high Palma ratio of 1.3 implying that LPG access is highly skewed towards the top deciles. These findings suggest that income alone is insufficient to characterize the energy consumption behavior and fuel choices of households in India and there are other socioeconomic deprivations which are embedding high levels of inequality in access, affordability, service and consumption.

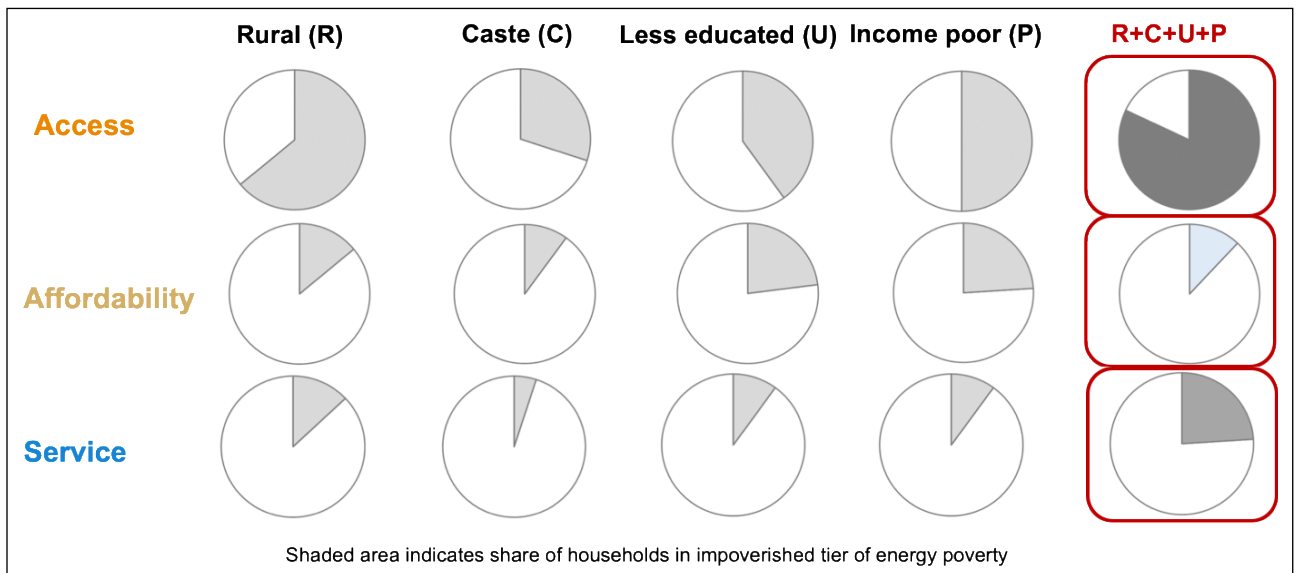
Therefore, we examine different horizontal inequities along social class (considered as caste “C” for the purposes of this analysis and includes the federal classifications of Scheduled Castes and Scheduled Tribes in India), geography (“R”, for rural-urban disparities) and education levels (“U”, indicating household head’s access or attendance at some college or professional education beyond high school), and how these couple with income poverty (“P”). This (non-comprehensive) set of factors is explained in Appendix D.13 and was chosen based on the existing literature indicating their salience to distributional inequities in energy poverty in India and other countries (Sharma et al. 2019; Gupta et al. 2020; Abbas et al. 2020; Graff et al. 2021). The distribution of the sampled population in IHDS across the different overlaps of these underlying deprivations is shown in Fig. 4.2, with a high share lying in the rural and less-educated category.



**Fig. 4.2:** Share of households in India with overlaps of four underlying derivational factors, based on IHDS-II



*Fig. 4.3(a): Representation of interactional effects on energy poverty dimensions for electricity from underlying deprivations and their combination*



*Fig. 4.3(b): Representation of interactional effects on energy poverty dimensions for cooking fuels from underlying deprivations and their combination*

It is found that households at the intersection of these inequities are more likely to belong to the lowest tier of energy poverty, with the effect magnified by increased intersectional deprivations. This finding generally holds true for both electricity and

cooking fuels (Fig. 4.3 a, b). While only 1 in 10 households deprived along geography or caste, education or income are impoverished, 7 in 10 households which face these combined inequities may fall in the bottom tier of energy poverty for electricity. The intersectional effects vary by dimension and fuel. For example, the intersectionality relationship is reversed for affordability in cooking fuels, with households showing combined deprivations less likely belong to the impoverished tier. Also, factors such as geography have much stronger impact relative to other deprivations when connected to the access dimension for cooking fuels.

In contrast, households with “no deprivations” (implying urban, non-caste, educated, and above the income poverty threshold) are always significantly better off than the national average (Fig. D.9, appendix), indicating positively reinforcing intersectionality.

Intersectional effects may be sub- or super-additive, and even partial overlaps along some underlying deprivations can leave households energy poor (Appendix D.15). However, as the order of overlaps increases, the proportion of energy deprived households increases.

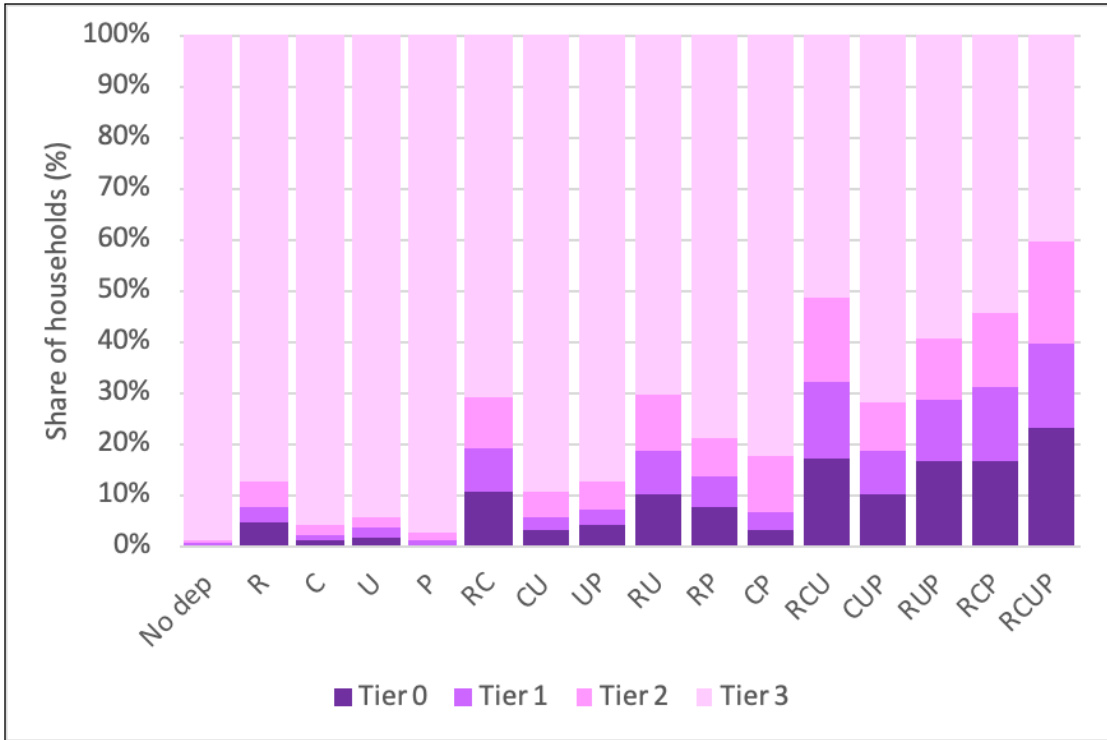
#### 4.3.2 Intersectional downstream outcomes

The surprisingly positive effects of intersectionality for affordability of cooking fuels conceals the effect of fuel choice and the use of less efficient, more polluting solid

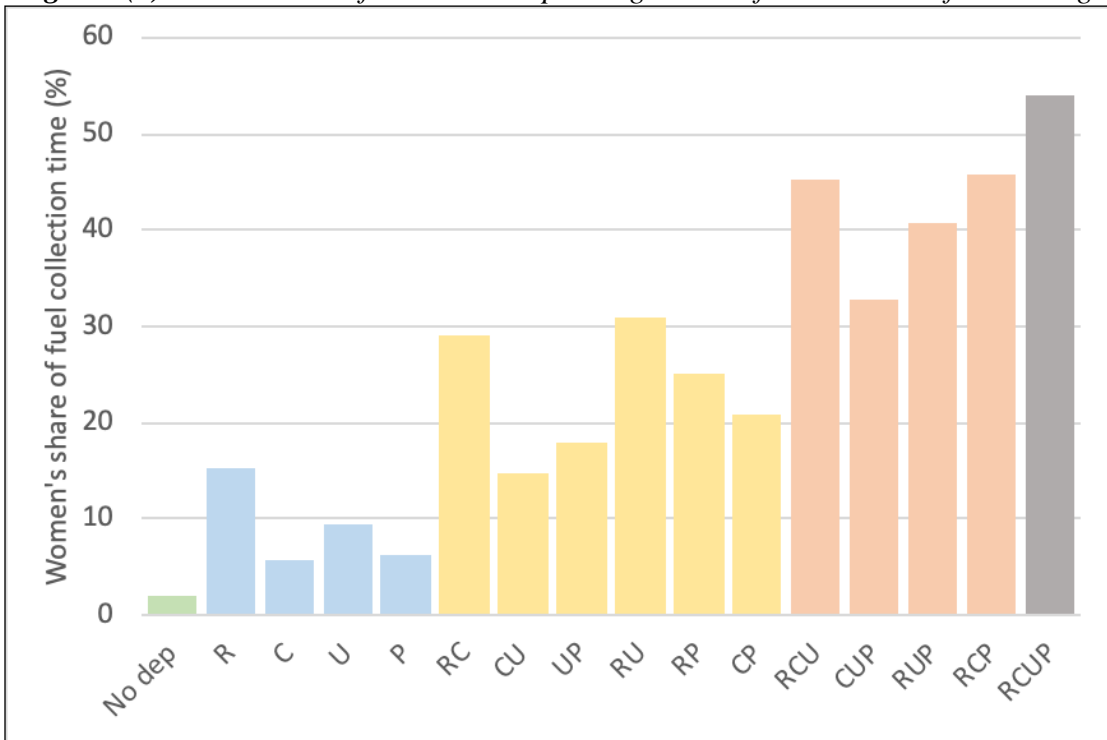
fuel sources. The effects of such fuel choices actually show up in downstream intersectionality, along gender dimensions.

While the energy poverty levels overall convey significant disparities between households, individuals within households may face ‘double burdens’ due to layers of gender disparities. The gendered division of labor generally assigns the responsibility for the provision of household energy in relation to the spheres of influence in the household. Women are disproportionately affected by energy poverty and the conditions get worse when gender inequities intersect with R-C-U-P factors. Fig. 4.4 (a) shows that households with a combination of deprivations spend much higher share of time on fuel collection, and even within those households, the average amount of time spent by women on fuel provisions is significantly higher when other deprivations co-exist (Fig. 4.4 b). In contrast, for households with none of the underlying deprivation factors, almost no time is spent on fuel collection even in the presence of stacking. A description of fuel collection time and tiers is provided in Appendix D.12.

Women’s disproportionate vulnerability to energy poverty is linked to an array of economic reasons, particularly the uneven share of unpaid work and gender pay gaps. Additional intersectionality of effects based on gender related to: fuel collection, security & injury risks, indoor air pollution, risks of fuel use and burns, impaired health and lack of refrigeration services, education, employment and fertility impacts.



**Fig. 4.4 (a):** Distribution of households spending time on fuel collection for cooking



**Fig. 4.4 (b):** Distribution of share of time spent by women in a household on fuel collection for cooking. Households deprived along multiple axes of R, C, U and P have much higher time consumption for fuel provisions, with disproportionate impacts on women.

#### 4.3.3 Statistical significance

We examine the statistical significance of these results using an ordered logit approach. The consideration of the product term in a multiple regression has been shown to be a legitimate way to test for interactions (Allison 1977). We find that these dimensions are generally statistically significant at the 95% level (Table 4.1), except for the link of caste & affordability of electricity. Intersectional effects are dominant for affordability and services in electricity, and have a negative correlation for affordability in cooking fuels consumption, as seen in the previous section. While statistically significant, the impacts of geography dominate for access and service dimensions of cooking fuel related energy poverty.

The results indicate insignificant impacts of caste on electricity affordability and income poverty on cooking fuels affordability. This is plausible since cooking fuels affordability is skewed by the prices of solid biomass fuels, and electricity prices do not vary significantly by category for residential consumers. The intersectional effects (R\*P\*C\*U in the table) are statistically significant, although weaker than some of the component variables such as rural geography. Intersectionality demonstrates the reverse effect on cooking fuels affordability, as seen in the previous section, with households belonging to more deprived sections showing better affordability outcomes due to the use of cheaper, inefficient fuels. The results are better demonstrated in the charts in Appendix. D.14 a & b), where we observe varying degrees of additive deprivations for both electricity & cooking fuels across dimensions. Only affordability in cooking fuels shows a reverse effect of the overlap

of deprivations, and as discussed in the previous section, relates to fuel stacking behavior, the uncompensated effort of fuel collection and downstream intersectional disparities for women.

**Table 4.1: Results of ordered logit regression analysis**  
*(coefficients indicate odds ratio of a household belonging to non- impoverished tier of energy poverty. Values in brackets indicate standard errors. \*\*\* significant at  $p < 0.05$ , \*\* significant at  $p < 0.1$ )*

Fuel	<i>Electricity</i>			<i>Cooking fuels</i>		
Variable	Access	Affordability	Service	Access	Affordability	Service
R	0.1821*** (0.0098)	0.5561*** (0.0165)	0.3031*** (0.008)	0.2545*** (0.0058)	1.1865*** (0.0347)	0.3985*** (0.0141)
P	0.4198*** (0.0145)	0.5694*** (0.0173)	0.3558*** (0.0106)	0.5312** (0.0176)	0.9561 (0.0346)	0.9258*** (0.0322)
C	0.8057*** (0.0261)	0.9586 (0.0258)	0.6742*** (0.0176)	0.7909*** (0.0197)	1.2839*** (0.0314)	0.7642*** (0.0221)
U	0.2518*** (0.0137)	0.4539*** (0.0149)	0.1794*** (0.0073)	0.5987*** (0.0143)	0.5039*** (0.0169)	0.5077*** (0.0184)
R*P*C*U	0.2585*** (0.0118)	0.4176*** (0.0183)	0.1739 (0.0076)	0.3204*** (0.0172)	1.4436*** (0.0918)	0.6007*** (0.0298)
McFadden's Pseudo R <sup>2</sup>	0.317	0.228	0.407	0.229	0.114	0.205
No. of samples	41148	41148	41148	41148	41148	41148

#### 4.4 Discussion

The results show empirically that energy poverty is often a symptom of other underlying deprivations and their interactions and overlaps. It is not just the income poor who are also energy poor across dimensions. Households disadvantaged on multiple axes have higher odds of facing more severe forms of energy impoverishment and would find it more difficult to escape it as well.

The current definitions of energy poverty in the Global South often take a narrow view, resulting in policy focus around connections and delivering LPG access to low-income households, while definitions in the Global North focus mainly on energy insecurity related to expenditures. Policies seeking to improve connectivity will surely have positive effects for many households but are unlikely to address all the facets of a complex problem. Vulnerable households often experience different dimensions of energy poverty bundled with other hardships.

It is also found that different energy poverty dimensions for different energy services may interact differently with underlying inequities. For example, caste did not seem to have as significant a relationship to affordability as other factors such as being a rural household. However, caste often reinforces other deprivations. Horizontal inequalities result from overt discrimination, or covert discrimination through exclusivity of public goods and unequal access to resources, which may be the result of underlying political, social or economic structures. Such inequalities then persist due to limited mobility between social groups. Some social networks can amplify

inequalities by fundamental mechanisms of social tie formation, sharpening social segregation, geographical impediments such as distance. Urban/ rural divides and physical and administrative boundaries also reinforce social segregation. Some disparities may have historical roots, where unequal access to technology or public services are a self-reinforcing mechanism compounding energy poverty across generations. Living in inadequately energy-serviced households has negative implications on respiratory and cardiovascular systems, apart from mental health and well-being. It is also important to highlight the resulting social exclusion where limited energy services or stigmatization hinders everyday life, including education and employment. We do not posit evidence that these interactive effects are deliberate mechanisms, but they can be the results of subtle power imbalances and not the result of explicit or intentional prejudices.

Energy poverty research and policy focused solely on vertical inequities such as income or economic factors leads to policy proposals for financially motivated interventions. Energy subsidies become a more popular option than structural measures such as energy efficiency upgrades or improving housing quality and urban planning. Since we find that energy poverty dimensions involve more than income effects, similar to the misplaced focus on connections alone, policies motivated on financial relief alone indicates only a partial awareness & recognition

Policies flowing from the intersection of two or more axes of subordination create burdens and further disempowerment (Crenshaw 2000). Hence, generic or ‘power-

neutral' approaches to an energy transition will not automatically lead to a Just Transition, and in many cases, will perpetuate existing structures of inequalities. Our results indicate support for the hypothesis that Just transitions are highly risky for households which enter the rapid transition at a disadvantage (Middlemiss 2022). With systems producing 'winners' and 'losers', the vulnerabilities can exacerbate the varying abilities to cope and respond to energy-climate policies. Along the same lines, technology alone would not determine the benefits of an energy transition, and outcomes may differ depending on power relations and spatial and social contexts. Different forms of intersectionality will play a role in social, political, economic and cultural processes of decision making & implementation and influence the distribution of benefits and impacts.

The results also show that gender, in concert with other identities such as geography, class, education, etc. has powerful influence on how household members will experience the co-benefits or tradeoffs of energy-climate policies by shaping their ability to adapt. Our work also suggests the need for gender-aware approaches to addressing energy poverty.

Thus, an intersectional framework can help explore the complex and overlapping experiences beyond income levels that spur different vulnerabilities. Energy-climate policies should explicitly address the factors beyond the vertical inequalities of income, such as geography, class, race, ethnicity, education and gender which can influence an individual and household's vulnerability to energy poverty dimensions

and should therefore be considered when applying solutions. The development of gender and intersectionality indicators of energy poverty would be an important step in influencing such policies to address the most vulnerable.

#### 4.5 Conclusion

##### 4.5.1 Policy implications

This study can be seen as uniting two disparate strains of analysis, energy poverty dimensions and intersectionality, in a single framework. For the first time, such analysis is able to show clear and significant linkages between different energy poverty dimensions and overlapping social identities.

It is revealed that it is not just the income poor who are energy poor, and this effect varies by the dimension considered (reliable access, affordable use or clean and efficient service). This matters for energy-climate policy success since households which are otherwise deprived would not be able to benefit from certain policies, while climate policy affecting energy consumption would also disproportionately affect such households and groups. Without addressing existing power asymmetries related to access and resource distribution upfront, these inequities will be replicated and transferred to the new energy regimes

The findings highlight the complex and intersecting nature of disadvantage in determining energy access in India. Addressing this issue will require multi-

dimensional strategies that take into account the specific contexts and needs of different communities. For example, targeted interventions that improve energy access for households in rural areas and those belonging to lower castes may be necessary to ensure that these communities are not left behind. Improving energy access across social groups and facilitating social desegregation through civic planning and supporting more equal service distribution can mend and improve outcomes for all.

Intersectional thinking can offer different potential approaches to addressing energy poverty under climate mitigation scenarios. While projects and processes can be designed or planned to address the most vulnerable sections with overlapping inequities, in many cases, simply bringing these aspects to their thinking can be helpful to policy makers.

#### 4.5.2 Caveats and future work

This analysis does omit consideration of the mediating processes, i.e. the specific discriminatory actions through which intersectional attributes impact outcome inequalities. Hence, it does not prove a cause-effect relationship since there may be other confounding factors influencing some of these findings at the local level.

Nevertheless, the observations suggest examining climate policy impacts through an

intersectional lens would be important for analyzing the distributional consequences of rapid energy transitions.

Another important limitation here is the claim of ‘comprehensiveness’ – we intentionally forgo efforts to identify all possible classifications and determinants, opting instead to focus on uncovering the most useful evidence. It could be inefficient and impractical to attempt comprehensive coverage since it may potentially draw from a wide variety of topics. We wish to clearly acknowledge this unavoidable limitation of this work, which aims to a more purposeful and targeted approach to the significant factors.

