Carbon Prices and Cooking Fires: How Decarbonization Pathway Design Shapes Household Energy Burdens

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Abstract

Climate mitigation pathways impose uneven burdens across income groups, yet analyses typically focus on revenue recycling rather than on how pathway architecture shapes distributional outcomes. We examine 17 pathways to 1.5°C and trace their impacts to household energy burdens across income deciles in India and the United States. Pathway architecture is a primary determinant of whether mitigation is progressive or regressive. Technology, pace, and cost-optimal pathways are regressive: the poorest households bear cost increases up to an order of magnitude larger than the richest. Demand-side pathways lower carbon prices by curbing demand among high-income consumers, creating development space that alleviates burdens in developing countries. Historical responsibility pathways with international transfers generate progressive outcomes for recipient countries at the expense of donor households. These patterns persist under consumption rebound, albeit attenuated. Distributional consequences are embedded in pathway design, not correctable through revenue policy alone.

Introduction

Under cost-optimal climate mitigation, India's poorest households face energy burden increases an order of magnitude larger than its richest. This disparity is not an unfortunate side effect to be corrected later through revenue recycling; it is a consequence of pathway architecture, the choices embedded in how we design routes to climate targets. Yet integrated assessment models (IAMs) typically report regional aggregates that render these consequences invisible[1,2].

Making low-carbon transitions just, equitable, and politically durable has become central to climate policy[3–5], driven in part by evidence that unequal distribution of mitigation costs erodes social cohesion and undermines policy acceptability[6,7]. These concerns have spurred calls to integrate justice considerations, encompassing distributional, corrective, and recognitional dimensions, into IAMs[8–11]. Translating such calls into practice remains difficult, however, particularly when the goal is to trace how pathway designs propagate to vulnerable populations.

Recent multi-model studies have sharpened the picture. Climate damages widen inequality; revenue recycling can narrow it[12]. Net-zero pathways tend to be regressive under uncompensated carbon pricing but become progressive with per-capita recycling[13,14]. Even so, stringent mitigation risks increasing poverty in developing regions absent careful pathway design[15]. A consistent theme in this literature is that revenue recycling determines distributional outcomes, a framing that treats pathways as distributionally neutral before compensation and locates all equity-relevant decisions at the revenue stage. But different pathway architectures, distinguished by technology choices, transition pace, effort allocation, or demand-side transformation, yield different distributional outcomes through their structure alone, before any revenue is collected or recycled. Effort-sharing pathways have been analyzed for country-level implications[16–18] but their within-country distributional effects remain unexplored. Demand-side mitigation has attracted attention for its well-being implications[19–22], yet not all demand-side approaches are equivalent: electrification differs from behavioral demand reduction in ways that matter for who bears the cost.

Here we examine 17 pathways to 1.5°C representing four architectural approaches (Table 1), tracing impacts to household energy burdens across income deciles in India and the United States using the Global Change Analysis Model (GCAM) linked with nationally representative household surveys[23–25]. This responds to calls for improved representation of heterogeneity in energy-climate models[10,26,27]. Standard IAM practice employs representative households, implicitly assuming that differences balance in aggregate[1,2]; energy burden research reveals they do not[28,29]. Downscaling to income deciles exposes distributional variation that aggregate reporting obscures.

We find that the architecture of mitigation pathways is a primary determinant of distributional outcomes. Most pathways are regressive, with the poorest deciles shouldering disproportionately large cost increases compared to the richest. A subset of pathways, those emphasizing demand reduction in wealthy populations or historical responsibility with transfers, instead yield progressive outcomes. These distributional consequences are embedded in pathway design; downstream revenue policies cannot fully undo them.

Results

Most pathways are regressive

Technology, pace, and cost-optimal pathways concentrate burden on the poorest households in both countries (Figure 2). In India, the poorest decile (D1) faces energy burden increases roughly ten times larger than the richest (D10). This steep gradient reflects both higher price sensitivity among poor households and a counterintuitive fuel switching dynamic: under cost-optimal mitigation, the traditional biomass share of India's residential consumption rises from roughly 54% in the reference scenario to 65%, as households retreat to self-collected fuels when modern alternatives become unaffordable.

The United States shows the same direction but a compressed gradient. More uniform consumption patterns and universal modern energy access narrow the spread between deciles. Faster net-zero timelines (NZ2040 vs. NZ2060) amplify the regressive pattern without changing its character. Among effort-sharing pathways, grandfathering is particularly severe for India, locking in low per-capita carbon allocations irrespective of household income, while capability-based approaches (CAP-A, CAP-B) also skew costs toward the poorest.

