Methodological and conceptual shortcomings of MEECC limit its transparency and policy relevance

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Kanitkar, Jayaraman & Lavanyaa (KJL from here on)[1] introduce the Model for Energy Equity and Climate Compatibility (MEECC_V.1), an analytical tool positioned as an alternative integrated assessment framework. MEECC is intended to facilitate the construction of scenarios to operationalize climate-compatibility, equity, and feasibility. The attention to the development-mitigation nexus and equitable effort-sharing in the context of global mitigation pathways is necessary and overdue, and we share it without reservation. Yet, we identify a number of methodological and conceptual shortcomings of the MEEC model that raise questions about its scientific robustness and ability to inform policy.

Balancing development with ambitious climate action has been a central preoccupation of global integrated assessment modelling (IAM) literature for more than two decades. Earlier work demonstrated that rapid decarbonization and continued development were not inherently incompatible, but that the distributional consequences of climate mitigation pathways depend critically on policy design and allocation of efforts across and within countries at different stages of development[2,3].

Using IAMs, researchers have examined how different effort sharing principles translate into national mitigation burdens (e.g., refs. [4,5]), and what kinds of policy designs are needed to ensure that mitigation policies do not indirectly increase risks of food insecurity, poverty and social inequalities (e.g., ref. [6]). The detailed representation of underlying processes and mechanisms governing the energy-economy-land-climate systems enables IAMs to do such analyses.

MEECC is not a substitute for this, as key components required to assess whether a mitigation pathway is physically achievable or technologically and economically feasible are not represented. It does not represent the basic mechanisms and systems that underlie the evolution of any of its three core variables (primary energy, CO_2, and economic growth). Most of the analytical explicitness and detail that ensures that IAMs are scrutable and auditable, and on which their policy relevance is built, is not represented.

Moreover, several elements of KJL's approach raise serious methodological concerns, and their engagement with recent literature on equity in IAMs remains limited. In the following sections we provide the summary of our analysis of MEECC, reflecting on: (1) its substantive and methodological issues, (2) KJL's claim on the four departures from IAMs' approaches and (3) definitional unclarity regarding integrated assessment models. A detailed analysis of our key methodological concerns is presented in the Supplementary Information.

Substantive and methodological issues with MEECC

We identify a set of substantive and methodological issues regarding the model's assumptions, including: (1) the empirical anchoring of multi-decadal high Gross Domestic Product (GDP) growth rates, (2) a conceptual conflation between primary energy and end-use provision of services that populations require, (3) an outdated base year for the assumed remaining carbon budget, (4) a counterintuitive operationalization of the Principle of "Common But Differentiated Responsibilities and Respective Capabilities" (CBDR-RC), and (5) the repercussions of the assumption of constant emissions intensity of energy.

The first issue relates to empirical anchoring of long-term GDP growth assumptions. A GDP trajectory specified in a model requires either a structural representation of the growth dynamics (e.g., productivity, capital accumulation, labor supply) that generates it along with a theory to substantiate this dynamic, or, absent such a representation, consistency with empirically observed growth. MEECC provides neither. Under the development threshold scenario (GDP_UMod-TS1/ GDP_DG2-TS2), 31 out of 179 countries in the sample would require GDP growth exceeding 9% per year, sustained over three decades, to reach the threshold of $28,000 per capita in 2050. 26 of those exceed growth rates of 10%, and 10 exceed 12% over three decades. While a historical precedent exists in the example of China between the 1980s and 2010s, this trajectory was shaped by specific institutional, socio-economic and resource conditions (see e.g., ref. [7]). KJL do not discuss in the manuscript that such high growth rates for more than 30 countries are outside the observed historical record, nor how such an exceptional growth like that of China would be transferable. Moreover, after 2050, in this scenario country groups are assigned growth rates between 0% (G1) and 2% (G5) (stated in the paper; and between 0% and 3% in code, line 549 and 564-565, v1.3). This lack of substantiation renders the GDP growth trajectories ad hoc and limits their utility in the context of evaluating plausible future development outcomes. In addition, KJL's documentation contradicts their own code, and thus we were unable to reproduce the numbers provided in the paper using the code supplementing the paper: GDP growth rates hard coded in the Python implementation published on Zenodo (v1.3 of 9 February 2026, the version current at acceptance, 10.5281/zenodo.18532397 and v1.3.1 of 9 July 2026, 10.5281/zenodo.21278878, the version current at the time of finalizing our manuscript; in both versions file MEECC_V.1_revision.py, lines 122-130 (161-169), accessed on June 15, 2026 and September 10, 2026) are between 0 and 2.5 percentage points higher for G2 to G5 country groups, compared to those reported in Table 9 of the paper (See Table *S1)*.