Future work can examine the impacts of recent policy actions aimed at improving access in India (Saubhagya, Ujjwala). This study has also not considered inequities based on religion, or the consideration of Other Backward Castes beyond the Scheduled Castes & Tribes in India and previous works in other fields have shown that these factors may also influence outcomes. There could also be regional and local variation that has not be accounted for here. Lastly, it would be imperative to examine the causal mechanisms and qualitative work in this area can contribute to improving our understanding of how intersectionality affects behavior and lived experiences of the energy poor.

## Chapter 5: Conclusions and Policy Implications

### 5.1 Summarizing key findings

#### 5.1.1 Findings from chapter 2

Individual analysis of mitigation pathway archetypes commonly expresses their findings as if there were little room for doubt on the tradeoffs; but taken together, the scenario ensemble analyzed here tells a very different story – one usually hidden from policy making. This study demonstrated that it is possible to achieve the dual goals of energy access & climate change mitigation, if the early diffusion of appropriate technology is promoted and take sufficiency is taken into account as a mitigation strategy for the affluent regions. Pathways employing demand side mitigation options were overwhelmingly successful at attaining multiple national energy goals.

In addition, our findings imply that targeted technology deployment for renewable energy, electrification or eliminating use of solid fuels in residential sector has to be coupled with income support or subsidization programs for vulnerable populations.

Another important finding is that focusing on the full basket of GHG emissions and going beyond CO<sub>2</sub> based targets could create “development space” for the Global South within the overall carbon budget, allowing for balancing climate ambition and growth targets. Such pathways also increase convergence in global energy service

consumption across regions and can possibly attain energy access goals (reduction in share of traditional solid fuels) beyond the reference scenario trends.

Lastly, grandfathering narratives around effort sharing are unfair to the Global South. While financial transfers to account for historical responsibility of climate change do limit some of the tradeoffs of mitigation for those regions, without appropriate burden sharing on other options (technology sharing, reduction in affluent consumption etc.), there remain limits to attaining energy poverty goals.

#### 5.1.3 Findings from chapter 3

The regressive impacts of a global carbon price-based mitigation policy are deeper for the Global South, and even higher for the poorest income deciles within those regions.

Supply side technology solutions do not address underlying within-region inequities. Supporting progressive impacts for the poorest and most vulnerable sections and achieving just transitions by limiting the household energy burden on the poorest deciles, therefore, require an enhanced focus on societal transformations and behavior changes and employing policies which support a shift in consumption patterns by the affluent globally, as well as by the affluent in the Global South.

Non-CO<sub>2</sub> reductions from affluent consumption are an important lever to redistribute the economic burdens of enhanced climate ambition while protecting the lowest income tiers.

This 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. Reduction in energy burdens for the poorest deciles is possible in the Global South when accounting for financial transfers towards historical responsibility of climate change by the Global North. However, such transfers significantly increase the distribution of costs to the poorest in the North, implying that they should rather be targeted at more affluent sections.

These findings based on examining within-region distributional effects offers a new view on the climate change challenge. They question the false choice that sacrifices justice and equity on the altar of economic growth. By assessing and measuring the impacts of climate change with poverty-related metrics, we can ensure that economic analysis better captures one of the main reasons for concern regarding climate change, namely the impact on the poorest and the most vulnerable. The downscaling analysis should extend to cover dimensions beyond income poverty.

#### 5.1.4 Findings from chapter 4

Energy poverty is often a manifestation of underlying inequities, more than a cause. It exceeds income poverty and is highly unequal in its distribution. Income-based

analysis implying purely financial support would be insufficient to address underlying non-economic deprivations faced by marginalized communities.

Intersectional effects between underlying horizontal socioeconomic deprivations such as social class, education or geography can link in different ways to affect different energy poverty dimensions. Income-based analysis of energy poverty risks writing other vulnerable communities out of the narrative. Different sub-groups of households are likely to experience different forms of energy poverty.

Intersectional effects of energy poverty manifest downstream in terms of disproportionate burdens along gender dimension. Women from households facing multiple underlying deprivations spend more time in collection of household energy needs, and this limits their educational outcomes, leads to imbalanced health impacts, and bounds their agency to access other rights.

Apart from mere access to cleaner fuel sources or electricity connections, significant impoverishment exists along energy services (ownership of appliances to utilize energy) and adequacy and reliability of electricity in many regions. Unequal ownership of efficient means to convert energy to usable services would increase energy burdens under rapid energy transitions.

The analysis adds depth to existing debates around energy goals, more accurately capturing key dimensions of energy poverty relevant to sustainable development, sub-setting by sub-groups, and treating outcomes as more than a binary choice.

### 5.2 Contributions to scholarship & policy

This dissertation demonstrated multiple novel results and the findings are particularly relevant for academic scholarship and policy makers at both the global and national levels. 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. The intersectionality analysis also adds nuance to our understanding of the story of energy poverty, and how it cannot be fully separated from associated deprivations.

In terms of scholarship, this dissertation builds on existing models and combine with household surveys to show distributional implications across spatial, temporal and income scales. It also buttresses the importance of modeling heterogeneity for just transition research. Crucially, it brings the intersectionality theory to analyze energy poverty and provides empirical support, revealing underlying deprivations may overlap to impact impoverishment along different energy poverty dimensions.

The main policy implications of the findings include the following:

- **Limits of technology-based climate policy for social goals:** 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.
- **Broad-based climate policy to achieve development through decarbonization:** Another important policy implication is that focusing on the full basket of GHG emissions and going beyond CO<sub>2</sub> based targets could create “development space” for the most vulnerable. Rather than isolated climate policies, a broad-based policy package approach can help accelerate the transition to meet ambitious societal objectives. Policies need to be framed from in local context, with thought given to targeting specific approaches to different sectors to limit downstream distributional impacts to vulnerable groups. This finding is also supported by other literature showing better distributional consequences from approaches such as energy standards (Zhou & Mattauch 2022). As the IPCC report explains, “This transition also probably requires a full quiver of fiscal, financial and monetary policy instruments to enable a favorable financial environment to unlock required investments across geographies and sectors.” (IPCC 2022a)
- **Effort-sharing is crucial for Just Transitions, globally and locally:** 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. While financial transfers compensating 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. Even fairness in global effort sharing does not result in progressive outcomes within regions, and reduction in affluent consumption and luxury emissions is another form of effort sharing on the demand side. This is in line with recent examples in the literature also suggest the possibilities of reduction in affluent emissions through policies impacting beef (Castonguay et al. 2023), sugar (King & van den Bergh 2022), or the lifestyle emissions related to super-rich (Otto et al. 2019).

- **Aggressive “all GHG” targets required:** Given the importance of non-CO<sub>2</sub> reductions for attaining national energy goals and progressive energy burden reductions for households, countries should be explicitly encouraged to incorporate enhanced mitigation goals for non-CO<sub>2</sub> emissions related to diet and HFC reductions when putting forth updated mitigation pledges in future climate negotiations.
- **Social policy coupling with climate policy:** In countries plagued by high socioeconomic inequality, the process of climate ambition itself cannot be posited as a panacea for the inherent challenges of the physical world. How

climate policy itself is implemented may influence impacts of climate change by affecting the capacity of the vulnerable socioeconomic groups and regions to adapt to rapid transitions. Policy makers should envision climate change mitigation technologies as forms of public utility and not a privilege, so as to bridge the structural inequity gap. Other options where social policy can support Just Transitions with climate policy may include increasing minimum wages, easing indirect tax burdens, provision of targeted health and education services, increasing energy efficiency options and ensuring delivery of such options affordably to vulnerable households, and better models of electricity access financing.

- **Energy poverty beyond access:** Energy poverty does not exist in binary conceptualizations along single dimensions of access and energy connections. Since deprivations do not exist as independent storylines, direct comparison between underlying factors to identify the “more consequential” should be avoided. Multiple factors matter, and matter differently among different subsets of households. Programs to improve energy access should consider going beyond mere connections or across-the-board financial subsidies, to expand eligibility requirements for support and access to efficient services and appliances. Policy should also emphasize adequate, reliable and quality supply instead of the focus on connections to improve access metrics.

The findings around the impacts of demand side reductions and improved energy access suggest ways to couple social goals with climate goals to increase mitigation ambition. While we find that an “all tools” approach does have better outcomes

across and within regions, it is also important to note that demand side shifts were critical and indispensable to those results. Demand side mitigation options in this study were not directly related with a cost and are assumed to be based on changes to societal norms and intra-budgetary allocations and progressive taxation options. As seen in chapter 3, mitigation schemes based on increased carbon taxation alone would be highly regressive and less likely to have broad socio-political acceptance. In contrast, demand side shifts which enable better access through improved and cheaper, cleaner and efficient technology for residences and transport or reallocation of carbon tax burdens can support positive outcomes. This gives us reason to consider subsidy schemes (“carrots”) for some sections of society to increase uptake of climate-friendly options, while having a provision for taxes (“sticks”) for more affluent classes or highly polluting sectors of the economy. The balance between these carrots and sticks can enable increased mitigation ambition, while meeting social goals. The main takeaway here would be that a change in climate policy to account for improved access to cleaner and more efficient technologies for the most vulnerable sections is actually highly effective for meeting social and climate goals together, as against the conventional thinking that improved access to poorer sections would end up increasing climate change impacts. We see evidence of such thinking in the way infrastructure allocations and subsidies have been distributed in the recent Inflation Reduction Act (IRA) in the US. While the IRA comprises many carrots and a few sticks (around taxation of non-CO<sub>2</sub> leaks from oil & gas facilities), going forward an increasing range of such options needs to be explored.

### 5.3 Uncertainty in modeling results

As with other computational tools for addressing large and socially relevant problems, IAMs need to account for the key uncertainties characterizing processes and socio-economic responses. In the case of climate change, these are particularly complex given the very long-term nature of climate and the deep uncertainty characterizing technological and human systems. Besides inheriting all the typical sources of uncertainty plaguing the physical models of the Earth system, IAMs rest on highly idealized assumptions about the dynamics of the socio-economical system too, thereby introducing additional sources of uncertainties to reckon with.

Uncertainty arises in conditions of incomplete knowledge, and there are two main kinds of uncertainty with modeling. Risk, or aleatory uncertainty, characterizes situations or phenomena that are stochastic and where probabilities are known objectively. This can be termed model ambiguity or model uncertainty. Aleatory uncertainty is defined as external: being truly stochastic, is not reducible but can be quantified.

Model uncertainty is typically referred to as internal or epistemic: it is due to a lack of sufficient knowledge about the phenomena under study, and as such can be reduced, at least to some extent. Socio-techno-economic systems evolution is particularly fraught by complexities and uncertainties which are difficult to capture in mathematical formulations and in multi-decadal projections.

For IAMs, the aleatory-epistemic uncertainty distinction is loose. Aleatory uncertainty may not matter significantly in IAMs and it can be measured with defined and agreed probability distributions. IAMs are characterized by formulations (i.e., model equations) and calibrations (i.e., model parameters) which are deeply uncertain. Both can be improved with additional knowledge, although some uncertainties (i.e., the climate sensitivity) may never be reduced. Furthermore, uncertainty takes also the form of model misspecification, which conceives the idea that models are by design approximations and therefore the true model is likely not to be included in the considered set. This last form of uncertainty is especially relevant for IAMs: the complexity of economic, technological and social processes is so high that IAMs are necessarily mis specified.

And there is evidence of that: for example, all IAMs reviewed by the IPCC have underestimated the expansion and cost decline of solar and wind power technologies that have occurred in the past 10 years. Similarly, they have often overestimated the costs of climate policies in those jurisdictions for which actual data is now available. On the other hand, social opposition and political economy dimensions are not captured in model-based assessment. Such model misspecification has not been addressed so far, arguably because it is the most challenging to account for.

There are three main types of model components, physical, socio-techno-economic and normative, which are inherently uncertain in IAMs. We discuss each of these here, along with possible approaches to account for the impacts of each.

Physical components of IAMs include most notably the climate module translating emission pathways into climatic outcomes and, when being present, into physical climate impacts.

Socio-technoeconomic components comprise most of IAM processes, including the description of energy technologies, of socio-demographics, and of basic economic systems. Uncertainty about socio-techno-economic components of IAMs is due to our imperfect understanding about the impacts of climate change on human societies and the response of different forms of world organizations both at global and local scales. Since climate change is a relatively recent phenomenon, the exact effects it has on human well-being are largely unknown, for instance in terms of health and food availability. Similarly, we don't know which are the most effective and economical strategies and technologies to transition to a low carbon world. Furthermore, mitigation and adaptation challenges will depend on the underlying socio-economic system. Thus, baseline drivers such as population and economic growth, inequality between and within nations, institutional constraints and technological progress, scenario narratives and policies matter a lot.

Normative components refer to the evaluation frameworks embedded into the model, either as objective functions to be maximized or other. uncertainty about normative model components concerns the correct standard of evaluation itself and is a subject of philosophy and economics intersecting. Each component is affected by aleatory

and epistemic uncertainty, but the normative components of models, more than the physical and socio-techno-economic ones, are the most fraught by uncertainty and yet the least understood. Most of IAMs adopt utilitarianism, but alternative social preferences such as egalitarianisms or prioritarianism exist, and have been proposed as valid alternatives, yielding different results (Adler et al. 2017). Most models focus on human welfare alone but valuing nature for both what it provides to humans as well as for its intrinsic value is a legitimate alternative. A recent IAM application (Bastien-Olvera and Moore 2020) shows this is possible and relevant. Important welfare parameters, such as preferences over time, inequality, consumption, and aggregation of cost and benefits, are known to play a critical role in the outcomes of IAMs; the best know example being the choice of the time discount factor (Stern 2016). Other sources of normative uncertainty are unstated or taken for granted, what is called implicit normativity (Cribb 2020). Often, they have been treated as physical uncertainties: their ethical nature warrants a distinction: uncertainty about value is not uncertainty about empirical features or consequences of options (Dietrich and Jabarian 2019). As such, normative component uncertainty is clearly epistemic.

Regarding methods of assessment, uncertainty has been typically dealt with using sensitivity analysis. Parameters of interests are drawn from probability density functions, obtained by either analysis of historical precedents or by expert assessments, and fed into the models. The great majority of IAMs have run sensitivity studies, though more for validation than for quantification of uncertainties. Sensitivities in mathematical models such as IAMs have been typically executed by

varying one factor at a time. The sensitivity methods, despite their clear relevant and still limited application, are clearly suited for evaluating aleatory uncertainty with clearly definable probabilities. However, it is model uncertainty which pervades IAMs.

A possible way to cope with it consists in taking into account ensembles containing multiple models with different structures, so as to compare their projections under given forcing scenarios. Robustness analysis can then serve to evaluate the results of a model's simulation in the face of uncertainty. Specifically, a result is regarded as being robust if it occurs in almost all models. So, the degrees of confidence in a certain result would increase if it is robust across the ensemble. The ensemble approach is embraced by both Earth System Models (i.e., the Coupled Model Intercomparison Project (CMIP)) and Integrated Assessment Models (i.e., the Energy Modeling Forum). It has become a gold standard for treatment of model uncertainty by climate-economic models. However, this approach doesn't resolve model uncertainty, which is fundamentally related to how to weight different models.

In rare cases, model ensembles and sensitivity methods are combined with the aim of capturing both aleatory and model uncertainties. Coordination and computational costs unfortunately limit the application of these approaches, but the few exceptions have proven particularly useful. For example, Marangoni et al. (2017) decomposed the sources of uncertainties in the Shared Socio-Economic Pathways (SSPs) emission trajectories with a set of detailed process models.

A final approach for dealing with deep uncertainties in IAMs is to develop fully stochastic versions of IAMs. Several approaches of this kind have been developed, resorting to stochastic programming (Bosetti and Tavoni 2009; Lamontagne et al. 2019). Fully stochastic models are the ideal way of incorporating uncertainties; however, they are computationally hard, and as a result their application has been limited to either simple models or by simple spaces with only few state variables.

#### 5.4 Directions for 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 in chapter 3 does not delve into specifics beyond income poverty and furthering this analysis in with additional axes of deprivations would be an important analysis for just transition objectives. An effort towards this is made in our SI (Appendix B.2). 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. Examining proportionate and progressive approaches (defined in Metcalf 2017) would be an important next step. 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.

Additional and more ambitious demand side pathways, if demand was more malleable rather than based on fixed preferences, are also candidates for future work. It must be noted that pathways demonstrated here do not model reduction in meat or

energy consumption below the SSP-2 reference scenarios and more ambitious possibilities could have other progressive outcomes.

There could be positive or negative impacts of some of the pathways in some regions for other SDGs, such as air pollution. With a delayed net zero goal, there may be some delay in retirement of fossil fuel generation capacity relative to the CO<sub>2</sub> pathway, although the effects are still likely to be significantly more beneficial relative to REF. Further, in contrast to the outdoor air pollution aspects around fossil fuel sources, there could be co-benefits for indoor air pollution inside households with improved access to cooking fuels and a shift away from traditional biomass. The combined effect of these air pollution impacts could be an interesting avenue to pursue.

Similarly, expanding the scope of this analysis to cover other sustainability dimensions, particularly along the food-energy-water dimension is a consideration for future work. The analysis in Chapter 3 has already shown the interactive effects of food prices on residential energy burdens and unpacking the other impacts and one can explore how water and sanitation access could be affected by different supply & demand side mixes in these pathways.

It is possible that the results demonstrated through the GCAM IAM may be influenced by the assumptions and modeling uncertainties embedded in the tool. The residential demand computation in GCAM is highly dependent on floor area, and

different service choices in future may not follow from the historical trends around floor space and service level relationships. Other sources of epistemic and aleatory uncertainty also remain to be explored, and it should be an important area to consider in future work for a multi-model comparison. If similar trends are buttressed by other IAMs with different assumptions, it would provide additional validation to the policy implications presented here.

An important caveat is that these estimates of economic impacts of mitigation do not include impacts from climate change itself, and the associated economic benefits of avoided impacts. These could include loss of agricultural productivity, heat-induced mortality and morbidity and loss of labor productivity, infrastructure losses from extreme events and sea-level rise, biodiversity losses etc. (IPCC 2022b). Climate stress also has a complex relationship with migration and related geopolitical instability and with financial instability. Hence, our framework to consider only relative impacts between pathways would be better at than accounting for the costs of benefits under each.

Accelerating energy transitions to mitigate climate change also offers an opportunity to create a more equal world. However, to realize these benefits, policies must be designed with equity and a just transition in mind. Such climate action will require structural changes to the economy and political systems. However, the shrinking carbon budget would not accommodate delays and these changes need to be ignited

and capacity building must be done within this decade to limit impacts on social goals, apart from climate outcomes as well.

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. There are also significant socio-political constraints around how demand side or consumption reductions are perceived as an assault on freedom of choice by some sections. While it suggests avenues for improved awareness as a means to support societal change and moving beyond the correlation of consumption and well-being, adoption of such changes can be fraught with political risks. Further, while subsidies or “carrots” for increasing adoption and inclusion within energy services coupled with “sticks” or taxes and limits for affluent consumption and high emission sectors has progressive outcomes, the connection between the “carrot” and “stick” is underexplored. An increased focus on “carrots” may have consequences for the magnitude and timing of the “stick”, and also build in resistance to adoption of stronger measures later. Understanding the political economy of such combinations across sectors would be an important and critical step for models in future. Despite these caveats, the evidence supporting the case for progressive impacts from behavioural and societal transformations presented in this dissertation, and global effort sharing is compelling enough in order to be taken seriously and studied in more detail in specific regional and societal contexts.