Demand-side measures and redistribution yield progressive outcomes

A distinct subset of pathways reverses this pattern (Figure 3). Behavioral change (BEH) and comprehensive demand-side mitigation (COMPR) deliver progressive outcomes in India: the poorest decile sees burden reductions relative to reference, while richer deciles absorb modest increases. Reduced demand in high-consuming populations depresses global carbon prices, opening carbon space for developing regions (the mechanism is detailed in Figure 4). Non-CO2 reductions from dietary shifts and HFC phase-down extend this headroom further.

Historical responsibility with international transfers (RESP) generates the most strongly progressive outcome for India. Financial transfers from wealthy countries more than offset domestic mitigation costs for the poorest households. The mirror image holds for the United States, where RESP imposes the steepest regressive burden as households bear transfer obligations on top of domestic mitigation costs.

The sovereignty-based pathway (SOVER) shows near-neutral burden effects for India in 2030, reflecting lower near-term mitigation stringency rather than structural redistribution: weak ambition embedded in NDC trajectories permits continued access expansion without significant burden increases.

Rebound attenuates but does not eliminate progressive transfers

When Indian households receive transfer income under historical responsibility, they may channel part of it into additional energy consumption. We model this rebound in RESP-POST. Progressive outcomes persist: the poorest decile still experiences burden reductions relative to reference, though benefits shrink compared to the no-rebound case. This is, to our knowledge, the first household-level analysis of consumption responses to international climate transfers. It suggests that climate finance mechanisms can deliver within-country equity benefits under realistic behavioral assumptions. At longer time horizons (2050), however, cumulative rebound eventually overwhelms transfer benefits (Supplementary Information).

Not all demand-side pathways are progressive

The demand-side category masks critical heterogeneity. Electrification (ELE) is regressive in India: its benefits accrue to households that can afford to electrify, while costs are distributed through the carbon price. Traditional biomass phase-out (NTB) is regressive for the opposite reason, removing a fuel source that poor households depend on without providing affordable alternatives. Only pathways that reduce demand in wealthy populations, rather than mandating fuel transitions among the poor, yield progressive distributional patterns.

Discussion

Pathway architecture shapes distributional outcomes before revenue policy

Decile-level burden analysis exposes distributional patterns that representative-household IAM reporting renders invisible. The gradient between poorest and richest households is not merely steep; it differs qualitatively across pathway categories, with technology, pace, and cost-optimal pathways systematically regressive while behavioral demand-side and historical responsibility pathways produce progressive outcomes for India's poorest without any revenue recycling. This pattern reframes the distributional question in the recent multi-model literature[12,13,14], which has focused on revenue recycling as the equity lever and treated pathway architecture as distributionally neutral before compensation. Our results indicate that pathway structure shapes the distributional landscape on which revenue policy then operates. Some architectures are progressive before any revenue is collected; others embed regressivity that redistribution alone cannot fully counteract.

The India-US pairing is analytically productive precisely because the two countries occupy different positions along several dimensions that matter for distributional outcomes. India's residential energy system remains partially dependent on traditional biomass, its income distribution is steeper, and it stands on the receiving end of most effort-sharing frameworks. The United States has universal modern energy access, a compressed consumption gradient, and bears transfer obligations under historical responsibility. Neither country alone would reveal the mirror effect under RESP, nor would a single-country study expose how the same pathway architecture propagates through fundamentally different fuel mixes to produce opposite distributional outcomes.

The causal chain runs through global commodity markets (Figure 4). Pathways that constrain carbon space elevate carbon prices that propagate to household energy bills, with the poorest households absorbing a disproportionate share due to higher price sensitivity and limited fuel-switching capacity. In India, this dynamic triggers a retreat to traditional biomass as modern fuels become unaffordable. The consequence is that climate policy partially reverses decades of progress on household energy transitions. Programs like India's Pradhan Mantri Ujjwala Yojana have expanded LPG access to hundreds of millions of households; carbon pricing under cost-optimal mitigation works against this trajectory by making the cleaner fuels these programs provide less affordable relative to self-collected biomass. The health implications are substantial: continued reliance on solid fuels for cooking is a leading cause of household air pollution and premature mortality, particularly among women and children. This tension between climate mitigation (SDG 13) and clean energy access (SDG 7) is often noted in abstract terms; our results quantify it at the household level. Pathways that expand carbon space, through demand contraction in affluent societies or explicit financial transfers, relieve this pressure and preserve room for development[32].

The double squeeze on the poorest households

Our energy burden metric differs from standard gross-income approaches in a way that matters for the magnitude of estimated regressivity. By accounting for food price increases in the denominator alongside energy price increases in the numerator, the metric captures an amplification that gross-income calculations systematically understate. The effect is largest for households with high food budget shares. In India's poorest decile, where food expenditure can exceed half of household income, mitigation-induced agricultural price increases substantially shrink the income available for energy purchases, roughly doubling the apparent burden increase compared to what a gross-income denominator would show. This measurement distinction is particularly consequential in countries where food expenditure dominates household budgets at the bottom of the income distribution, and it suggests that existing analyses of carbon pricing regressivity in developing countries may systematically understate the burden on the poorest households.