The second issue pertains to KJL's central energy equity metric: a 75 GJ per capita primary energy convergence target for all. Primary energy is a poor indicator of the energy services people obtain, and even on its own terms, equality does not amount to equity.

First, primary energy is an accounting quantity that lies several conversion steps from the services that reach people. For non-combustible sources, primary energy is an accounting construct rather than a measured physical flow, and sensitive to accounting conventions: KJL state neither the accounting convention nor the data source for primary energy, which leaves the threshold open by up to a factor three for electricity from non-combustible sources before any equity claim is even assessed (SI Table S5). More fundamentally, the services obtained from a given primary energy budget depend on the energy system. A household burning biomass on a traditional stove captures only a fraction of the useful heat that a modern gas or electric appliance delivers, so equal consumption need not mean equal access to the service it is meant to provide[8]. The pattern also applies to the system level: from 75 GJ of primary energy, useful energy ranges from 3 to 12 GJ in biomass-based systems, 17 to 19 GJ in coal-based grids, and 53 to 73 GJ in clean electrified systems using heat pumps and electric vehicles (using the physical content method while a clean electrified system would be 19-25 GJ under the substitution method, for example. SI Table S3). This order of magnitude variation implies that a primary energy convergence threshold equalizes an input to the energy system which only loosely relates to human wellbeing.

Second, even if primary energy were an adequate indicator of services, equality is not equity. Equity, in most accounts, concerns the capabilities and equal freedom of people to achieve valued functionings[9]. The energy required for the same functionings or living standards differs with climate, geography, and available technology (SI Table S6)[10]. We therefore understand KJL's uniform primary energy threshold as embedding a normative assumption on system inputs, weakly related to equity in terms of human wellbeing.

Two further methodological aspects relate to KJL's operationalization of climate equity: an accounting window that grandfathers the (historical) responsibility it purports to allocate, and misleading labelling of the resulting allocations (see SI section 3). First, the framework invokes historical responsibility while allocating only the post-2020 remaining carbon budget (RCB). Setting the accounting boundary at 2020 exempts all pre-2020 emissions from the allocation, the actual emissions conventionally considered relevant when looking at historical responsibility. The paper also fails to include the >200 $GtCO_2$ that was emitted between 2020 and 2025[11]. Using an outdated budget (starting from 2020) compounds the issue of exempting these recent emissions. Updated estimates place the remaining 1.5 °C budget at roughly 130 $GtCO_2$ for a 50% probability[12], so the RCB values used in MEECC are overstated (SI section 3.1). Second, the budget allocations that KJL describe as "per capita fair share of the RCB *based on grandfathering past emissions*" and "per capita fair share *weighted by both* historical responsibility and capability" are in effect nearly identical, both largely reflecting equal per capita allocations (see SI Fig. S5). Their quantifications for the concepts underpinning CBDR-RC are not in line with other academic interpretations.

KJL further characterize as circular those approaches that place distributive transfers outside the optimization core, citing ref. 13 as an example. This misreads the argument. Treating redistribution as an explicit, external mechanism is not a logical circularity but a transparency choice about which mechanisms sit inside the model and which sit outside it.