## Appendix – A: Supplementary Information for Chapter 2

### A.1: 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 “REF” 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<sub>2</sub> 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 A.1. The RE, CCS-NUC, DAC, ELE, NoTrBio, BEH and COMPR 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 A.1:** *Assumptions over SSP-2 baseline in mitigation scenarios modeled in this report*

<b>Pathway name</b>	<b>Key assumptions</b>	<b>Remarks on implementation, if any</b>
RE	- Wind power capital costs fall at a higher rate initially, starting at	Assumptions in line with the high RE levels in SSP-1 implementation in

	<p>7% every 5 years to 0.1% fall by 2100</p> <ul style="list-style-type: none"> <li>- 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.</li> <li>Capital cost of Photovoltaic storage falls by 40% by 2100</li> <li>- Capital costs for geothermal power reduce by 25% till 2100</li> <li>- Renewables are equally preferred as other options, starting 2020 i.e. the choice between generation options is purely based on costs</li> </ul>	<p>GCAM. The last assumption was added to account for grid parity for RE and increased acceptance of the technology.</p>
CCS-NUC	<ul style="list-style-type: none"> <li>- CCS costs are 1/5 or 0.2X of SSP2 assumptions</li> <li>- Advanced nuclear (Gen III) is available and capital costs decline by approx. 2% every 5 years</li> </ul>	<p>Assumptions in line with high CCS and high nuclear implementation in GCAM for SSP-5</p>

DAC	<ul style="list-style-type: none"> <li>- DAC is limited to a level of 5 GtCO<sub>2</sub></li> <li>- DAC has lower preference over other negative emission technology options, and gradually rises to equal preference by 2050</li> </ul>	<p>Similar to SSP-1 implementation of DAC in GCAM</p>
ELE	<ul style="list-style-type: none"> <li>- Doubled preference (share-weights) for electricity as a fuel for buildings &amp; industry sectors, increasing along a linear trend from 2020.</li> <li>- 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.</li> </ul>	
NoTrBio	<ul style="list-style-type: none"> <li>- Zero share-weights for traditional biomass as a fuel for</li> </ul>	

	<p>buildings sector across all regions starting 2030, and linear reduction from the 2020 preference levels.</p>	
CAP-A	<p>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.</p>	<p>A version of this pathway and the broad principle has been demonstrated in George et al. (2022) and Yu &amp; Edmonds (2020)</p>

CAP-B	<p>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</p>	
SOVER	<p>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<sup>th</sup> in the subsequent 10 years and so on, representing a gradual and exponential</p>	<p>Modified version of the NDC Increased Ambition scenario in Ou &amp; Iyer et al. 2021.</p>

	tapering of mitigation ambition in the negative emission regions.	
GR.FATH	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.	
HIST.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.	
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The floor space satiation levels vary by regions based on income levels. The demand side pathways (BEH & COMPR) assume reduction in these levels for higher income regions, while leaving low income regions unchanged.

Region class in GCAM based on income levels	Residential floor space satiation levels in SSP-2, in sq.m. per capita	Residential floor space satiation levels in BEH & COMPR scenarios	Remarks
<b>A</b>	60	48	20% reduction over SSP2, 10% over SSP1
<b>B</b>	50	40	20% reduction over SSP2, 10% over SSP1
<b>C</b>	45	41	10% reduction on SSP2, same as SSP1
<b>D</b>	40	36	In line with SSP-1
<b>E</b>	35	32	In line with SSP-1

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 A.2) 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 A.2:** Assumptions in demand side mitigation pathways

Pathway	Assumptions
BEH	<ul style="list-style-type: none"> <li data-bbox="509 1224 1341 1549">- 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 &amp; fish) and a minor increase in sheep/goat meat consumption.</li> <li data-bbox="509 1591 1365 1770">- 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</li> </ul>

	<p>regions every 5-year period. Equivalent reduction in feedstocks.</p> <ul style="list-style-type: none"> <li>- Reduced floor space and smaller houses, limiting to an average of 30 sq.m/cap. Implemented through satiation values</li> <li>- Increased preference for ridesharing options, gradually increasing vehicle load factors by 25% to 2050.</li> <li>- Increased preference for public transport, akin to SSP-1</li> <li>- Reduced demands for aviation &amp; shipping, a 20% reduction in income elasticity of demand across regions</li> <li>- Increased preference for electric vehicles, as in the ELE scenario</li> </ul>
COMPR	<p>A combination of the BEH scenario, the ELE scenario (buildings &amp; industry), low CCS, high RE &amp; DAC, in addition to the following:</p> <ul style="list-style-type: none"> <li>- 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.</li> <li>- Constraining bioenergy to 100 EJ levels in 2100, a linear increase from current values</li> <li>- Lower preference for Nuclear technologies due to concerns on safety; Nuclear is only 1/4<sup>th</sup> as preferred compared to other equally priced technologies.</li> </ul>

	<ul style="list-style-type: none"> <li>- Gradual afforestation, involving a roughly equally balanced share of NETs in 2050 between DAC, forests and CCS</li> <li>- Reduction in oil &amp; gas methane leaks as in SSP-1</li> <li>- Reduced non-CO<sub>2</sub> from shipping (lower demand)</li> <li>- Complete ban on fossil fuel vehicle sales after 2050 for road transport options</li> <li>- Increased efficiency in cement, industrial feedstock conversion by 20% till 2050 and constant thereafter</li> <li>- Smarter buildings and increased energy efficiency, implemented through technology change rates doubling over the century</li> </ul>
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## A.2 Synergies and tradeoffs in other Global South regions

In this section, we show additional results for section 2.4, 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:

Africa East: 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

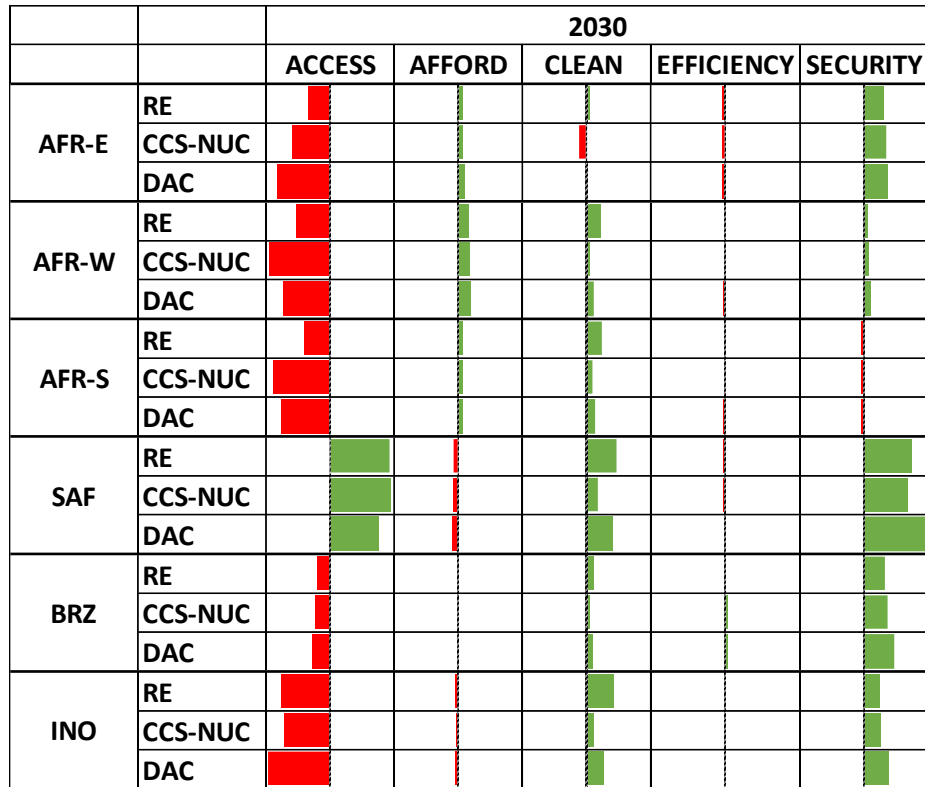
Africa South: Angola, Botswana, Lesotho, Mozambique, Malawi, Namibia, Swaziland, Tanzania, Zambia, Zimbabwe

Akin to the results in 2.4, 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. A2.1). 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.

		2030				
		ACCESS	AFFORD	CLEAN	EFFICIENT	SECURITY
AFR-E	NZ2040	Red	Green		Red	Green
	NZ2050	Red	Green		Red	Green
	NZ2060	Green	Green		Red	Green
AFR-W	NZ2040	Red	Green	Green		Green
	NZ2050	Red	Green	Green		Green
	NZ2060	Green	Green	Green		Green
AFR-S	NZ2040	Red	Green	Green		Red
	NZ2050	Red	Green	Green		Red
	NZ2060	Green	Green	Green		Red
SAF	NZ2040	Green	Red	Green		Green
	NZ2050	Green	Red	Green		Green
	NZ2060	Green	Red	Green		Green
BRZ	NZ2040	Red	Red	Green		Green
	NZ2050	Red	Red	Green		Green
	NZ2060	Red	Red	Green		Green
INO	NZ2040	Red	Red	Green		Green
	NZ2050	Red	Red	Green		Green
	NZ2060	Red	Red	Green		Green

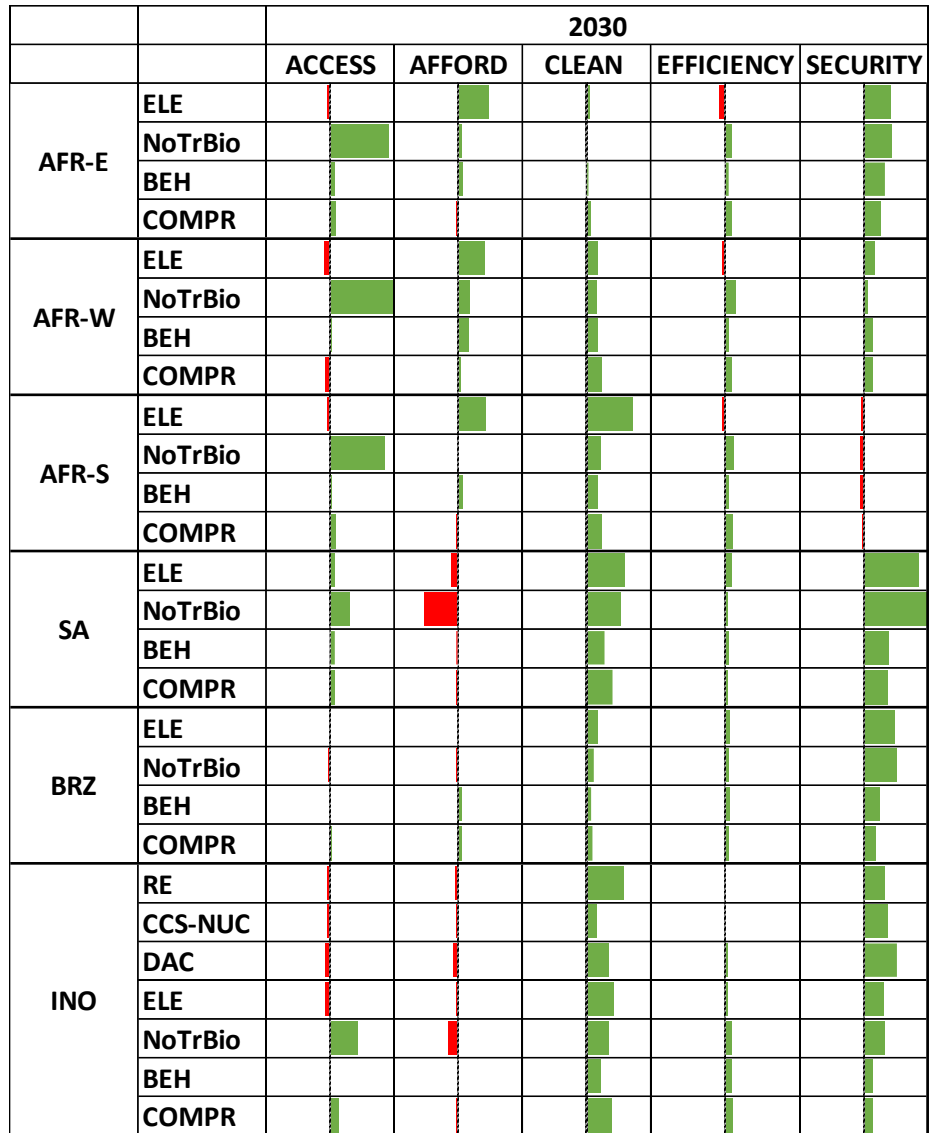
*Fig. A2.1: Synergies & tradeoffs for national energy goals for pathways varying by pace of transition*

For the technology & demand side pathways (fig. A2.2), 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 REF.

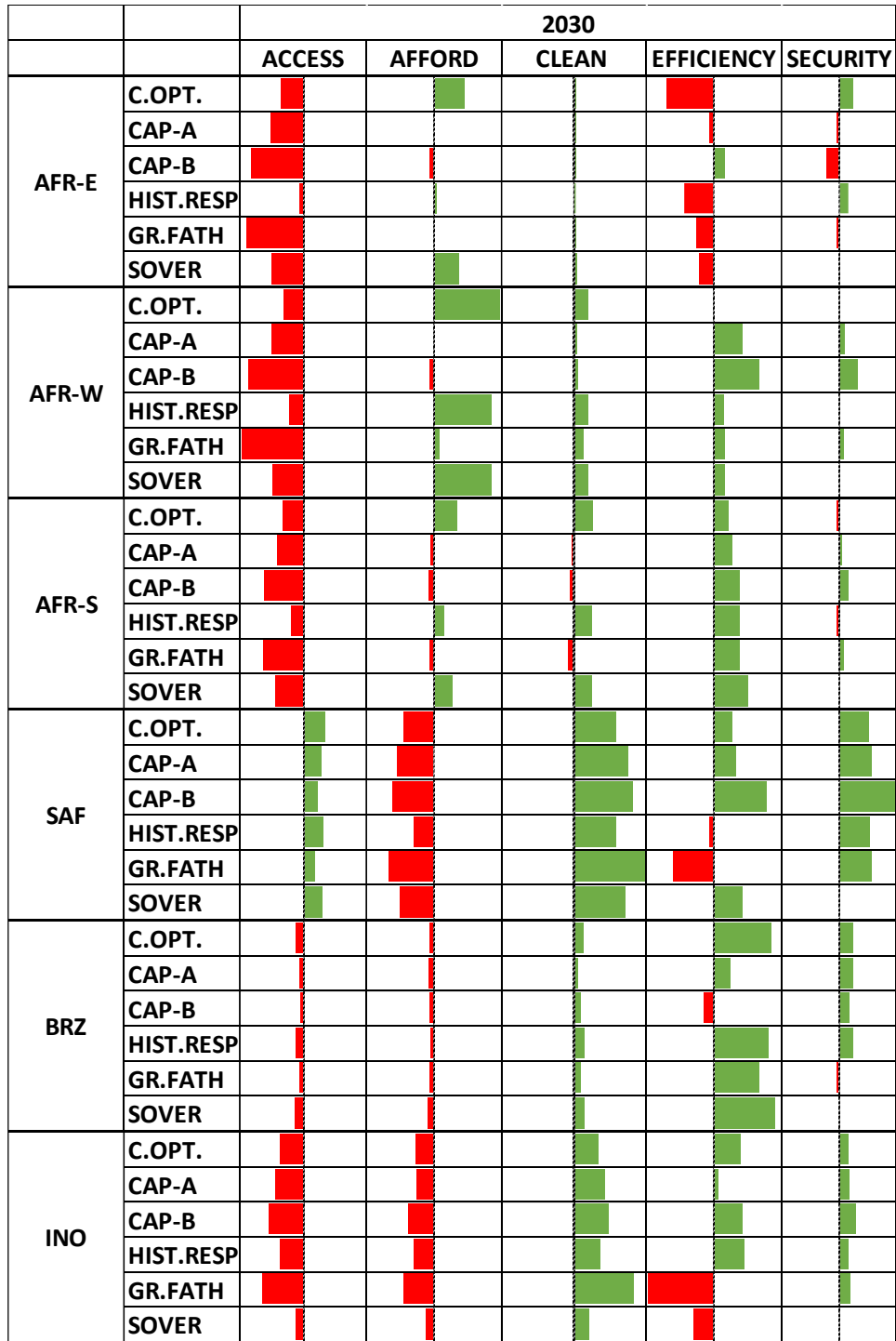


*Fig. A2.3: Synergies & tradeoffs for national energy goals for pathways varying by supply side technology choices*

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. A2.4: Synergies & tradeoffs relative to reference for national energy goals for pathways varying by demand side mitigation options*



*Fig. A2.4: Synergies & tradeoffs for national energy goals for pathways varying by effort sharing principle*

### A.3 Longer term synergies and tradeoffs

		2050				
		ACCESS	AFFORD	CLEAN	EFFICIENT	IMPORT
CHINA	NZ2040	█	█	█	█	█
	NZ2050	█	█	█	█	█
	NZ2060	█	█	█	█	█
EU-15	NZ2040		█	█	█	█
	NZ2050		█	█	█	█
	NZ2060		█	█	█	█
INDIA	NZ2040	█	█	█	█	█
	NZ2050	█	█	█	█	█
	NZ2060	█	█	█	█	█
USA	NZ2040		█	█	█	█
	NZ2050		█	█	█	█
	NZ2060		█	█	█	█

*Fig. A2.5: Synergies & tradeoffs for national energy goals for pathways varying by pace of transition, long-term results for the year 2050*

		2050				
		ACCESS	AFFORD	CLEAN	EFFICIENT	SECURITY
CHINA	RE	█		█	█	█
	CCS-NUC	█		█	█	█
	DAC	█		█	█	█
EU-15	RE			█	█	█
	CCS-NUC			█	█	█
	DAC			█	█	█
INDIA	RE	█		█	█	█
	CCS-NUC	█		█	█	█
	DAC	█		█	█	█
USA	RE			█	█	█
	CCS-NUC			█	█	█
	DAC			█	█	█

*Fig. A2.6: Synergies & tradeoffs for national energy goals for pathways varying by technology & demand side mitigation options, long-term results for the year 2050*

		2050				
		ACCESS	AFFORD	CLEAN	EFFICIENT	SECURITY
CHINA	ELE	█		█		█
	NoTrBio	█		█		█
	BEH	█		█		█
	COMPR	█		█		█
EU-15	ELE			█		█
	NoTrBio			█		█
	BEH			█		█
	COMPR			█		█
INDIA	ELE	█		█		█
	NoTrBio	█		█		█
	BEH			█		█
	COMPR	█		█		█
USA	ELE			█		█
	NoTrBio			█		█
	BEH			█		█
	COMPR			█		█

*Fig. A2.7: Synergies & tradeoffs for national energy goals for pathways varying by technology & demand side mitigation options, long-term results for the year 2050*

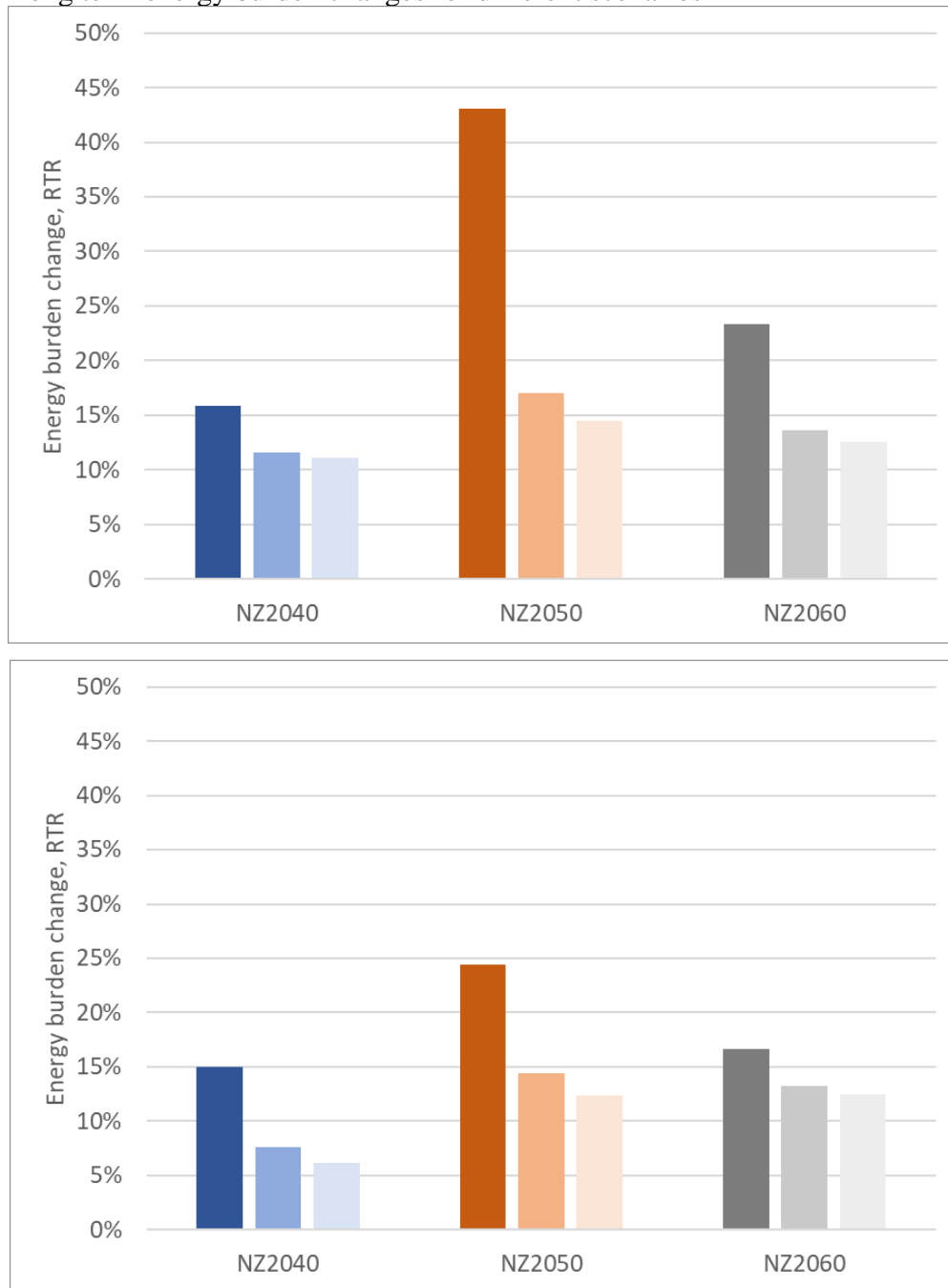
		2050				
		ACCESS	AFFORD	CLEAN	EFFICIENT	SECURITY
CHINA	HIST.RESP	█	█	█	█	█
	GR.FATH	█	█	█	█	█
	CAP-A	█	█	█	█	█
	CAP-B	█	█	█	█	█
	SOVER	█	█	█	█	█
	C.OPT	█	█	█	█	█
EU-15	HIST.RESP		█	█	█	█
	GR.FATH	█	█	█	█	█
	CAP-A		█	█	█	█
	CAP-B		█	█	█	█
	SOVER	█	█	█	█	█
	C.OPT		█	█	█	█
INDIA	HIST.RESP	█	█	█	█	█
	GR.FATH	█	█	█	█	█
	CAP-A	█	█	█	█	█
	CAP-B	█	█	█	█	█
	SOVER	█	█	█	█	█
	C.OPT	█	█	█	█	█
USA	HIST.RESP		█	█	█	█
	GR.FATH		█	█	█	█
	CAP-A		█	█	█	█
	CAP-B		█	█	█	█
	SOVER		█	█	█	█
	C.OPT		█	█	█	█

**Fig. A2.8:** 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 2.4 results, fig A2.5-A2.8 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.