Demand-side heterogeneity and the cost-optimal default

The demand-side findings give quantitative substance to the sufficiency literature[19,42,43] while complicating its narrative. Not all demand-side approaches produce equivalent distributional outcomes. The progressive character of behavioral demand reduction operates through a specific mechanism: lower aggregate demand depresses global carbon prices, creating space for developing regions. Electrification and traditional biomass phase-out lack this mechanism and instead impose costs on households least able to bear them. This distinction has practical implications for how "demand-side mitigation" is categorized in scenario assessments. Treating it as a single analytical category, as is common in IPCC scenario databases and model comparison exercises, obscures a consequential difference in who bears the cost.

More broadly, cost-optimal pathways are not distributionally neutral defaults. They embed a particular allocation of burden that prioritizes aggregate economic efficiency, with disproportionate costs falling on the most vulnerable. The IPCC AR6 scenario database is heavily populated with cost-optimal and near-cost-optimal pathways; if each of these embeds regressive distributional consequences by construction, the evidence base informing climate policy carries an unexamined distributional assumption. Selecting a cost-optimal pathway is itself a distributive choice, even when framed as a technical benchmark. These results are consistent with arguments that reducing demand in affluent populations can create distributional space, though we do not assess whether resulting consumption levels meet sufficiency thresholds as defined in the decent living standards literature.

Global versus domestic justice

The effort-sharing results expose a tension that the existing literature on burden-sharing frameworks[16,17,18] has not traced to household level. Historical responsibility with transfers produces a mirror effect: the pathway that delivers the strongest progressive outcome for India simultaneously imposes the steepest regressive burden in the United States. This is not a modeling artifact; it reflects the arithmetic of transfers large enough to offset mitigation costs in recipient countries being financed by households in donor countries, where the burden falls disproportionately on those with the highest energy expenditure shares.

This finding is directly relevant to ongoing negotiations over climate finance architecture. The Paris Agreement's Article 6 mechanisms and the loss and damage fund established at COP27 both involve financial flows from wealthy to developing countries, yet their design has proceeded largely without household-level distributional analysis in donor countries. Our results suggest that the political feasibility of such mechanisms depends not only on the aggregate fiscal burden but on how that burden distributes across income groups domestically. Transfer obligations that land disproportionately on a donor country's poorest households risk generating the same political backlash that has undermined domestic carbon pricing.

International negotiations would benefit from anticipating these within-country consequences. Domestic policy must accompany international commitments so that transfers do not simply relocate burdens from Global South poor to Global North poor. The viability of transfer-based approaches is also time-dependent: at 2050, cumulative rebound overwhelms progressive benefits (S4), suggesting climate finance mechanisms require design features that account for consumption responses over longer horizons. This transfer-rebound dynamic extends the effort-sharing literature into household-level territory it has not previously reached, and it indicates that progressive outcomes at 2030 cannot be assumed to persist without active policy adjustment.

Limitations

Several limitations qualify these findings. Household survey data from 2011-2015 may not capture recent shifts in consumption patterns. We do not model the costs of implementing demand-side shifts, including infrastructure investment and behavior change programs; if financed regressively, some progressive benefits could be offset. Energy burden, while informative, does not capture the full welfare picture: health effects of continued traditional biomass use, time poverty from fuel collection, and non-monetary well-being dimensions all warrant separate study. We model representative households within deciles rather than full distributions, leaving intersecting vulnerabilities to future work. Our analysis relies on a single IAM; multi-model assessment would strengthen confidence in regional allocations. Results at 2050 amplify the 2030 patterns but carry correspondingly greater uncertainty. Sensitivity analyses using the MESSAGE-Access fuel choice model for India and heterogeneous demand elasticities for the US confirm the directional findings, though the latter shift peak burden increases from D1 to D2-D3 for some pathways (S2, S3). The food expenditure calculation applies GCAM agricultural price projections following the approach in Soergel et al. (2021), developed for REMIND; testing this linkage against model-specific agricultural price dynamics would strengthen confidence in the double-squeeze magnitudes. GCAM's biomass pricing may understate the true cost to households who collect rather than purchase fuel, since it does not capture the time poverty associated with fuel collection.