Finally, the authors state explicitly the assumption of constant emissions intensity of energy in their baseline projections, while acknowledging that the intensity decreases with improving technology. This assumption inflates the required level of emissions reductions reported in Figs. 5 and 6 because a degree of carbon intensity improvement may take place even without dedicated mitigation policies, as globally CO2 intensity of energy use has declined over the past decade[11].

The four claimed departures from IAMs

KJL list four ways in which they depart from IAMs. However, instead of providing a novel point of departure from IAM modelling, the MEECC approach (including its simplified application of a Kaya-identity) resembles a different class of well-established analytical approaches focusing on carbon-budget allocations (such as e.g., the Climate Equity Reference Calculator)[5]. Such models are structurally different, as they focus on deriving emission allocations rather than plausible energy-economic transformations. Transparent allocation tools have a legitimate and valued role. Our objection is thus to the IAM labelling and the various internal errors, rather than the simplification that can be useful for addressing specific questions. The methods KJL apply do not seem appropriate for most purposes that IAMs are used for. Furthermore, their claimed four points of departure from the "usual approach" in IAMs overlooks that these aspects are very much part of the standard IAM literature already:

1. **Development based rather than geographical classification of regions.** Regions in IAMs tend to be grouped on a combination of levels of development and spatial proximity to, for example, allow for modelling economies that are highly integrated. Some IAMs have high spatial granularity and therefore can do both. In many exercises, across models, much of the scenario work takes place on the national level before aggregation to the regional level. Foundational socio-economic projections (population, income, urbanization, poverty, energy access) are constructed at country level prior to regional aggregation[14,15]. The regional structure of global IAMs is a modeling choice driven by tractability and interaction between countries at the global scale, not an inability to represent national circumstances.
2. **Economy-wide metrics rather than a general equilibrium framework.** In practice, MEECC specifies GDP growth rates based on ad-hoc assumptions by country group, without modelling productivity, capital accumulation, labor supply, or substitution dynamics. While this represents a departure from general equilibrium approaches, it does not introduce an evidence- nor theory-based alternative economic structure that captures these processes.
3. **Analytical exploration of energy futures rather than carbon price optimization.** IAMs have long examined prescribed budget scenarios, normative targets, and policy packages without relying on optimization (e.g., refs. [16-18]). These analyses typically retain representations of energy systems, technology diffusion, and costs, which remain central to any assessment.
4. **Carbon budget allocation rather than optimized emission outcomes.** Fair share allocation of carbon budgets has been extensively studied over several decades (e.g., refs. [4,19]), and ongoing multi-model comparisons continue to develop this line of work[20]. The framing and approach are therefore well established within the literature.

In contrast, the principal differences between MEECC and state-of-the-art IAMs lie in its omission of several core components that allow conceptual, structural and scholarly scrutiny, including energy technology representation, sectoral disaggregation, economic structure, climate processes, land use and carbon cycle dynamics.

Definitional unclarity

Finally, KJL define an IAM as *"a model that combines representations of environmental processes, economic dynamics, and policy interventions to explore sustainable development pathways and climate mitigation strategies"*, referring to the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) as the source. This formulation does not appear in the AR5 Glossary of the Working Group III (WGIII). The AR5 Glossary instead defines "integrated models" as requiring *"full and disaggregated representations of the energy system and its linkage to the overall economy"*. The KJL IAM definition can also not be matched with the 6th Assessment Report (AR6) IAM glossary definition (see SI section 1). Since MEECC does not align with relevant IPCC definitions used in WGIII scenario assessments, the description as an "alternative integrated assessment framework" may mislead readers and overstate its applicability and scope.

Conclusion

We share the core motivation of KJL to explore scenarios that operationalize climate-compatibility, equity, and feasibility. However, we identify methodological and conceptual shortcomings of the

MEECC. Addressing them matters precisely because we share the goal. A transparent, simple allocation tool built on wellbeing-based equity metrics, current carbon budgets, and empirically grounded development trajectories would be a welcome contribution. In its current form, MEECC requires further development to substantiate its claims as an alternative integrated assessment framework.

Competing interests statement

The authors develop and apply integrated assessment models.