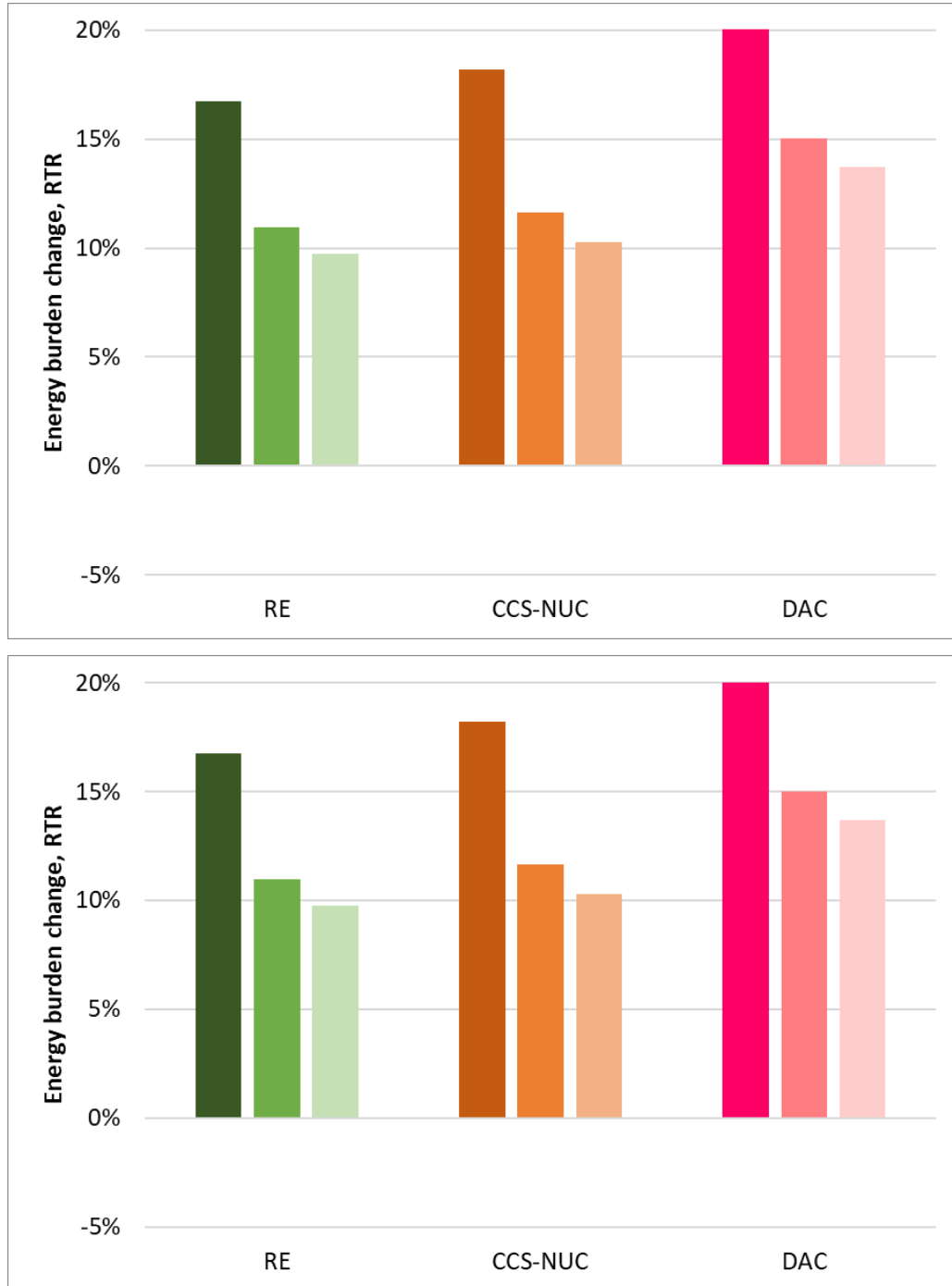
## Appendix – B: Supplementary Information for Chapter 3

### B.1 Long term energy burden changes for different scenarios



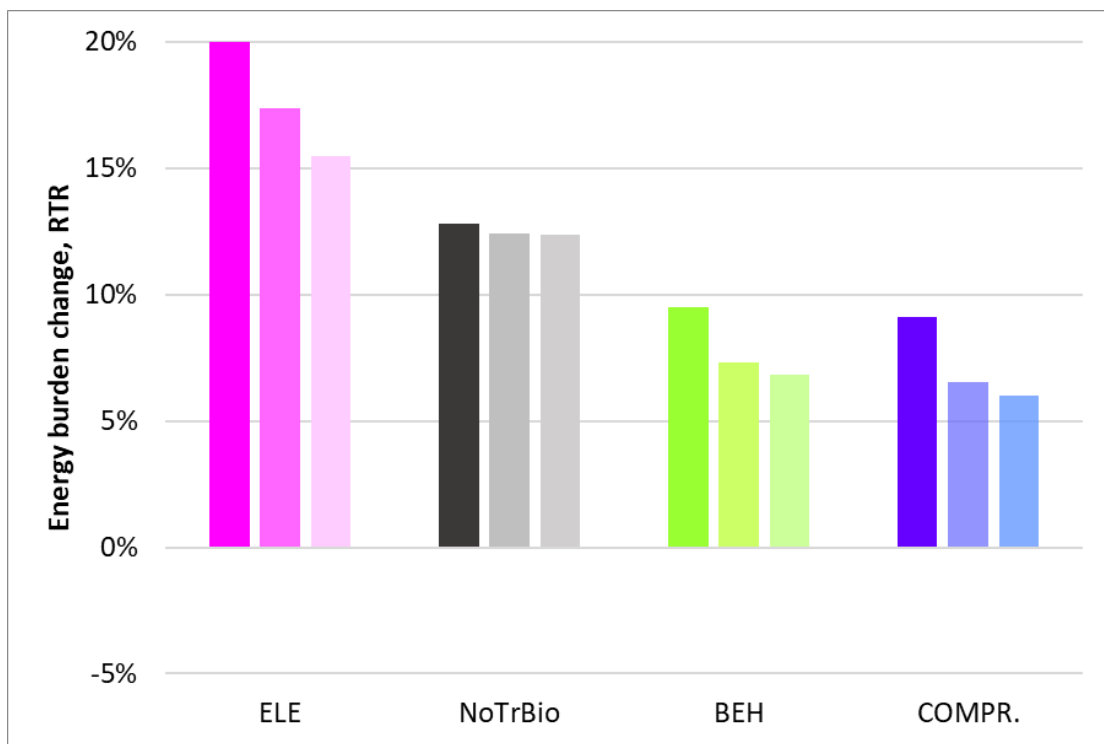
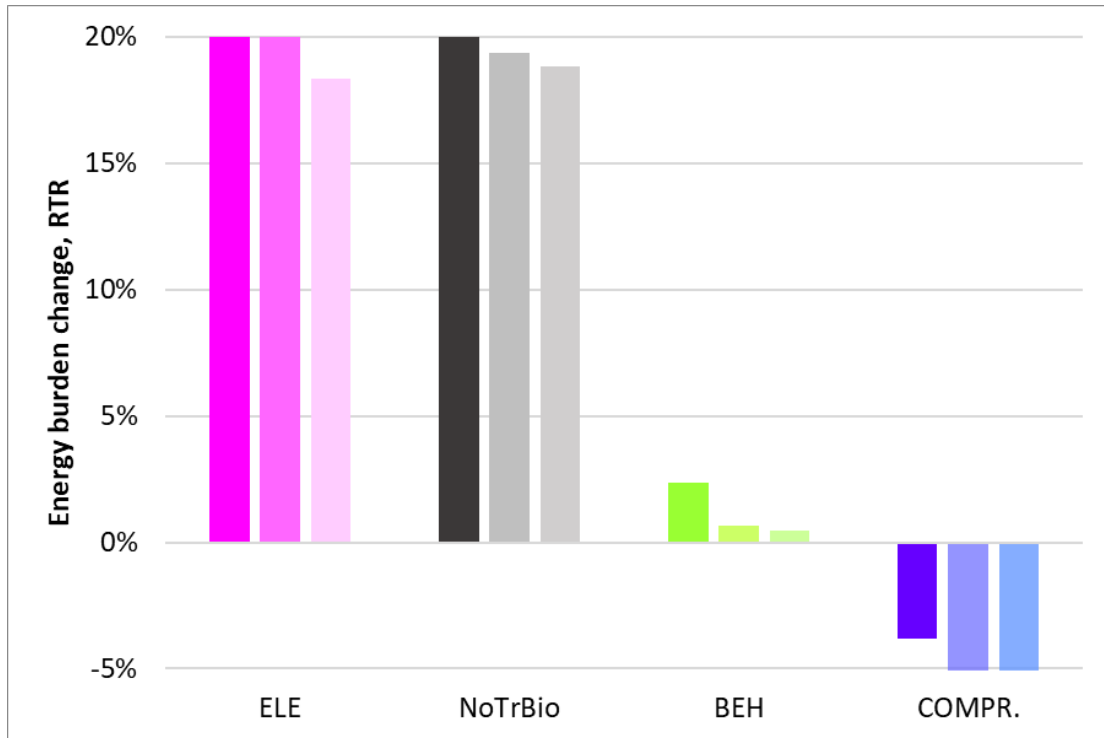
**Fig. B.1** Long term distributional impacts of mitigation policy on income deciles ranging from the poorest (D1), middle (D5) and richest (D10) in top panel (a) India,

and bottom panel (b) USA, for different mitigation pathways to 1.5C varying by pace of transition

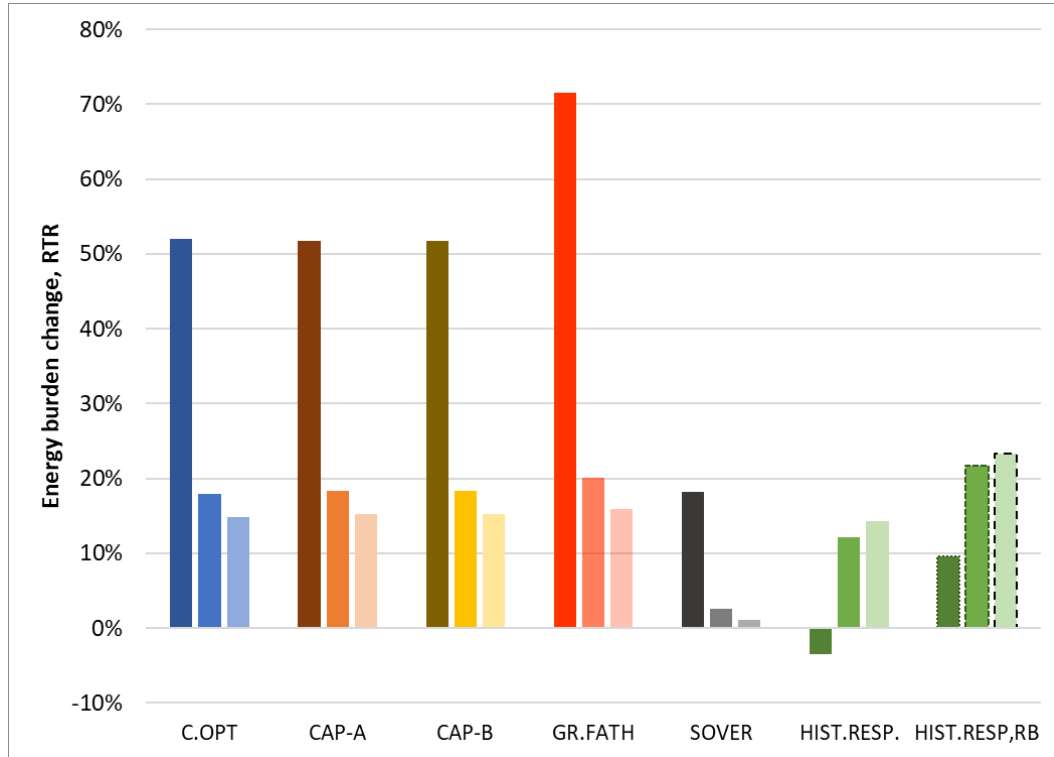


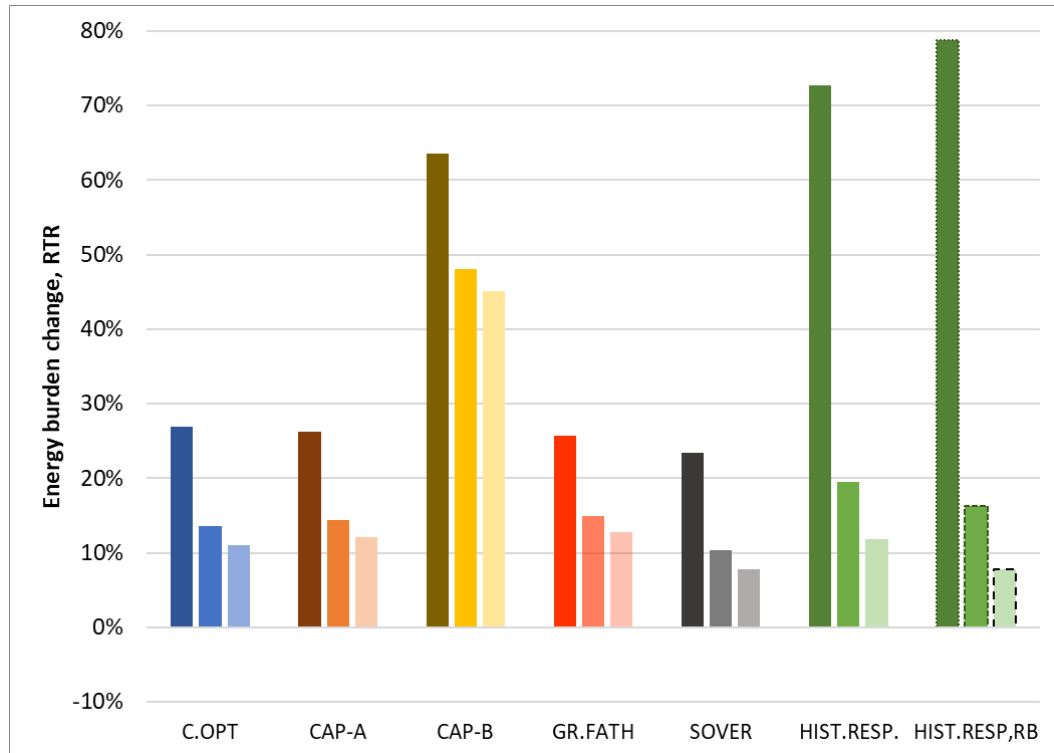
**Fig. B.2** Long term distributional impacts of mitigation policy on income deciles ranging from the poorest (D1), middle (D5) and richest (D10) in top panel (a) India,

and bottom panel (b) USA, for different mitigation pathways to 1.5C varying by supply side technology changes



**Fig. B.3** Long term distributional impacts of mitigation policy on income deciles ranging from the poorest (D1), middle (D5) and richest (D10) in top panel (a) India, and bottom panel (b) USA, for different mitigation pathways to 1.5C varying demand side technology changes





**Fig. B.4** Long term distributional impacts of mitigation policy on income deciles ranging from the poorest (D1), middle (D5) and richest (D10) in top panel (a) India, and bottom panel (b) USA, for different mitigation pathways to 1.5C varying by global effort sharing changes between regions

## B.2 Sensitivity Analysis – Alternative downscaling approaches

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:

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

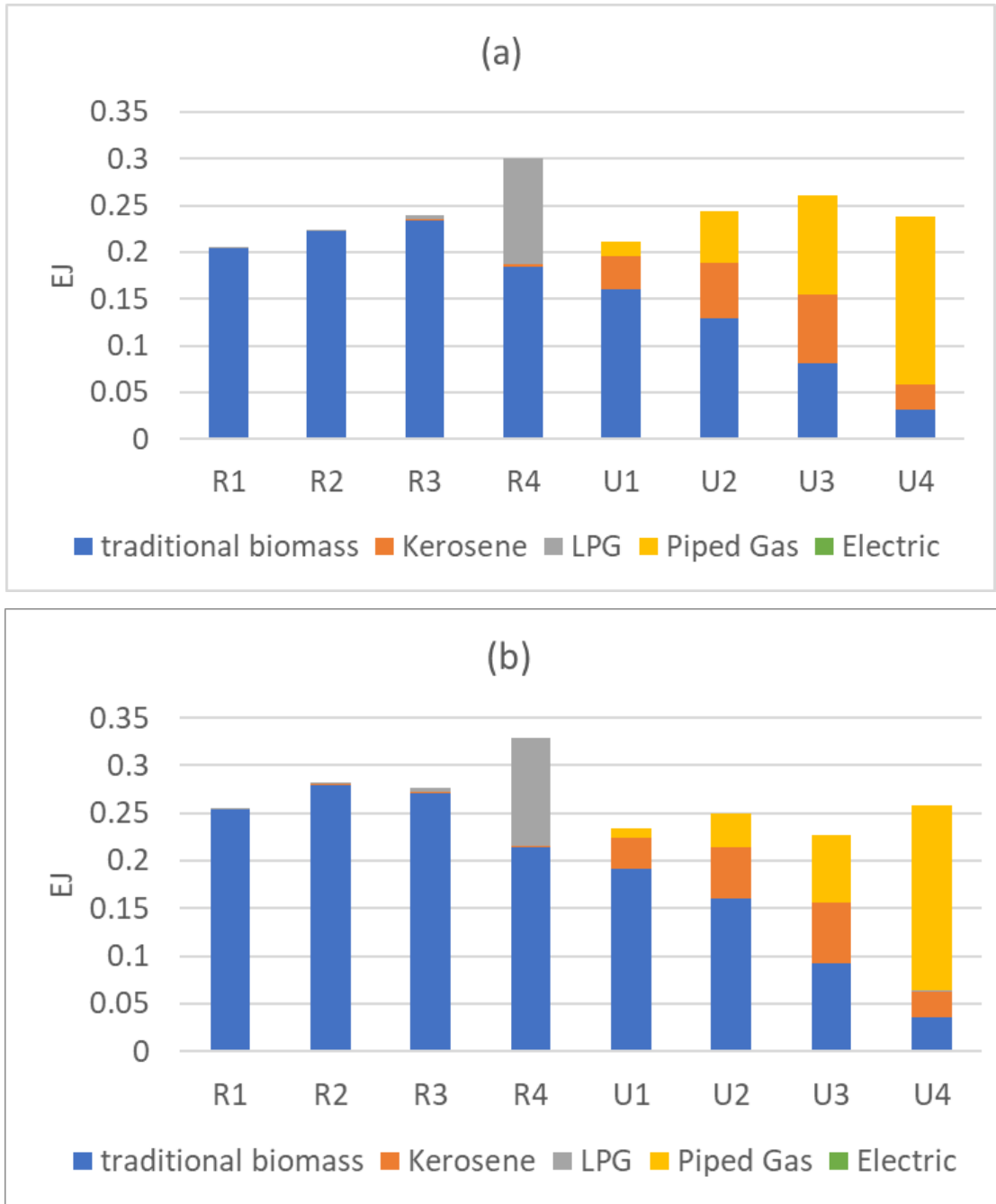
We assume,

$$\begin{aligned} & (\textit{Energy use for cooking in year } y) \propto \\ & (\textit{population in year } y) \quad (\text{E. 3}) \end{aligned}$$

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.