Methods

Modeling framework

We use GCAM (Global Change Analysis Model), v6.0, an integrated model of energy, water, land, and climate systems across 32 regions[30,31], solving for market-clearing prices and quantities at five-year intervals with detailed technology representation. All 17 pathways achieve approximately 1.5°C end-of-century warming, isolating the effects of pathway architecture from differences in climate ambition (Figure S8). Prior work analyzed how these pathways affect national energy goals[32]; here we extend that work to household-level distributional impacts.

Pathways are organized into four categories (Table 1). Technology pathways emphasize supply-side solutions: high renewables (RE), nuclear with carbon capture (CCS-NUC), and direct air capture (DAC). Pace pathways vary net-zero timelines (NZ2040, NZ2050, NZ2060). Effort-sharing pathways allocate responsibility through grandfathering (GR.FATH), historical responsibility with transfers (RESP), capability-based staging (CAP-A, CAP-B), and sovereignty-based NDC trajectories (SOVER). Demand-side pathways include electrification (ELE), traditional biomass phase-out (NTB), behavioral change (BEH), and comprehensive demand-side mitigation (COMPR). Reference (REF) and cost-optimal (C.OPT) scenarios serve as baselines. BEH operationalizes IPCC AR6 demand-side estimates through changes to income elasticities, floor space satiation levels, and vehicle load factors in GCAM (see S1.1 for all pathway specifications). RESP adjusts regional GDP values to reflect financial transfers computed from cumulative excess emissions, then re-runs cost-optimal mitigation (S1.1).

Table 1. Pathways analyzed in this study. All pathways achieve approximately 1.5°C end-of-century warming. See Supplementary Information for detailed specifications.

Category	Pathway	Description
Baselines	REF	Reference scenario without climate policy
	C.OPT	Cost-optimal pathway with uniform global carbon price minimizing aggregate mitigation cost
Technology	RE	High renewable energy deployment with accelerated solar PV and wind cost reductions following SSP1
	CCS-NUC	Nuclear expansion with carbon capture and storage at reduced costs following SSP5
	DAC	Direct air capture deployment capped at 5 GtCO2, rising preference to 2050
Pace	NZ2040	Global net-zero CO_2 emissions by 2040
	NZ2050	Global net-zero CO_2 emissions by 2050
	NZ2060	Global net-zero CO_2 emissions by 2060
Demand-side	ELE	Accelerated electrification of buildings and transport
	NTB	Phase-out of traditional biomass in residential sector
	BEH	Behavioral changes following IPCC AR6 demand-side estimates: diet shifts, reduced floor space, modal shifts, increased ridesharing
	COMPR	Comprehensive demand-side: BEH measures plus Kigali HFC phase-down, bioenergy constraints, efficiency mandates
Effort-sharing	GR.FATH	Grandfathering: emission rights and negative emission responsibilities allocated proportional to 2015 shares
	CAP-A	Capability-based: regions advance net-zero timelines by 5-10 years based on GDP per capita relative to Brazil's 2050 level
	CAP-B	Capability-based: regions exceeding Brazil's 2050 GDP per capita today move to net-zero in 2025
	SOVER	Sovereignty: NDC trajectories continued with gradual tapering
	RESP	Historical responsibility: cumulative per-capita emissions since 1850 converted to financial transfers at prevailing carbon prices
	RESP-POST	Historical responsibility with consumption rebound modeled

Household data and downscaling

For India, we use the India Human Development Survey (IHDS-II, 2011-12), covering approximately 42,000 households with detailed fuel expenditure data[33]. For the United States, we use the Residential Energy Consumption Survey (RECS 2015) covering approximately 5,700 households[34]. Income distributions are projected using log-normal parameterizations with regional GDP per capita and Gini coefficients[35-37].

We downscale GCAM regional outputs to income deciles by allocating residential energy consumption according to fuel-specific patterns observed in surveys (Figure 1). For each fuel, income-specific consumption shares preserve within-country heterogeneity while respecting regional energy balances. For India, we distinguish electricity, LPG, kerosene, firewood, dung and agricultural waste, and coal or charcoal. For the United States: electricity, natural gas, propane, and fuel oil. Household energy expenditure is the product of consumption and GCAM-projected prices, including carbon costs. Traditional biomass is valued at GCAM-projected prices, which reflect the model's representation of biomass supply costs in each region and period.

Energy burden calculation: the double squeeze

Our outcome variable is household energy burden: energy expenditure divided by income net of food costs. This formulation differs from standard approaches that use gross income, and the distinction matters. GCAM projects both energy prices and agricultural prices under mitigation scenarios. When mitigation raises energy prices, the numerator increases. When it raises food prices, net income in the denominator shrinks. Poor households, who allocate larger shares of income to food, are squeezed from both directions, an amplification that standard gross-income calculations miss.