Author contributions statement

RS, KR, MA, JK, CFS conceived the response. MA, JK, ML and CFS performed the analysis. RS, MA, JK, AN, CFS led the writing of the manuscript. All authors contributed to the development of the manuscript.

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Supplementary Information

The concern for equity in climate mitigation modelling is both legitimate and urgent. It is precisely for this reason that modelling approaches such as MEECC must meet the analytical standards required to inform policy. The supplementary information provides further background and detailed assessments of our concerns with the MEECC approach as it has been laid out by KJL.

1. Fundamental definitional, structural and conceptual differences between MEECC and IAMs

The authors define an IAM by citing the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) as the source of the following definition: *"a model that combines representations of environmental processes, economic dynamics, and policy interventions to explore sustainable development pathways and climate mitigation strategies"*. However, this definition does not appear in the AR5 Working Group III Annex I Glossary, nor in any subsequent IPCC Glossary.

The AR5 does not provide a definition of the term "integrated assessment model". What it does provide are two relevant definitions for "Integrated Assessment" and "Integrated Models". These definitions are substantively different from the paraphrase used by the authors (see Table S1). The official AR5 Glossary of the Working Group III definitions are explicitly broader, encompassing biological and social sciences and requiring disaggregated energy system representations.

Table S1. *Comparison of KJL statement with relevant IPCC AR5 WGIII Annex I Glossary definitions.*

KJL statement	**Actual AR5 WGIII Glossary definition:** **Integrated Assessment**	**Actual AR5 WGIII Glossary definition:** **Integrated Model**
Integrated Assessment Model has been defined by the IPCC as a "*Model that combines representations of environmental processes, economic dynamics, and policy interventions to explore sustainable development pathways and climate mitigation strategies.*" (provided with a reference to IPCC AR5 WGIII)	Method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions among these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.	Integrated models explore the interactions between multiple sectors of the economy or components of particular systems, such as the energy system. In the context of transformation pathways, they refer to models that, at a minimum, include full and disaggregated representations of the energy system and its linkage to the overall economy that will allow for consideration of interactions among different elements of that system. Integrated models may also include representations of the full economy, land use and land use change (LUC), and the climate system.

The subsequent IPCC Sixth Assessment Report (AR6), also available at the time of writing of KJL, then provides an explicit definition of "Integrated Assessment Models" as "*Models that integrate knowledge from two or more domains into a single framework. They are one of the main tools for undertaking integrated assessments. One class of IAM used with respect to climate change mitigation may include representations of: multiple sectors of the economy, such as energy, land use and land-use change; interactions between sectors; the economy as a whole; associated greenhouse gas (GHG) emissions and sinks; and reduced representations of the climate system. This class of model is used to assess linkages between economic, social and technological development and the evolution of the climate system. Another class of IAM additionally includes representations of the costs associated with climate change impacts, but includes less detailed representations of economic systems. These can be used to assess impacts and mitigation in a cost–benefit framework and have been used to estimate the social cost of carbon.*"

MEECC does not satisfy the minimum requirements of the Integrated Model definition, as it contains no disaggregated energy system representation.

Weyant (2017) distinguishes two principal classes of IAMs: detailed-process (DP) IAMs, which provide rich, sector-disaggregated representations of the energy system, land use, agriculture, and the carbon cycle (e.g. COFFEE, GCAM, IMAGE, MESSAGEix-GLOBIOM, REMIND-MAgPIE, WITCH, COFFEE) and aggregate benefit–cost (BC) IAMs, which combine highly aggregated economy and climate damage functions and are used principally to estimate the social cost of carbon (e.g. DICE, FUND, META, PAGE). Characteristic components identified by Weyant across both classes include socioeconomic drivers, energy and/or land-use system representation, an emissions and carbon-cycle/climate response component, and in BC IAMs explicit damage functions and welfare aggregation. MEECC_V.1 satisfies none of the component requirements of either class, beyond a minimal level of global coverage and emissions accounting, yet the authors claim it constitutes an 'alternative integrated assessment framework.' This claim is not substantiated by the model's architecture and is inconsistent with established disciplinary practice and IPCC definitions.