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 REF scenario (Fig. B.5), 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 shifts in some income strata, and hardly any changes in the most affluent tiers which has high demand elasticity.



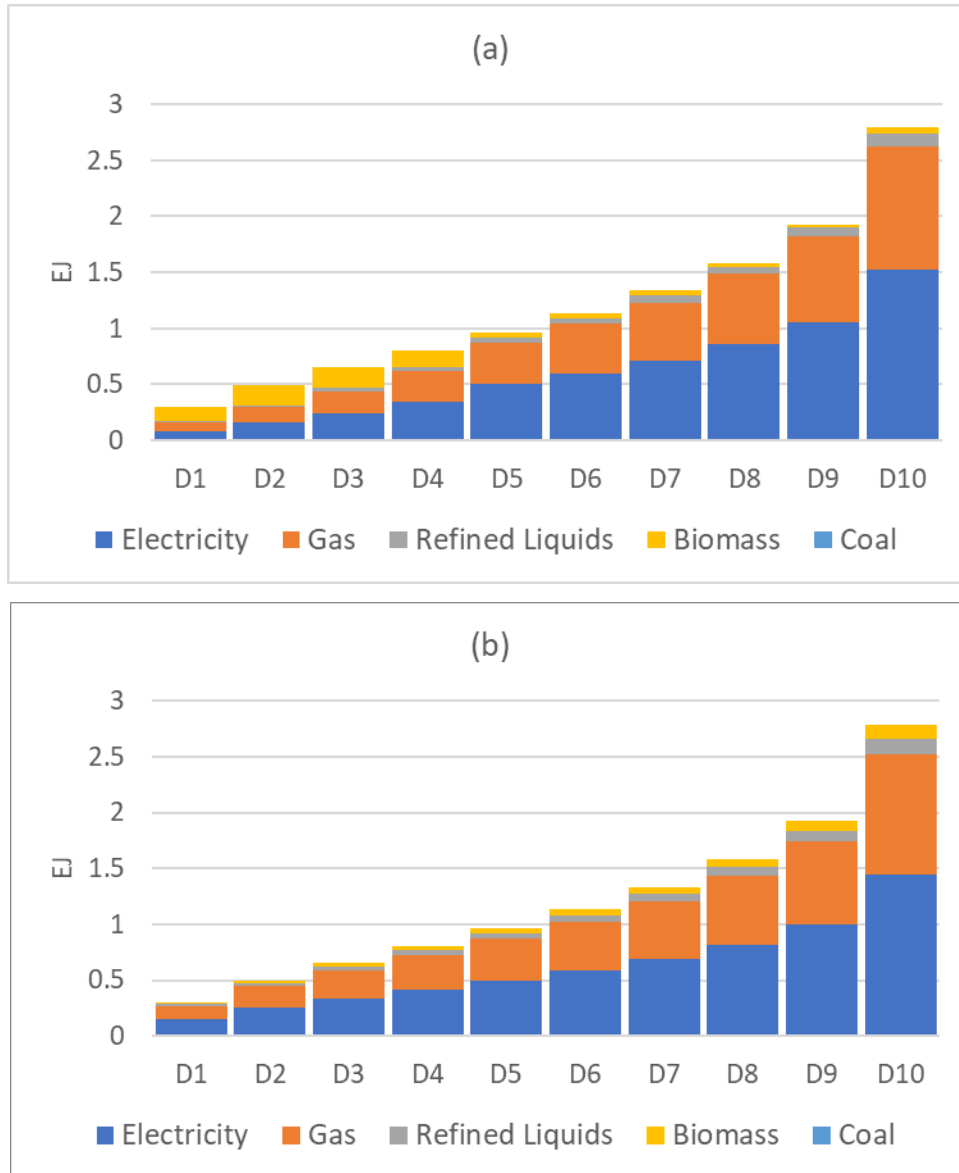
**Fig. B.5:** Downscaled results for rural (R1-R4) and urban (U1-U4) households in India showing energy consumption levels in the BAU (panel a) and net zero CO<sub>2</sub> 2050 mitigation pathway (panel b).

### B.3 Alternative downscaling approach – USA example

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. 3.4, 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.

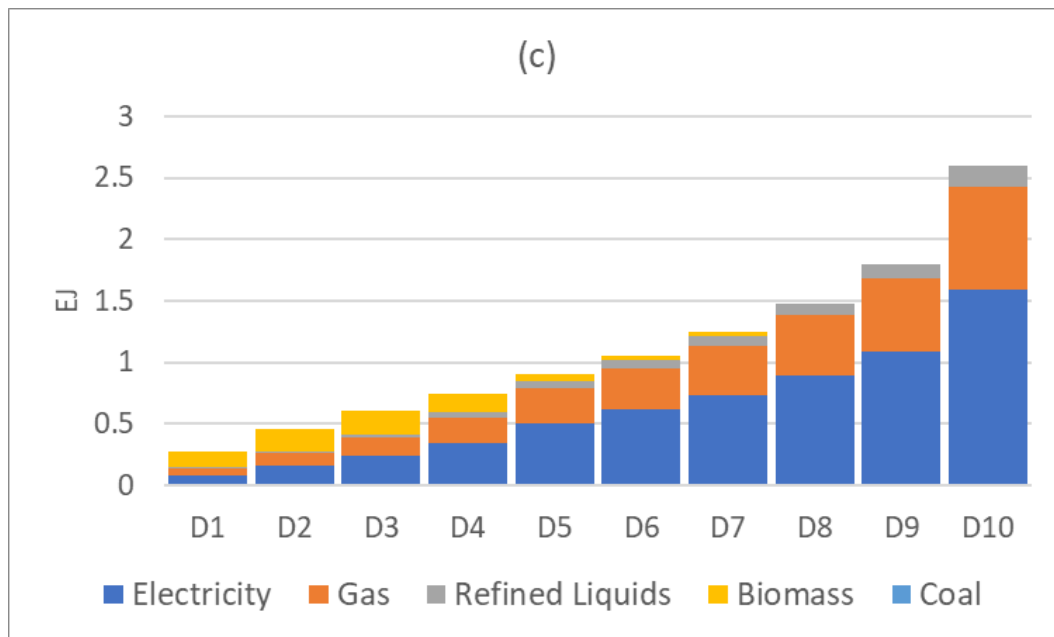
For example, poorer deciles consume lesser proportion of electricity and higher proportions of biomass-based fuels in the US; and the converse holds true for the top deciles. To account for this difference, we examined the results for the BAU scenario from the representation of income quintiles for USA 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. B.6(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. B.6 b). The difference in fuel choices by income strata between the two models are noticeable for the REF scenario in this study when we compare the two

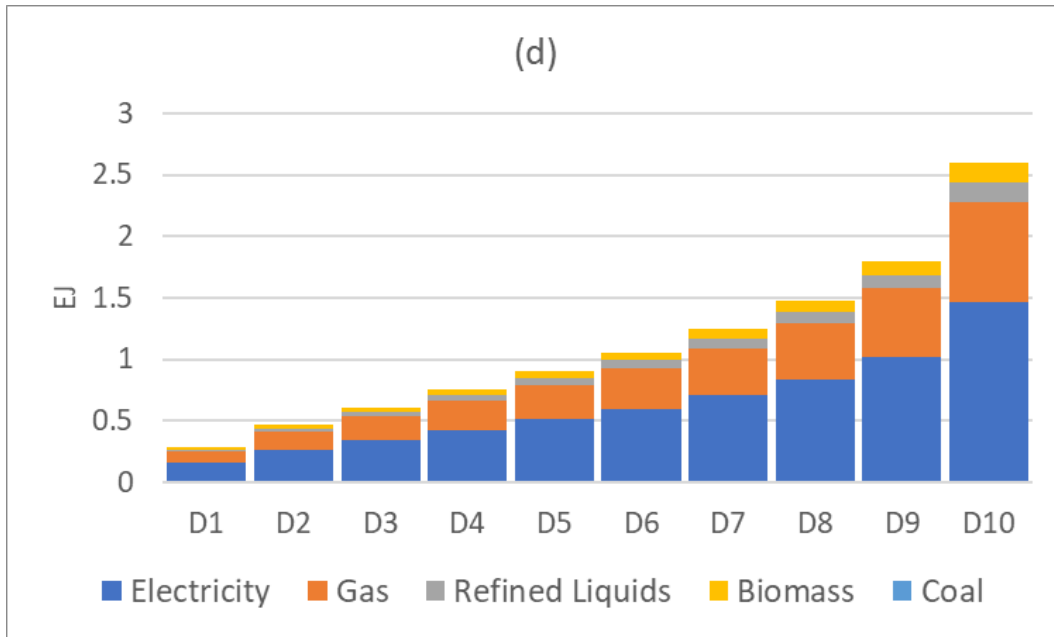
approaches, with richer households consuming greater shares of electricity and less of biofuels (Fig. B.6 e).



**Fig. B.6:** (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)

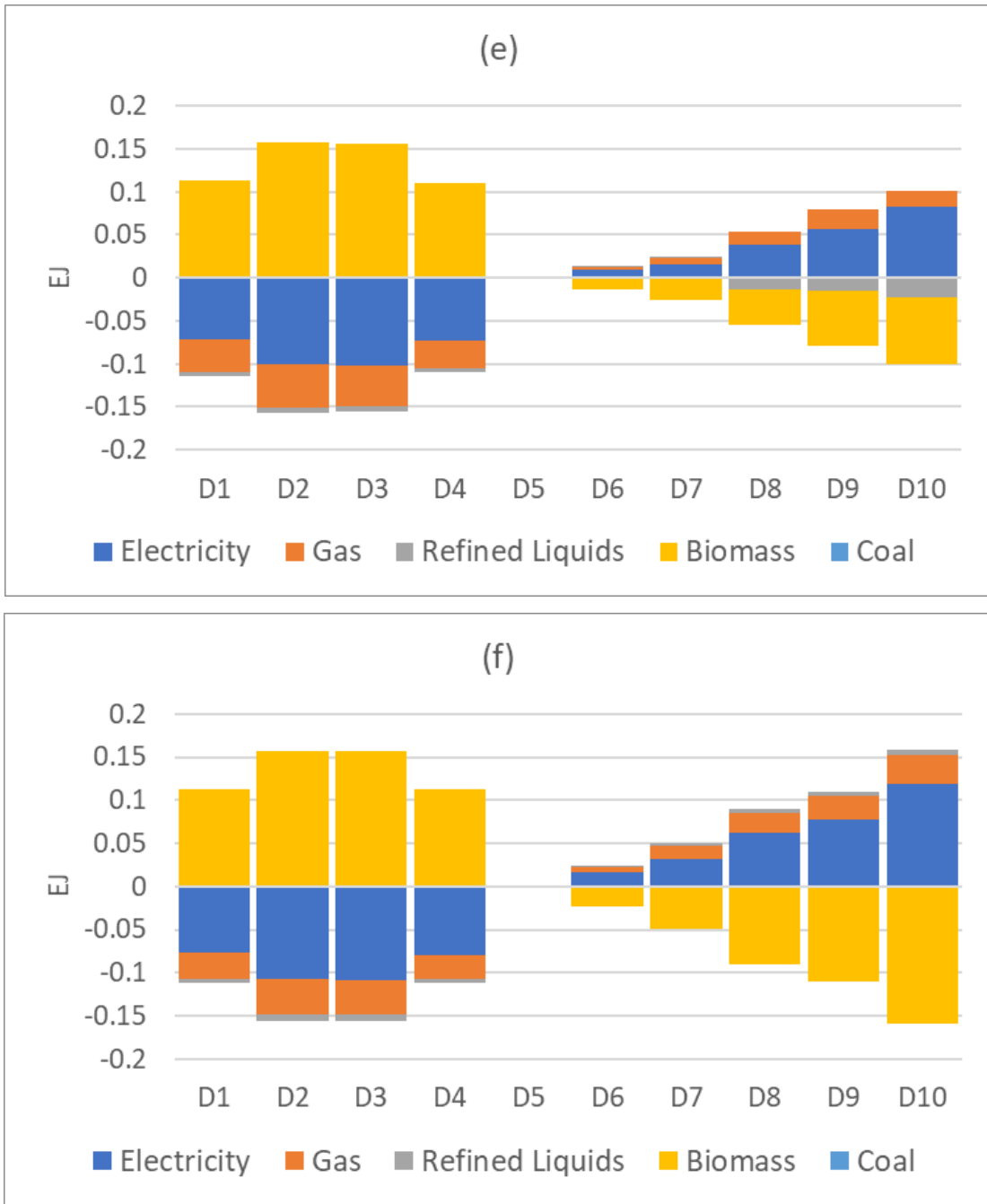
The demand price elasticity for electricity may be almost 0 for the richest households and closer to 0.5 for the poorest ones. For the affluent households, this means that there would be very small changes to electricity consumption with price increase, while poorer households would reduce consumption, as well as shift to other cheaper fuels under mitigation scenarios. We show an example of this below where the current downscaling model (Fig. B.6 d) and the model derived from Sampedro et al. (Fig. B.6 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. B.6 f).





**Fig. B.6:** (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<sub>2</sub> 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. B.6:** Difference in fuel choices by deciles compared when using the fuel choice model versus the current downscaling approach in this work, for the REF 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.

## Appendix – C: Literature Survey on Energy Poverty Measurement

Energy justice is a modern branch of environmental justice, centered around the notion that all individuals should have access to energy that is affordable, safe, sustainable and able to sustain a decent lifestyle, as well as the opportunity to participate in and lead energy decision-making processes with the authority to make change. It incorporates multiple dimensions of justice – distributional (sharing of benefits and burdens), procedural (participation of all), recognition (understanding historic and ongoing inequalities) and restorative (interventions and redistribution to address the first three) (Feenstra & Ozerol 2021, Lee & Byrne 2019, Jenkins et al. 2016).

Much of the literature on energy poverty is focused on defining and measuring it, an imperative to deal with the multiple justice dimensions that link to it.

### C.1 Defining energy poverty

There are many different definitions and visions of energy access and energy poverty, but they all refer to a level of energy consumption that is insufficient to meet certain basic needs. Energy poverty can be defined as ‘the absence of sufficient choice that allows access to adequate energy services, affordable, reliable, effective and sustainable in environmental terms to support the economic and human development’ (Reddy, 1999). According to this definition, energy poverty is an obstacle to

economic development, but energy poverty is basically explained by a low-income situation.

The access-based approach of measuring energy poverty depends on whether a household has access to desirable energy services. The IEA uses the access-based approach to assess worldwide energy poverty by calculating the number of people lacking access to electricity and modern cooking fuel (IEA, 2017). This approach has a binary nature that identifies households as with and without access to energy services (Culver, 2017). In this sense, this method suits for the discreteness requirement in categorizing people as poor and nonpoor.

While the term “access” can simply refer to physical proximity to modern energy carriers such as electricity, natural gas, liquefied petroleum gas (LPG), biogas and ethanol, according to the Global Energy Assessment, GEA (2012), access also implies the availability of affordable improved and more efficient end-use energy devices such as improved cookstoves (those using traditional fuels but burning in a cleaner fashion), more efficient lights, water pumps, low-cost agro-processing equipment as well as energy-efficient housing and transportation options. In a much broader sense, access refers to the affordable and stable services of cleaner energy options that are delivered in a reliable fashion and ensure consistent quality (GEA, 2012). Santika et al. (2019) use the definition in the UN’s Sustainable Development Goal, SDG 7 - Energy access includes electricity access and clean cooking fuel access, and the target is represented by two indicators:

Indicator 7.1.1 - Proportion of population with access to electricity and

Indicator 7.1.2 - Proportion of population with primary reliance on clean fuels and technology.

Kaygusuz (2011) conceptualizes energy poverty in terms of vicious and virtuous circles linking energy services and poverty. Energy services for poverty reduction are less about technology and more about understanding the role that energy plays in people's lives and responding to the constraints in improving livelihoods.

### C.2 Measuring energy poverty

While the UN SDGs have enabled a broader conceptualization of energy poverty, going from mere access to services, national and global measurements have lagged. The methodologies and indicators that have been proposed in the literature to measure energy poverty are quite diverse. Some are subjective approaches based on personal or third parties' perceptions of affordable warmth at home; whereas others calculate objective indicators. Pachauri & Spreng (2011) appraise alternative measures of household energy poverty, that aim to inform policy and programs and call for widening the focus of evaluation and necessity to design indicators that adequately assess the needs of beneficiaries and describe the living conditions of families and communities.

The economic approach to energy poverty is linked to economic parameters. The most common factor of such an approach is mapping energy poverty to income (or expenditure) poverty (Pachauri et al., 2004). Under this approach, energy poverty line is considered as the value of average energy consumption of households who are at income poverty line (Foster et al., 2000; Pachauri et al., 2004). There are two other alternatives under economic approach. One is based on the energy budget share, i.e., share of household expenditure spent on energy, where one finds poor spending greater share on energy compared to higher income groups (Leach, 1987; Pachauri et al., 2004; Kemmler, 2007). The other is based on the effective price, i.e., price paid by the household per unit useful energy, which shows a wicked gradient: better-off paying a lower price per unit energy (Leach, 1987; Foster et al., 2000; Pachauri et al., 2004; Kemmler, 2007). Lack of access to affordable modern energy services encourages the poor to use inefficient fuels along with inefficient devices and spend more time as well as effort in availing the same (Pachauri et al., 2004; Kemmler, 2007).

The engineering approach of assessing energy poverty is basically a bottom-up approach that estimates directly the energy requirement of households based on normative requirements of different energy services on the part of households. It calculates the poverty threshold by considering the specifications of different energy carriers (calorific value of fuels) and energy appliances (size, efficiency, etc.) used to derive these basic energy services (Pachauri et al. 2004; Goozee, 2017). For instance, Reddy (1999) estimated that the basic final energy requirements were 100 W per

capita assuming safe, clean, and efficient cooking with liquefied petroleum gas (LPG) or LPG-like fuel, and electricity for lighting, space comfort, food preservation, and entertainment.<sup>12</sup> Other examples of estimations of energy poverty based on engineering approach are: 1 kW per capita primary energy by Goldemberg et al. (1985), 50 kg of oil equivalent (kgoe) of annual commercial energy per capita (40 kgoe for cooking and 10 kgoe for lighting) by Modi et al. (2005), among others.<sup>13</sup> Another example under this approach is the minimum annual electricity requirement specified by IEA (2014, p.81) to be 250 kWh and 500 kWh in rural and urban households, respectively. This approach has the flexibility of finding energy thresholds for different needs in different geographical and socio-cultural settings. Recent efforts have also examined avoided or under-consumption of energy (Day & Walker 2016). An interesting innovation has been the use of temperature, using thermostat settings, as a proxy dimension (Cong et al. 2022).