Food expenditure derives from GCAM agricultural projections and income-specific food budget shares, following the approach in Soergel et al.[38] where these shares are applied to GCAM agricultural price projections. We report changes relative to reference as percentage point differences: positive values indicate increased burden (regressive), negative values indicate reduced burden (progressive). The main text focuses on 2030 results; 2050 results, which amplify the same patterns with greater uncertainty, appear in Supplementary Information.

Sensitivity analyses

We test robustness through three approaches detailed in Supplementary Information. First, for India, we apply the MESSAGE-Access model to incorporate fuel choice dynamics across eight rural and urban household types[39,40]. Second, for the United States, we employ decile-specific income elasticities capturing heterogeneous price responses[41]. Third, we model consumption rebound under historical responsibility (RESP-POST), allowing households receiving transfer income to increase energy consumption in response.

Conclusions

The architecture of mitigation pathways shapes distributional outcomes independently of revenue recycling. Cost-optimal, technology, and pace pathways concentrate burden on the poorest households, and the regressivity is amplified when food price effects are accounted for in the burden metric.

Behavioral and comprehensive demand-side pathways achieve equivalent climate outcomes with progressive profiles by depressing global carbon prices through demand contraction, while historical responsibility with transfers creates a mirror in which recipient and donor countries experience opposite distributional consequences from the same pathway.

Several practical implications follow. Scenario design embeds distributive choices that representative-household aggregation obscures; making these visible requires the kind of decile-level analysis demonstrated here. Effort-sharing frameworks reshape within-country distributions in ways that require complementary domestic policy, particularly in donor countries where transfer obligations concentrate on the poorest households. Demand-side policy must distinguish between approaches that create space for the poor and those that eliminate options they depend on. And the tension between climate mitigation and energy access goals, visible in the biomass retreat under cost-optimal pathways, underscores that pathway design is not only a distributional choice but a development choice with consequences for health and welfare that extend beyond the energy burden metric.

Declarations

Data Availability

GCAM is open source (https://github.com/JGCRI/gcam-core). The IHDS-II survey is available through ICPSR (ref 24). RECS 2015 is available from the U.S. Energy Information Administration (ref 25). GCAM scenario output databases are not publicly available due to their large size and complexity but are available from the corresponding author on reasonable request.

Code Availability

Scenario analysis was conducted using GCAM v6.0 (https://github.com/JGCRI/gcam-core). GCAM scenario outputs in IAMC format for all 17 pathways will be deposited in Zenodo before publication. Downscaling to income deciles and energy burden calculations were performed using structured spreadsheet tools implementing the procedures described in S1.2-S1.3; these are available from the corresponding author on request.

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Author Contributions

M.G. conceived the study, developed methodology, conducted analysis, and wrote the manuscript. H.M. contributed to scenario design and GCAM modeling. S.P., J.M., and N.D.R. contributed to downscaling methodology, income projections, effort sharing pathway design, energy burden conceptualization and interpretation of results. S.P., N.D.R., H.M., L.C. and A.P. supervised the research. All authors reviewed the manuscript.

Competing Interests

The authors declare no competing interests.

Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work, the author(s) used the GPT-5 artificial intelligence model for preparing the draft of the article to improve readability and language. After using this tool, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