Considering the multidimensional nature of energy poverty, and the need to capture a range of various elements to adequately reflect the complexity of the nexus between access to modern energy services and human development, a multicriteria framework therefore appears ideally suited. Nussbaumer et al. (2012) first suggested a composite index as a means of capturing multiple deprivations. The new index – the Multidimensional Energy Poverty Index (MEPI) – focuses on the deprivation of access to modern energy services. In contrast to other tools, we focus on quantifying energy deprivation, as opposed to energy access. number of indices include consumption-based indicators under the assumption that energy consumption is

correlated to development. While recognizing the value of such conglomerative approaches, a deprivation perspective offers a valuable complement by focusing specifically on the poor, thereby providing a more direct indication of the relevant aspects of poverty. Multi-dimensional Energy Poverty Index' or MEPI proposed by Sadath and Acharya (2017) and Acharya and Sadath (2019) is one such example which aggregates household's energy deprivation in cooking and lighting fuels using the AF framework multi-dimensional poverty (Alkire and Foster, 2011). Another example of MEPI is the one developed by Okushima (2017). This MEPI is composed of three attributes (dimensions) of energy poverty, specifically for developed countries: energy costs, income, and energy efficiency of housing.

There are energy poverty measures in literature which combine different approaches. For instance, the World Bank (Bhatia & Anjelou 2015) has developed a multi-tier framework (MTF) to go beyond the binary notion of access and to include various service quantity and quality, affordability, and pollution parameters, and different tiers specify different threshold values for these parameters. The specifications under MTF are combination of different approaches. For example, thresholds on certain tier on household electric supply specifies a minimum of 800 W peak capacity (engineering-sense), minimum of 16 hours of supply with minimum of 4 hours of evening supply (access-sense), maximum spending of 5% of household income (income-sense), and absence of past accidents and risks in future (outcome-sense). This framework is comprehensive yet compromised on simplicity and made the methodology complex and cumbersome (Culver, 2017). Additionally, the 'Energy

Access Index' or EAI conceived in this method being an aggregated measure across all services, turns out to be less meaningful as highlighted above (Culver, 2017).

Beyond the definition and measurement of energy poverty, which have mainly attracted research interest over the last decades, attention has recently begun to turn to a broader notion of energy vulnerability and energy burdens. So far, this has mostly been approached on a theoretical base, suggesting the incorporation of broader socio-economic aspects into the energy poverty framework. An example is the 'Vulnerability Index' developed in Papada & Kaliampakos (2019), which, based on stochastic analysis, quantifies the vulnerability of a population to the energy poverty ratio, compared to a reference population. Another example is the household energy burden measured for the US (Drehbol & Ross 2016).

Comprehensive reviews of energy poverty metrics are available in Pelz et al. (2018) and Nathan & Hari (2020).

### C.3 Knowledge Gaps

The different metrics and terms for energy poverty have shown a variation by geographical context, but the most important elements remain access (especially reliability, beyond mere access to supply sources), affordability (as a share of household income) and service (having appliances or means to convert energy to useful forms). Energy is an "intermediate" commodity or carrier. It is valued not so

much for its own sake as for the services it enables and the objective of measuring populations that experience a degree of hardship in achieving a decent standard of living must be kept in mind. Access based metrics provide very limited information about well-being and obfuscate injustices. Access does not imply utilization and even utilization may not imply agency, considering the affordability dimension. Global-North metrics examining energy affordability or avoided energy use are not amenable to the Global South where access and service dimensions dominate.

An under-appreciation of the transitional nature of energy poverty is also a feature – many more households which energy poor may be based on conditions or circumstances than measured by these metrics. Examining the set of conditions leading the circumstances is important (Bouzarvoski 2014). Most metrics also miss the depth, severity or geographical and socioeconomic distribution of the energy poverty dimensions measured.

Another gap remains in identifying the causes or driving factors leading households into energy poverty. This has often been studied from an energy pricing or income poverty dimension (Khandker et al. 2012, Brown et al. 2020) or using approaches such as principal component analysis to identify a set of household characteristics as the cause (Gupta et al. 2020). It has been shown that more people are energy poor or deprived of decent living standards than are income-poor, even when numbers are measured against medium income poverty thresholds (Kikstra et al 2021), but identification of underlying factors remains sketchy. Bouzarovski and Simcock

(2017) show how certain social groups literally appear to “fall off the map” with respect to fairness, energy access, and policy recognition. Understanding the driving factors is important since transitional energy poverty may result from climate action and many households may remain vulnerable or at the thresholds, falling back into an energy poverty trap under certain policies. One of the most important contributions in identifying populations that are often missed by conventional or single dimension analysis like income or energy prices would be to consider intersectionality. Intersectional theory can shine a light on the hidden costs of resource extraction, as well as renewable energy development (Chatalova and Balmann 2017), which go beyond environmental or health risks to include the socio-cultural impacts on both communities adjacent to these sites and those who work in them (Daum 2018). development decisions often do not properly integrate the burdens and risks placed on marginalized groups, like indigenous peoples, while risk assessments tend to reinforce existing power imbalances by failing to differentiate between how benefits and risks might impact on certain groups (Healy et al. 2019; Kojola 2019)

## Appendix – D: Supplementary Information for Chapter 4

### D.1 Intersectionality theory

Intersectionality is an analytical framework and a key tenet under the Critical Race Theory (Bell 1979, Ladson-Billings & Tate 1995) for understanding how interlocking aspects of a person's social and political identities combine to create different modes of discrimination and privilege. The term was coined by Kimberlé Williams Crenshaw in 1989 to explain structural, political and representational factors that influence how women of color experience violence (Crenshaw 1990).

Intersectionality identifies multiple factors of advantage and disadvantage. Examples of these factors include gender, caste, sex, race, class, sexuality, religion, disability, physical appearance, and height. These intersecting and overlapping social identities may be both empowering and oppressing (Crenshaw 1990). Human beings are shaped by intertwined social identities, and each level of identity has differences in power and privilege within society. Privilege itself is a system of advantage that occurs in society based on membership and identification with the agent group, unearned advantages and opportunities afforded to those who identify with agent groups, but not afforded to those who identify with target groups (Bell, 2007). These multiple identities interact in different ways with systems and structures of power to create and perpetuate oppression of marginalized or target groups. These, in turn, alter lived experience of prejudice and discrimination, privilege and opportunities, and perspectives from particular social locations.

Adopting an intersectional approach involves dismantling the systems of oppression and placing marginalized people at the center of policy making, working towards distribution of collective power, rather than outcomes based on an underlying hierarchy.

The term “Intersectionality” made it into the Oxford English Dictionary in 2015, which calls it a sociological term meaning “The interconnected nature of social categorizations such as race, class, and gender, regarded as creating overlapping and interdependent systems of discrimination or disadvantage; a theoretical approach based on such a premise.” Merriam-Webster’s definition is a little less academic: “the complex, cumulative way in which the effects of multiple forms of discrimination (such as racism, sexism, and classism) combine, overlap, or intersect especially in the experiences of marginalized individuals or groups.” (Coaston 2019). Intersectionality operates as both the observance and analysis of power imbalances, and the tool by which those power imbalances could be eliminated altogether.

‘Standing at the path of multiple forms of exclusion makes you likely to get hit by both’ (Crenshaw 2016). Using separate reference frames for energy poverty has led to a preponderance of studies emphasizing a single dimension, usually income poverty. Intersectionality theory suggests that these separate reference frames do not work independently, and some identities slip through where the frames overlap. The overlapping frames imply multiple levels of social deprivation or injustice and involve communities that policy makers, politicians and journalists often ignore.

Crenshaw also suggested that addressing deprivations on the single frame approach is similar to a ‘trickle-down approach to social justice’ and is likely to fail. Applications of intersectionality to aspects beyond racial justice dimensions have been few, such as Ferguson (2021) on seafood trade.

#### D.2 The “Alternative Framework” for energy poverty measurement

This study adapts the Alternative Framework (AF) developed by Pachauri & Rao (2020) – separating the dimensions of energy access, affordability and service by household tiers. A similar approach was demonstrated by Jain et al. (2018), though it was inherently susceptible to mixing fuel and dimension of poverty. The advantage of the AF is that it enables a distinction between the condition of energy poverty and the conditions or causes that lead to it. Pachauri & Rao (2020) demonstrated the approach for electricity poverty in developing countries. Following from Pelz et al. (2021), I propose the AF to cooking fuels in India as well. The different household tiers based on this framework are shown in **Tables D.1 & D.2** for electricity and cooking fuels respectively.

**Table D.1:** Application of AF to electricity access in India

	<b>Supply condition</b>	<b>Household (HH) conditions</b>		
<b>Energy poverty level</b>	<b>Access (hrs)</b>	<b>Affordability (% of HH spending)</b>	<b>Service levels (appliance ownership)</b>	<b>In Pachauri &amp; Rao (2020)</b>
Impoverished	0	>10%	None	Tier 0
Burdened	<8	7.5-10%	Minimal	Tier 1
Stressed	16-Aug	5-7.5%	Decent	Tier 2

Non poor	>16	<5%	Affluent	Tier 3
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For appliance ownership and service levels, an impoverished household is defined as one with mere subsistence services of lighting, minimal appliance ownership implying lighting, fans & phone charging. A decent level is defined as the addition of a television or means of entertainment, and addressing the refrigeration needs to a degree (an air cooler) and food preservation means (refrigerator), while the affluent tier would further have air conditioning options and other electronics.

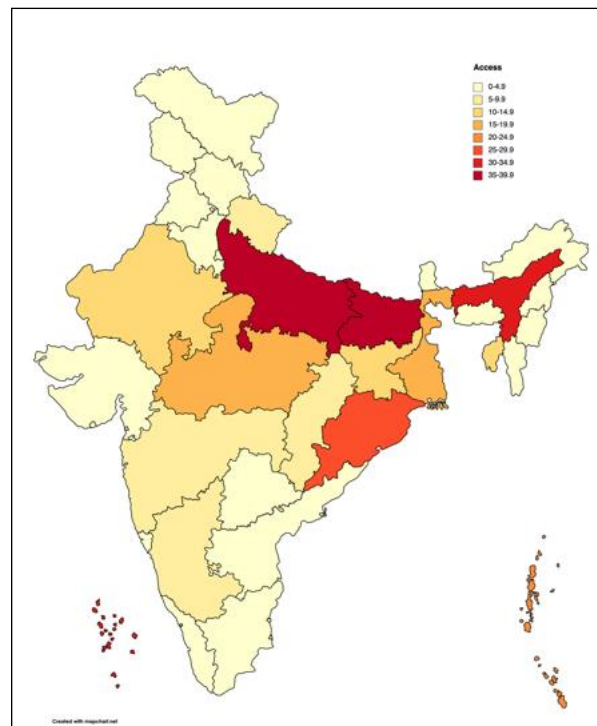
**Table D.2: Application of AF to cooking fuels in India**

Energy poverty level	Supply condition	Household (HH)condition	
	Access (hrs)	Affordability (% of HH spending)	Service levels (appliance ownership)
Impoverished	Firewood, twigs, dung cakes, crop residue	>10%	Wood stove, open flame etc.
Burdened	Coal, charcoal	7.5-10%	Chulha (Indian stove) without chimney
Stressed	Kerosene, LPG stacking, LPG from black market	5-7.5%	Chulha with chimney
Non poor	LPG use only	<5%	LPG/ kerosene stove, electric cooking

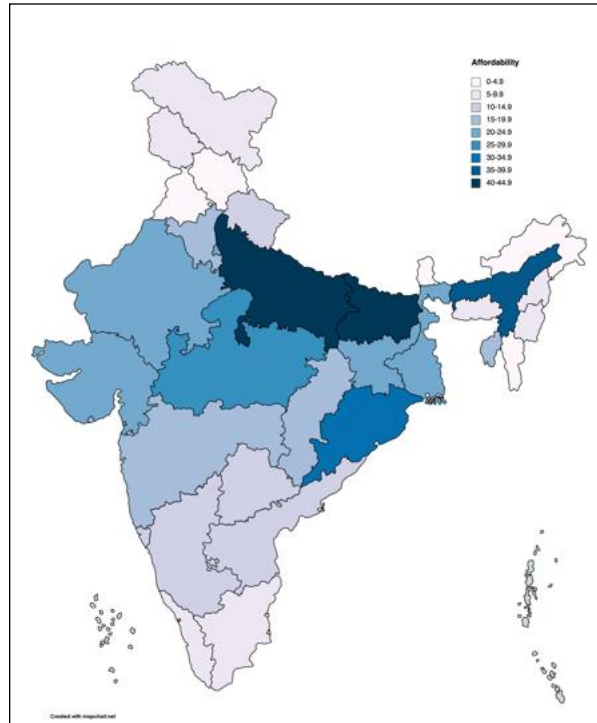
We adopt a similar structure for cooking fuels in table D.2, also accounting for the wider basket of fuel sources possible and unique difficulties in sourcing them, such as the black market. The appliance ownership tiers in this case evolve to consider the cooking stoves which are the means of converting the energy to service and the aspects of indoor air quality which may be affected by them.

The affordability tiers in both cases are largely synonymous with existing literature, though it may vary with the national context as well.

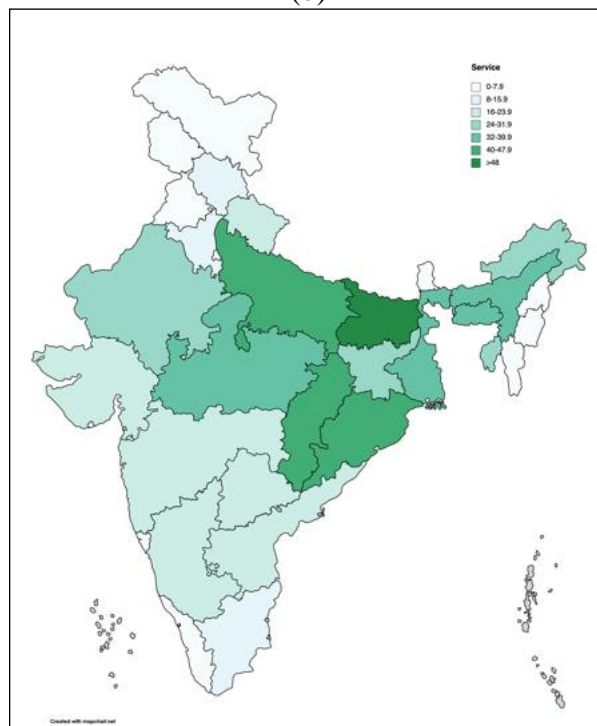
### D.3 The distribution of energy poverty in India



(a)

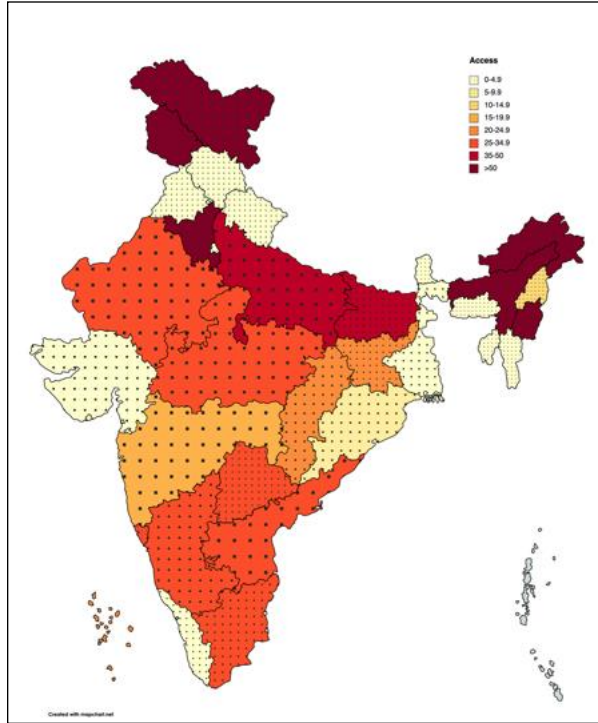


(b)

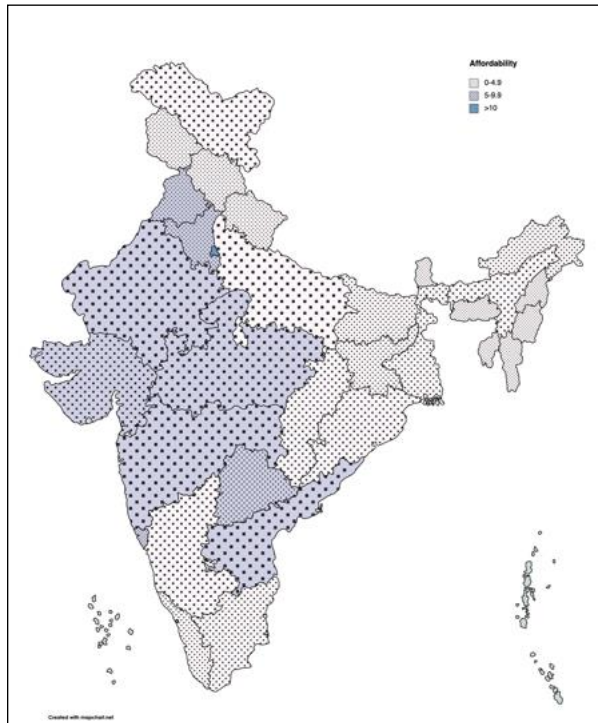


(c)

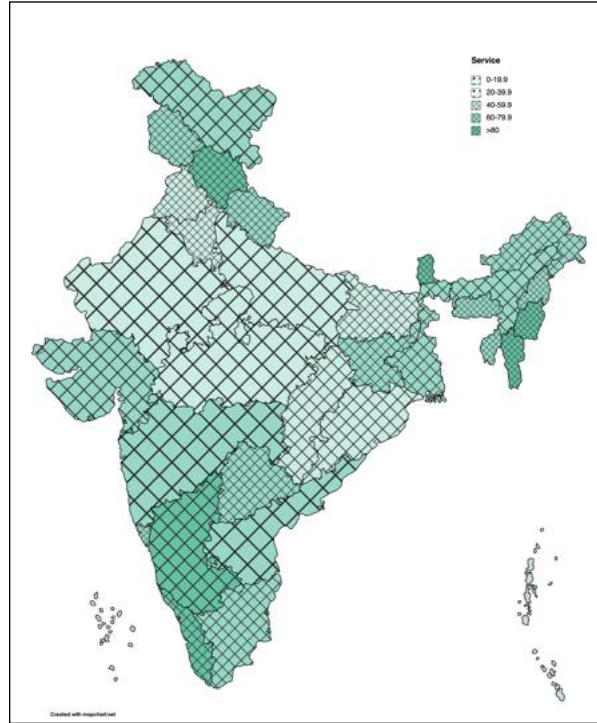
**Fig. D.1:** Percentage of households in the bottom/ impoverished tier in terms of electricity dimensions for (a) access, (b) affordability and (c) services and appliance ownership across different Indian states



(a)

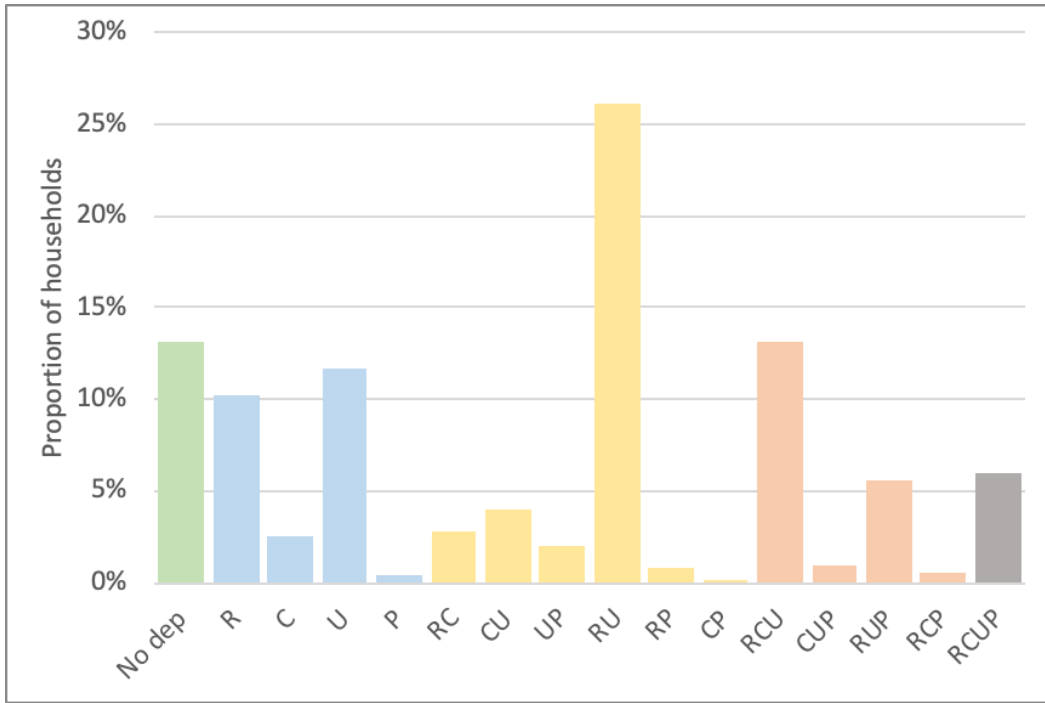


(b)

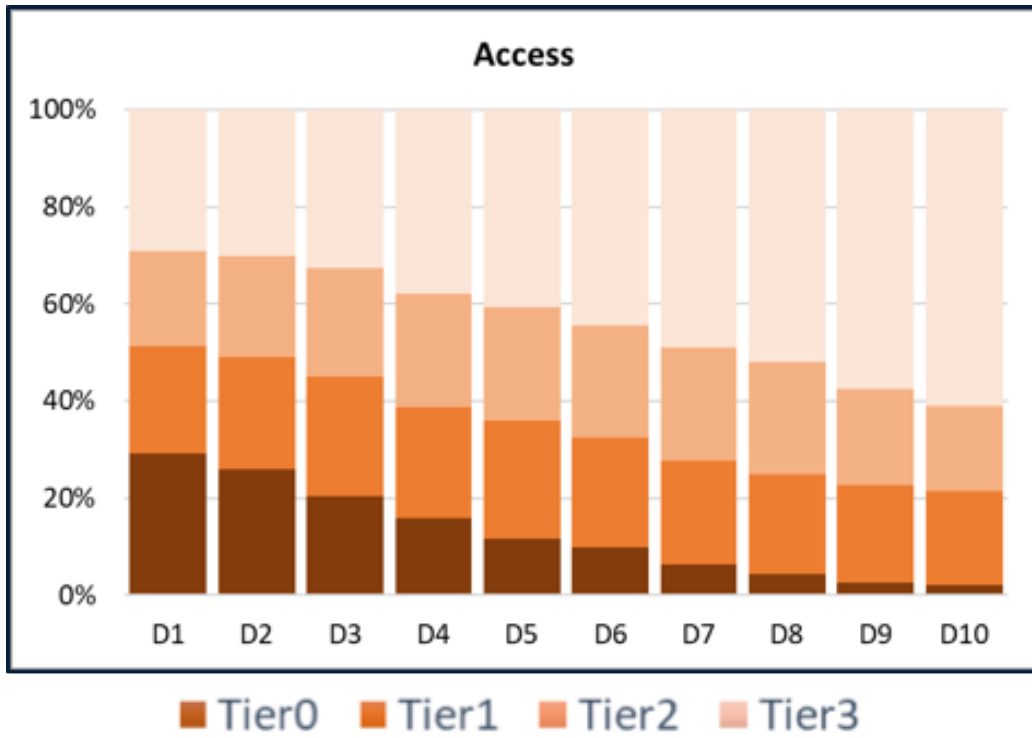


(c)

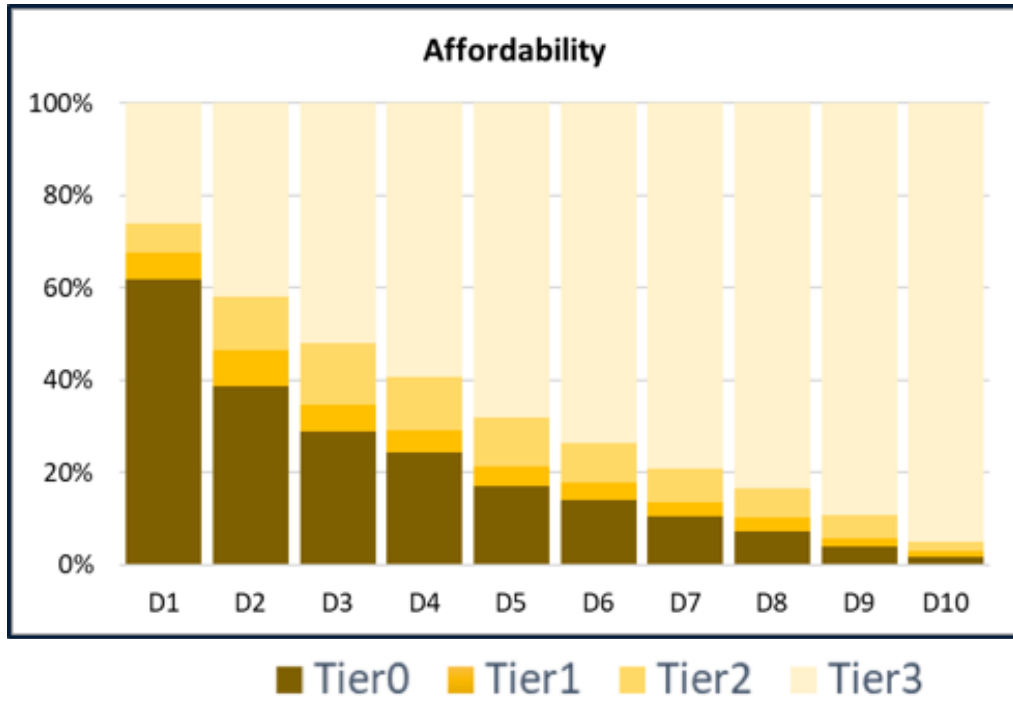
**Fig. D.2:** Percentage of households in the bottom/ impoverished tier in terms of cooking fuel AF dimensions for (a) access, (b) affordability and (c) services and appliance ownership across different Indian states



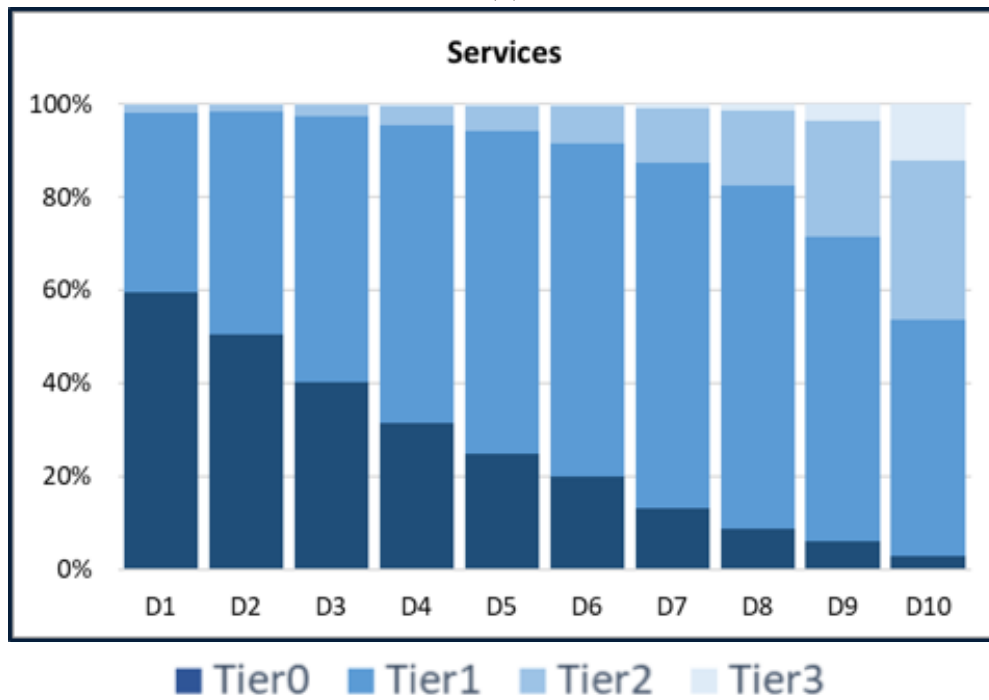
*Fig. D.4: Distribution of households across intersectional deprivations in the IHDS*



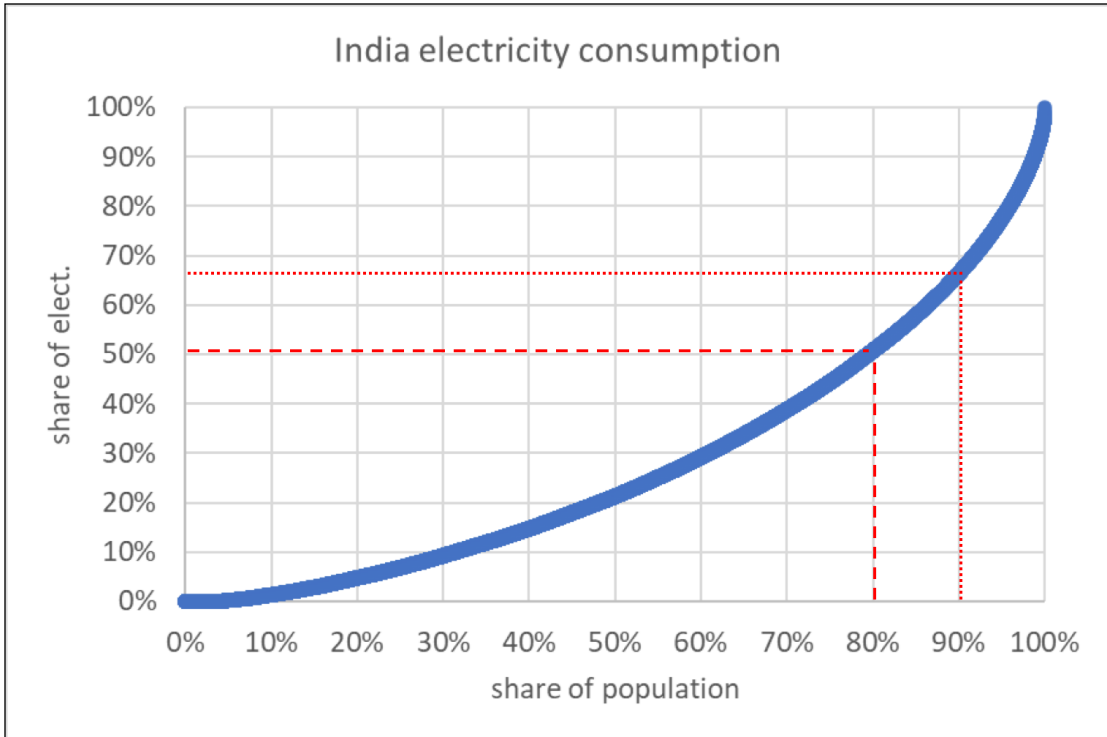
(a)



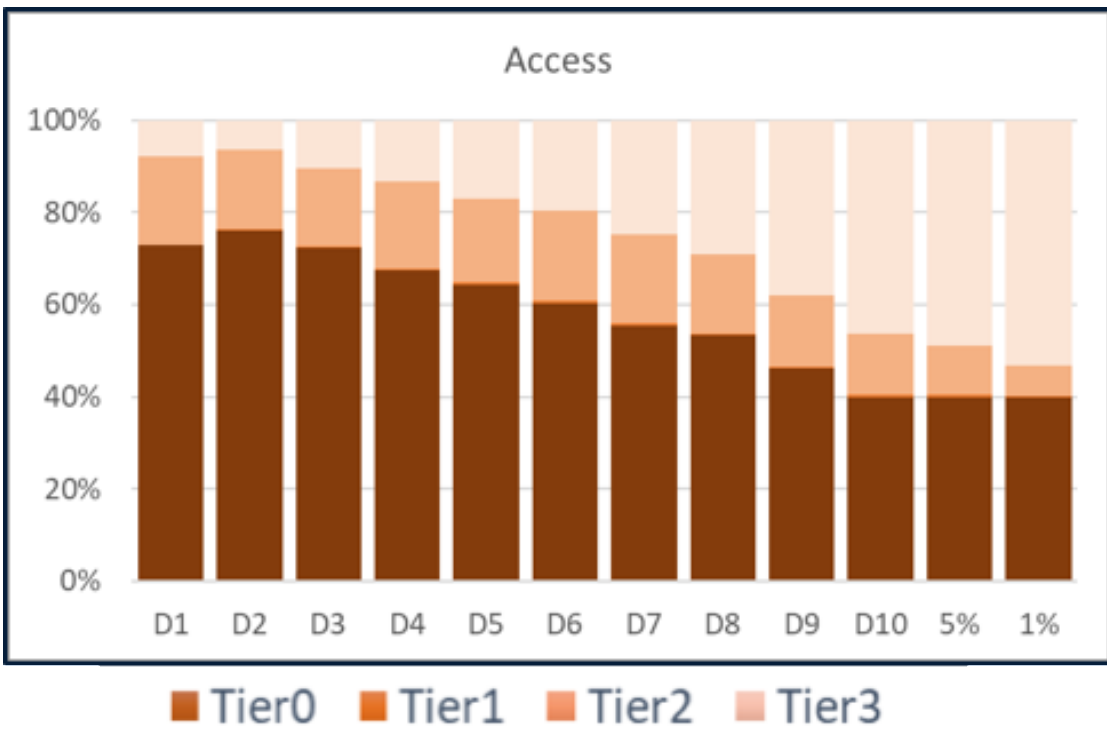
(b)



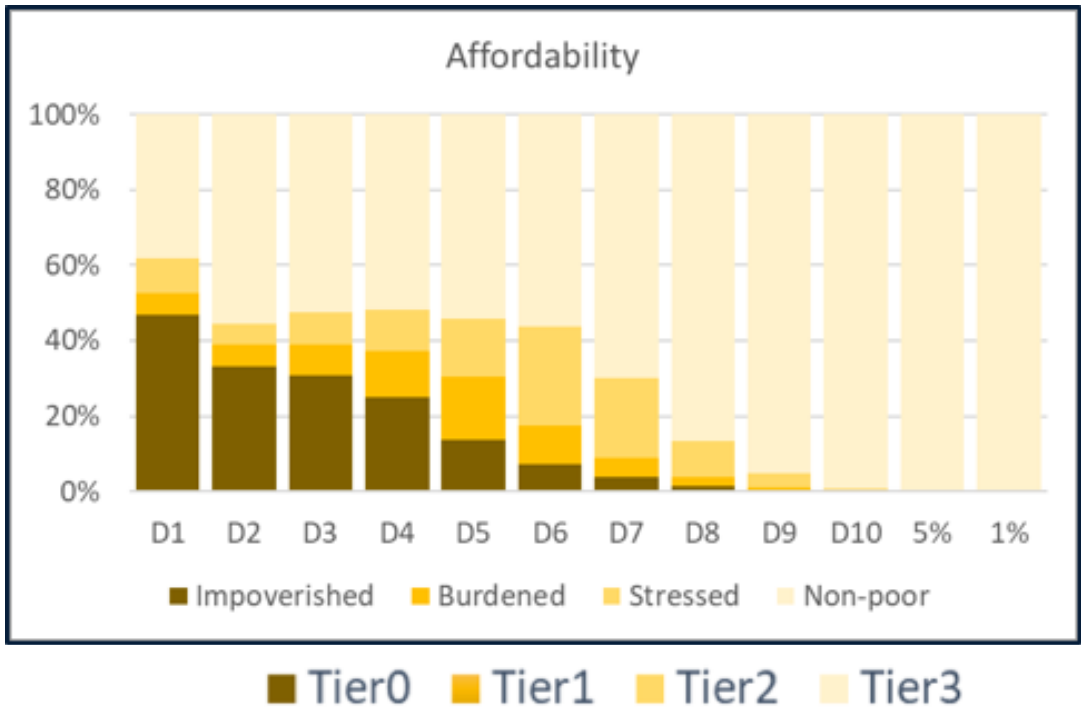
*Fig. D.5 (a-c): Distribution of households across energy poverty tiers in AF for electricity, by income deciles*



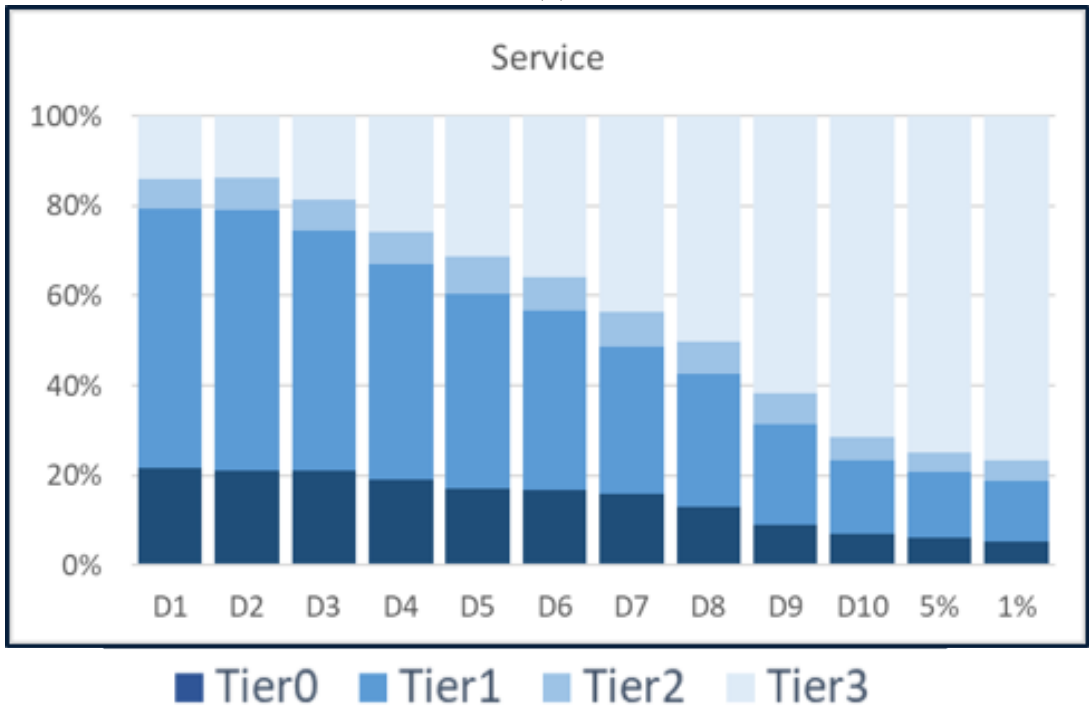
*Fig. D.6: Lorenz curve for electricity consumption inequality in India*



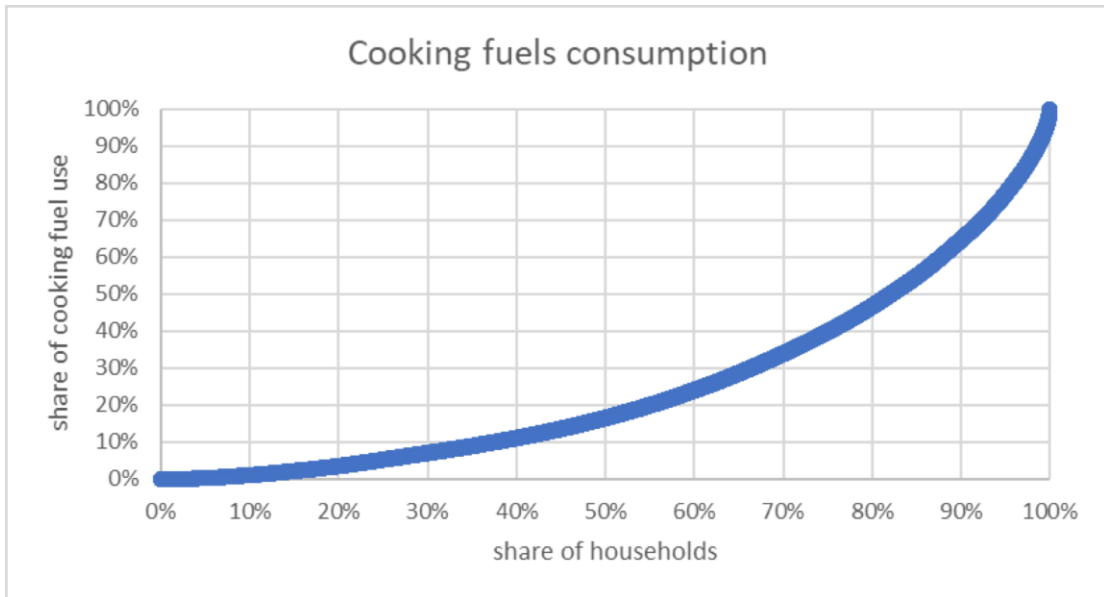
(a)