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Figures

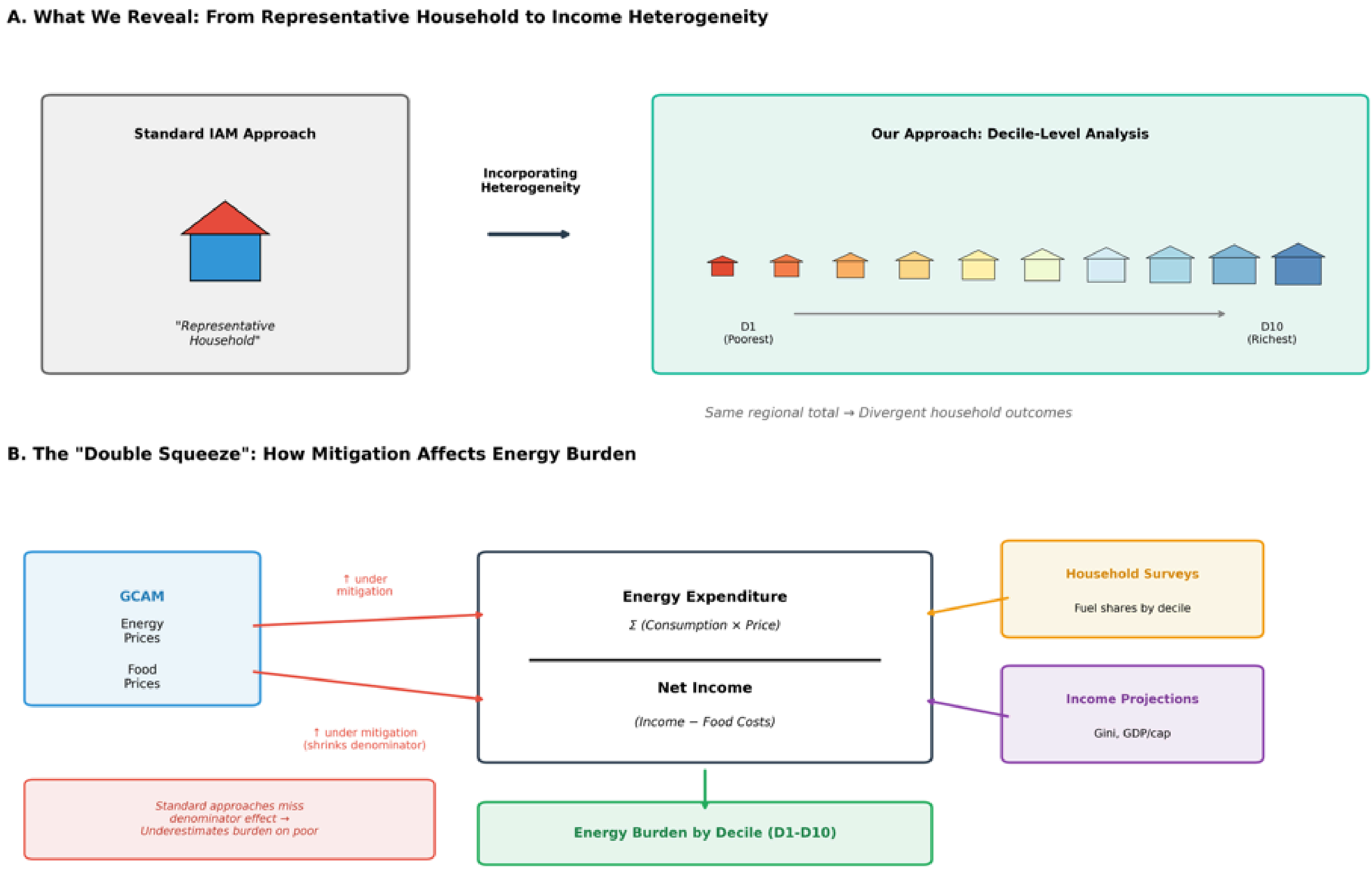

Figure 1

Methodological framework. Panel A: Standard IAM approaches use representative households that obscure distributional variation; our approach incorporates income heterogeneity across deciles. Panel B: The 'double squeeze' on energy burden. Under mitigation, GCAM projects both higher energy prices (increasing the numerator) and higher food prices (decreasing net income in the denominator). Poor households, with higher food budget shares, experience amplified burden increases that standard gross-income calculations miss.