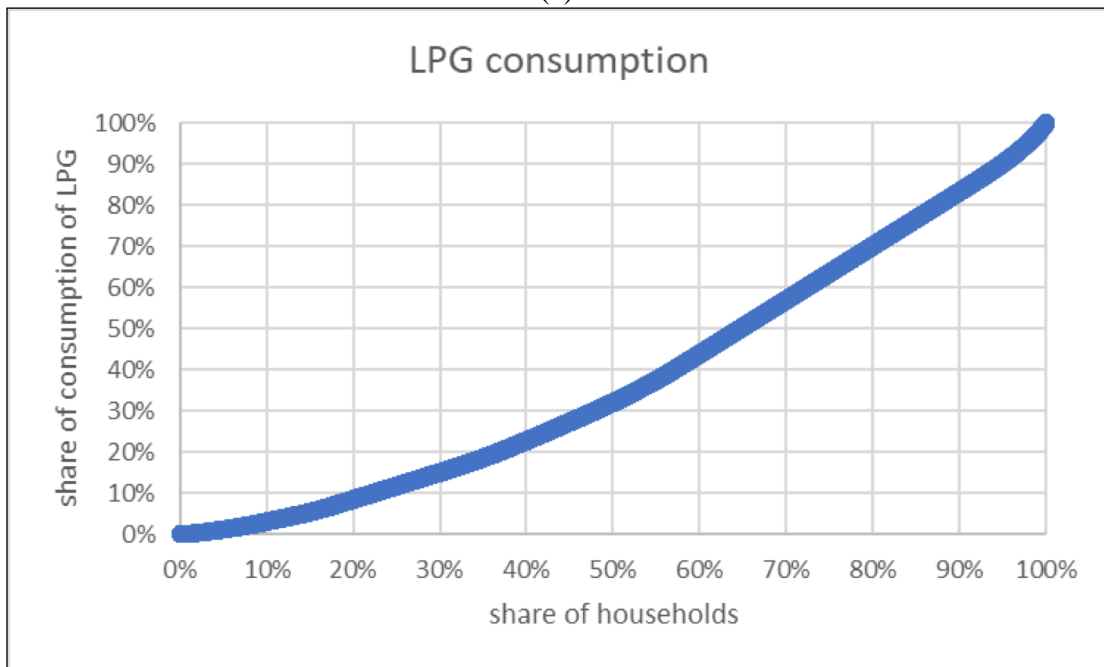
(b)



*Fig. D.7 (a-c): Distribution of households across energy poverty tiers in AF for electricity, by income deciles*

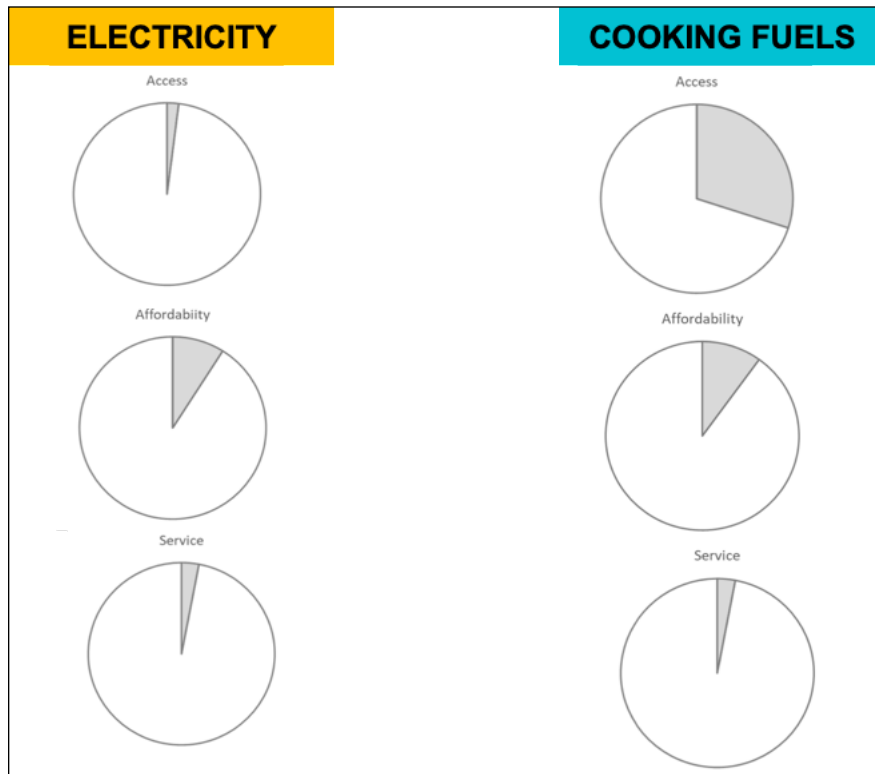


(a)

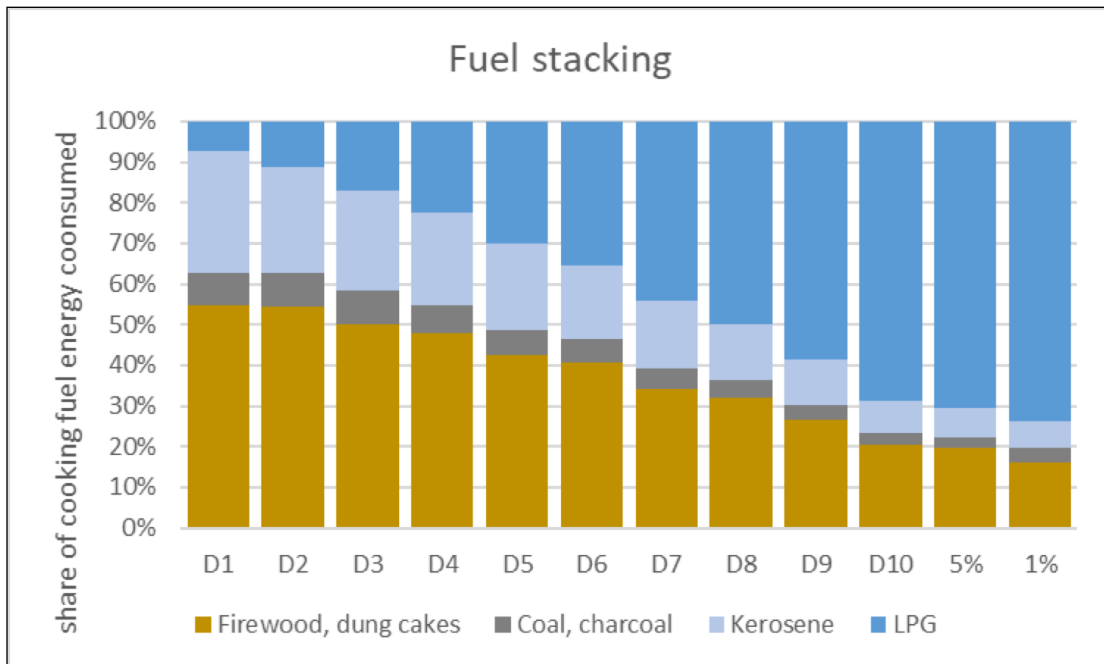


(b)

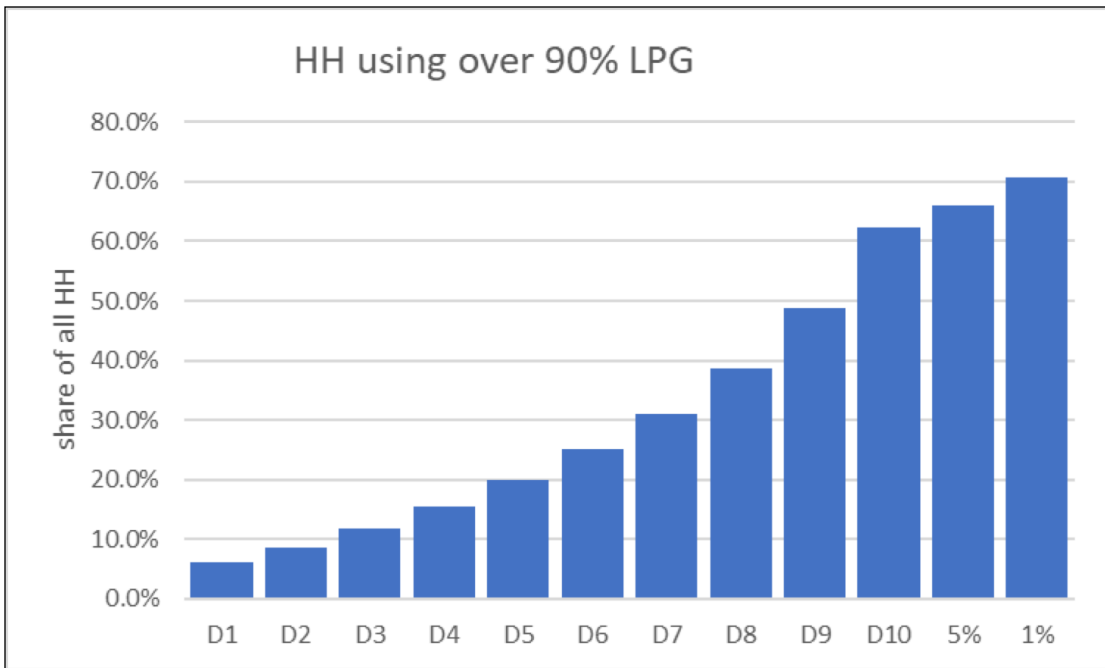
**Fig. D.8:** Lorenz curve for cooking fuel consumption inequality in India. Panel a shows all cooking fuels, panel b shows LPG only. Data from NSSO Round 66



**Fig. D.9:** Intersectionality observed in privileged households, showing much lower energy related deprivations across dimensions, relative to the national average or deprived households.



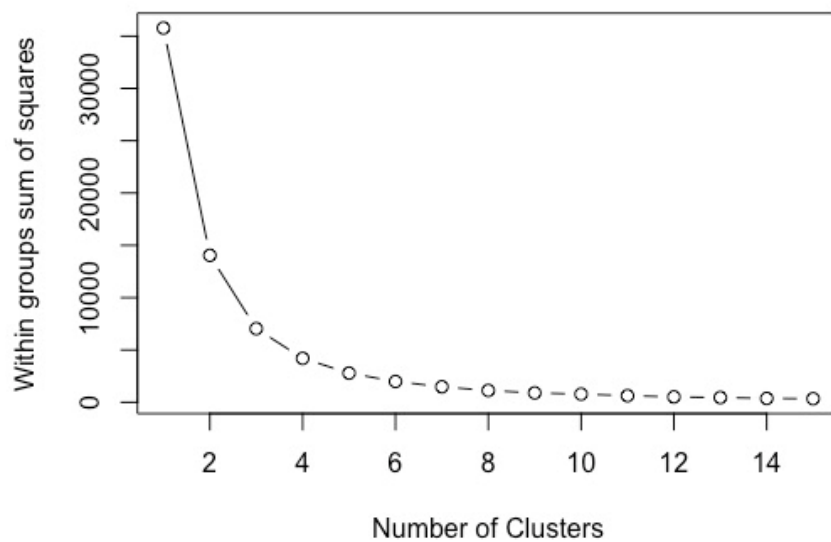
(a)



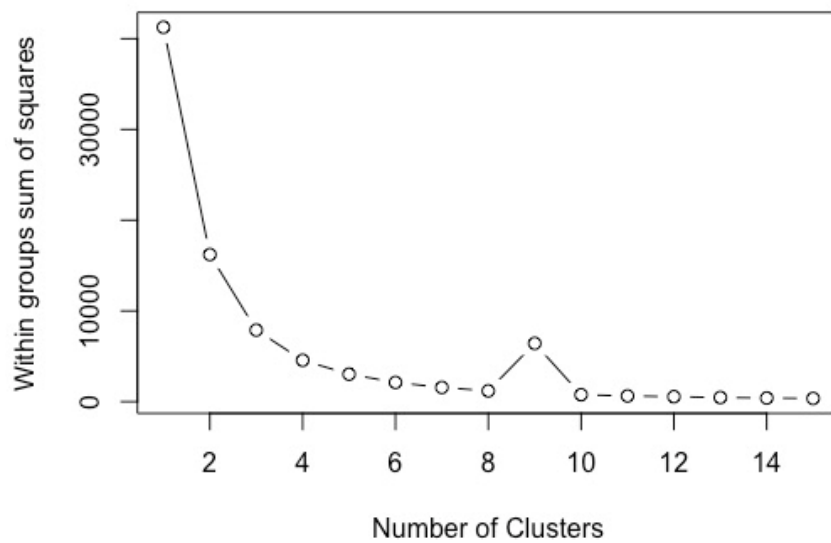
(b)

**Fig. D.10:** Fuel stacking behavior across income deciles in India. Panel a shows share of cooking fuels used by each income decile and the top 5% and 1% by income.

Panel b shows the share of households within each income strata using LPG for almost all cooking fuel needs (cut-off assumed as 90%)



(a)



(b)

**Fig. D.11:** *K-means clustering analysis for affordability tiers in AF for electricity (panel a) and cooking fuels (panel b). The results imply there is no significant*

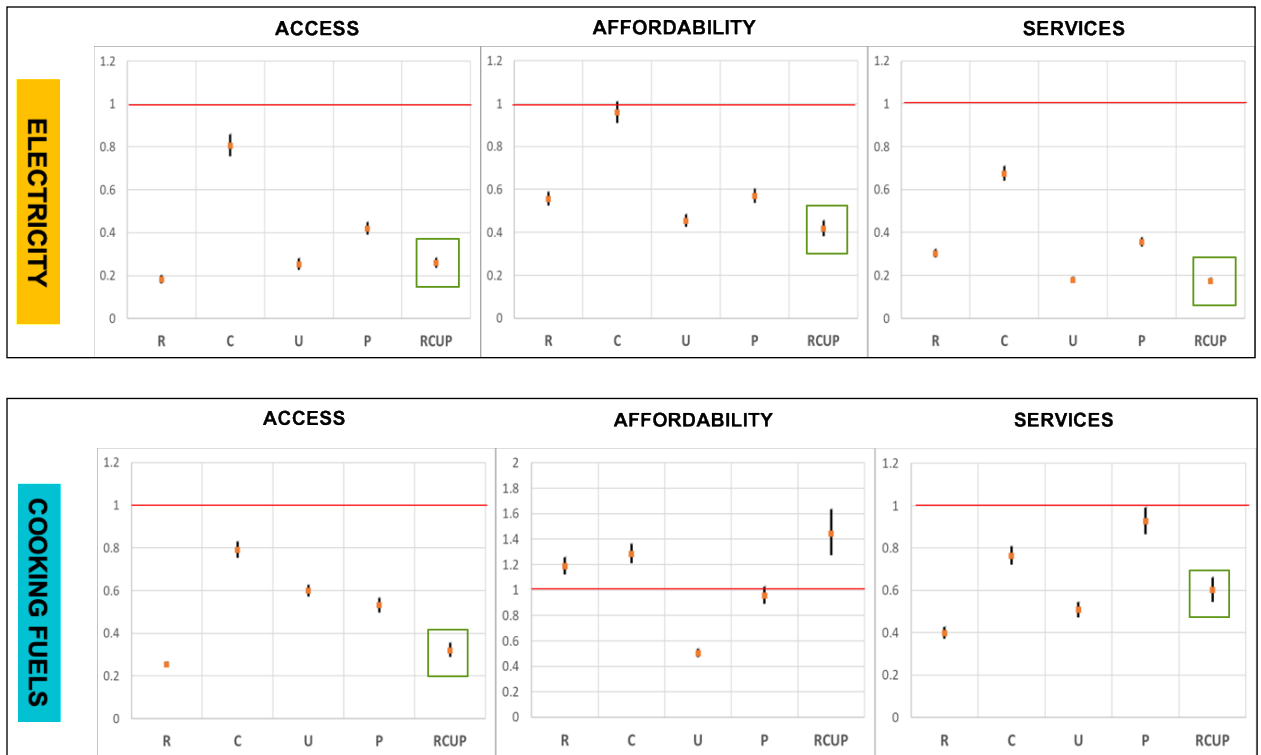
*improvement in distributional representation by increasing the number of affordability clusters beyond the 4 levels used in the AF for this data set.*

**Table D.12: Fuel collection time tiers**

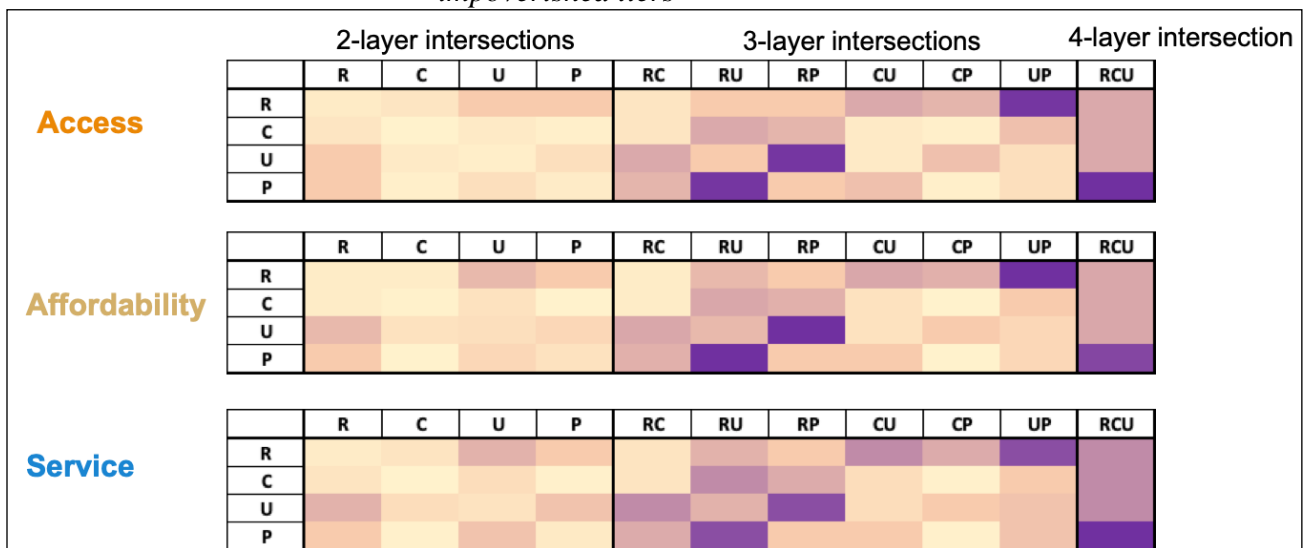
<b>Tier</b>	<b>0</b>	<b>1</b>	<b>2</b>	<b>3</b>
Daily time spent in minutes	<15	15-30	30-60	>60

**Table D.13: Axes of deprivation and definitions chosen for this study**

<b>Axis</b>	<b>Deprived</b>	<b>Not deprived</b>
<i>Geography</i>	Rural	Non-rural
<i>Income</i>	Below national poverty line	Above national poverty line
<i>Social class</i>	Scheduled Caste, Scheduled Tribe	All others
<i>Education</i>	High school education or lower, for head of household	Head of household attended any course of study above high school



**Fig. D.14:** Results from ordered logit regression: Coefficients with 95% significance limit. Top panel (a) shows results for electricity, and bottom panel (b) for cooking fuels in India. Lower values indicate increased likelihood of belonging to impoverished tiers



**Fig. D.15:** Intersectionality heat map for electricity. Darker colors indicating higher share of households belonging to lowest tier of energy poverty. It can be seen that sometimes intersection of 3 of 4 underlying deprivations can have significant effects. It is also observable that higher order overlaps are generally more discriminatory.

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