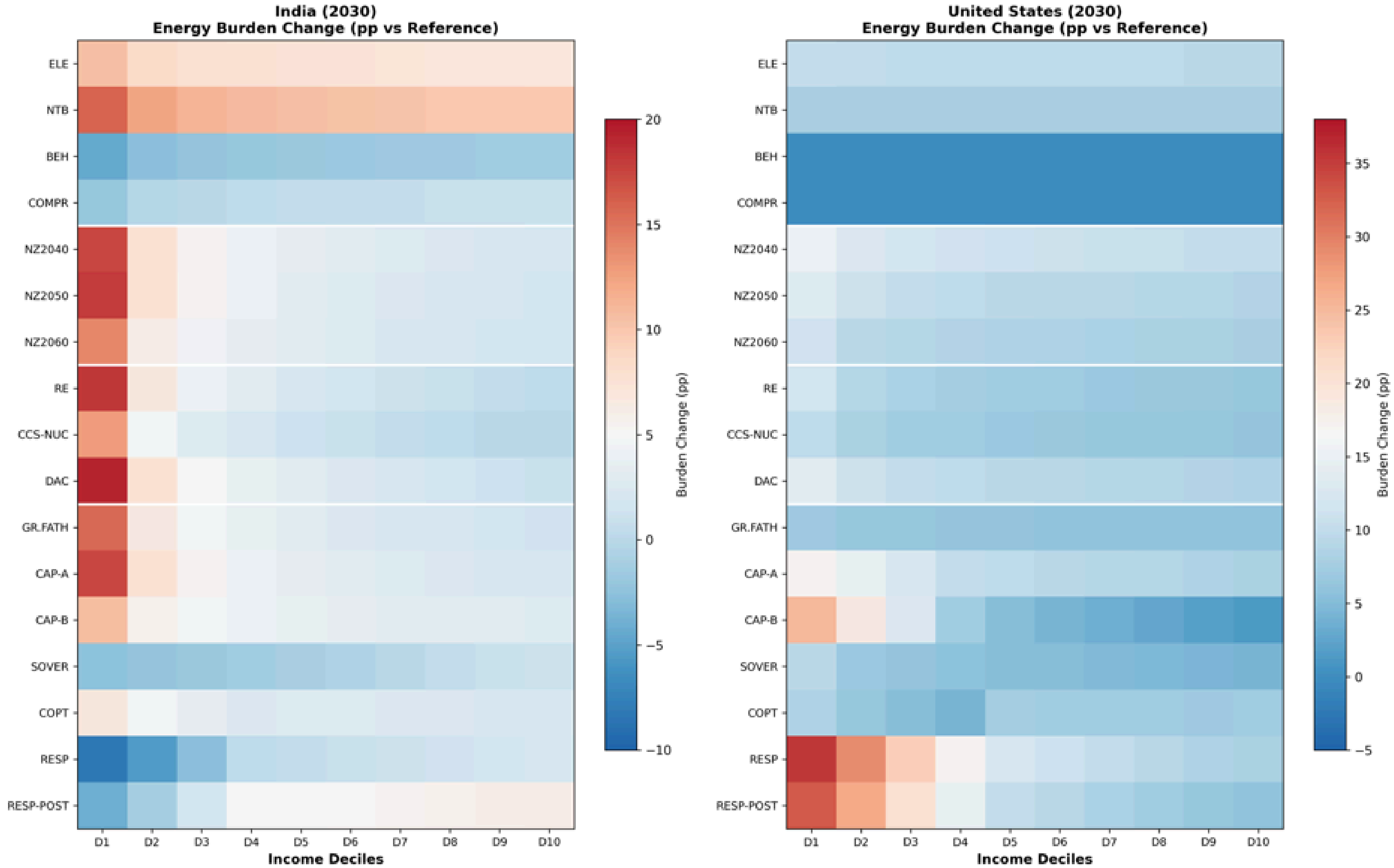

Figure 2

Energy burden changes across all pathways and income deciles, 2030. Heatmaps show burden changes (percentage points relative to reference) for India (left) and USA (right). Pathways grouped by category. Red indicates regressive impacts (burden increase); blue indicates progressive impacts (burden decrease). Most pathways show regressive gradients with poorest deciles (D1) experiencing larger increases than richest (D10).

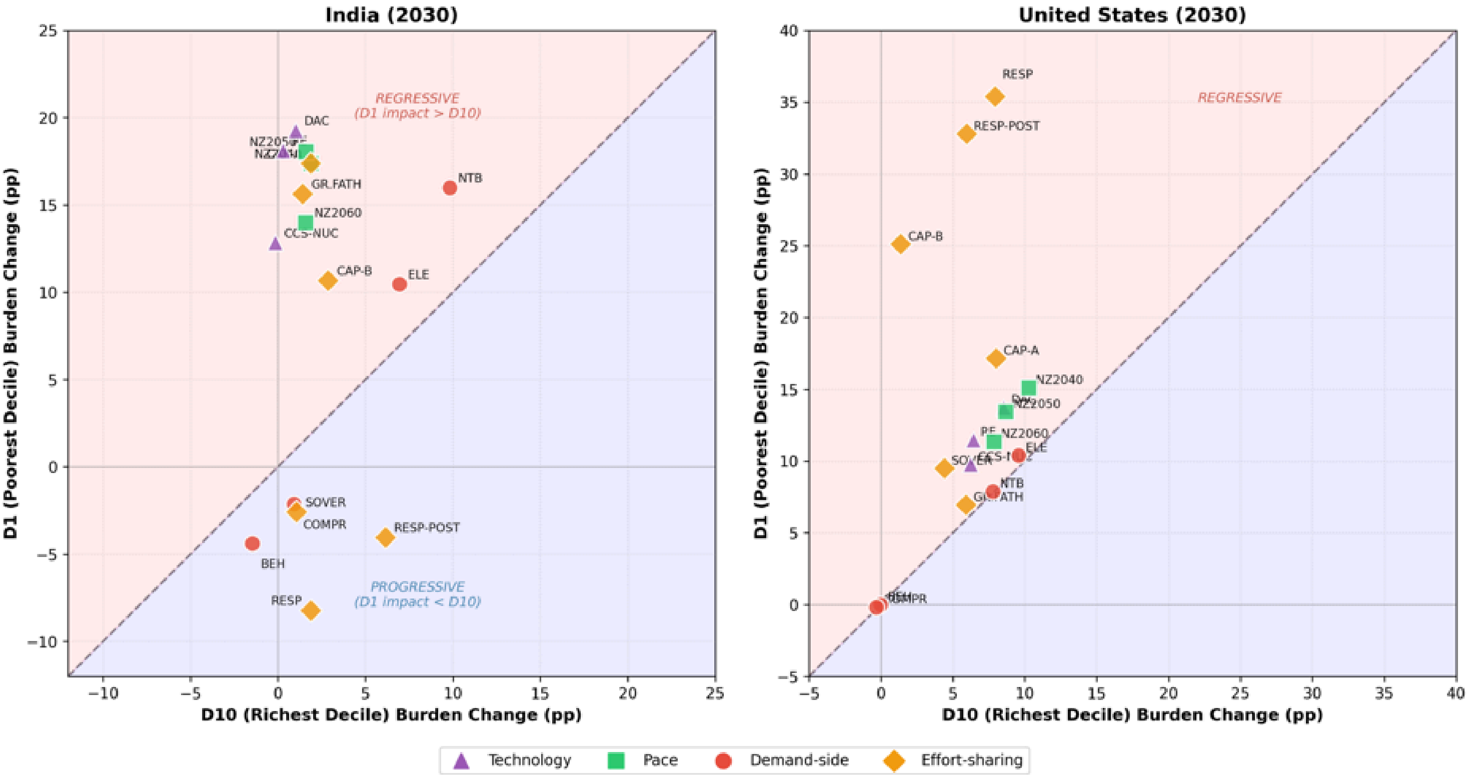

Figure 3

Distributional character of pathways: D1 versus D10 burden changes. Scatter plots for India (left) and USA (right). Points above the diagonal (shaded red) indicate regressive outcomes where D1 impact exceeds D10; points below (shaded blue) indicate progressive outcomes. Markers distinguish pathway categories. Note the contrast between RESP outcomes: progressive for India (below diagonal), highly regressive for USA (far above diagonal).

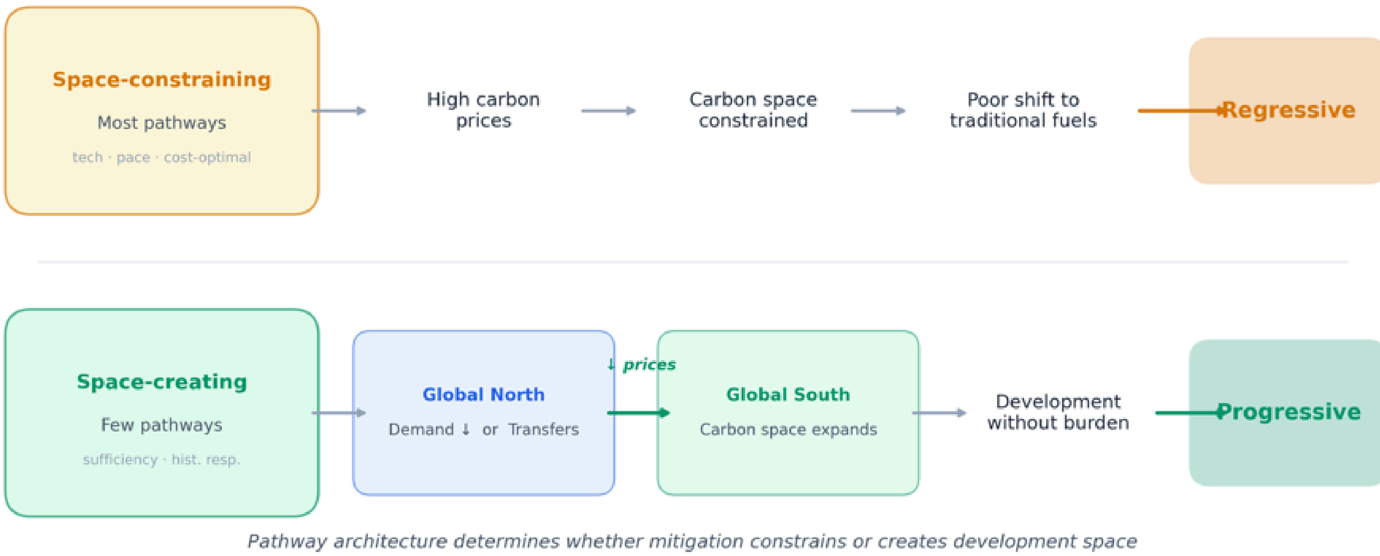

Figure 4

Mechanism linking pathway architecture to distributional outcomes. Space-constraining pathways (most technology, pace, and cost-optimal approaches) produce high carbon prices that burden poorest households most. Space-creating pathways (demand reduction, historical responsibility) reduce demand in wealthy populations, lower global prices, and create development space for the Global South.

Supplementary Files

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- graphicalabstractv16.png