One element that is commonly used as part of IAM scenario construction is the minimization of costs under a global carbon constraint. Depending on international trade assumptions, this can yield a uniform shadow price across regions and focus near-term mitigation where marginal abatement costs are lowest. This can, in turn, result in a pattern in which later-developing economies bear a relatively larger share of mitigation effort (Pachauri et al. 2022; Rubiano Rivadeneira and Carton 2022; Pachauri et al. 2026; Low et al. 2025). Equity considerations in the financing of mitigation investments have been analyzed in recent research, indicating, for example, that financial flows from North America and Europe to other regions would have to increase substantially relative to present levels to meet the Paris Agreement goals (Pachauri et al., 2022).

A growing body of national modeling work demonstrates a developing integrated assessment capacity in the Global South. For instance, Brazil's two prominent national IAMs (BLUES and COFFEE-TEA) have been applied across energy, land-use, and sectoral decarbonization questions (e.g., Lucena et al., 2016, Köberle et al., 2020). Within the Global Change Analysis Model (GCAM) family, national variants for Chile (Arriet et al., 2022), India (Chaturvedi et al., 2022), China (Wang et al., 2026) and Saudi Arabia (Apeaning et al., 2025) develop context-specific carbon neutrality pathways. A recent application adapts GCAM to explore the land-energy-water systems for the African continent (Dioha et al., 2025). Similarly, across China, India, Vietnam, Malaysia, Nepal, long-term strategies and decarbonization scenarios have been developed using the Asia-Pacific Integrated Model (AIM) (Hibino and Masui, 2023). These are only some examples of local expertise and knowledge exchange helping to extend this type of work to many countries.

The authors claim four ways in which MEECC departs from standard IAMs: (1) development-based rather than geographical classification of regions; (2) economy-wide metrics rather than a general equilibrium framework; (3) analytical exploration of energy futures rather than carbon price optimization; and (4) carbon budget allocation rather than optimized emission outcomes. For all four points, at a high level of abstraction, we agree that such approaches can be valid, with appropriate methods. However, the methods KJL apply do not seem appropriate for most purposes that IAMs are used for. Moreover, we do not agree that these four points cannot (or are not) part of the standard IAM literature already.

On point (1): regions in IAMs tend to be grouped on a combination of spatial proximity, e.g. to allow for modelling economies that are highly integrated but are often also grouped based on levels of development. Some IAMs have high spatial granularity and therefore can do both together, like the GCAM model (>30 regions) (Calvin et al., 2019), POLES model (>50 region) (Keramidas et al., 2018), the International Futures (IFs) model which operates at the country level (Hughes et al., 2004). In many exercises, across models, a lot of the scenario work takes place on the national level before aggregation to the regional level. This is the case for economic modelling of GDP (Dellink et al. 2017), demographic modelling of population growth and educational attainment (KC and Lutz 2017), the modelling of current poverty and future eradication of it (Soergel et al. 2021, Kikstra et al. 2025), or the modelling of multiple ambitious sustainable development pathways (Soergel et al. 2024). For all of these elements, as they are aware of the national context, the scenario narratives all depart with a development-based understanding.

On points (2) and (3): KJL do not model the economy. Here, with 'economy-wide metrics' and 'analytical exploration', the authors mean setting a GDP growth pathway for each country without providing information about productivity, physical capital, employment, or human capital developments that would be consistent with pathways achieving such goals. In other words, from a macroeconomic perspective, this approach is inconsistent. While 'what-if' explorations of specific target-driven futures has a place in the literature as also explored with IAMs (e.g., Weyant et al. 2017; Wilson et al. 2021, Min et al. 2024, Li et al. 2024), their policy-relevance is reduced and should be determined by systematically analysing the internal consistency, plausibility, feasibility, and desirability of each of the elements of such scenarios, for which more information is required on the processes used for the energy and land transitions, and the costs related to them. KJL do not calculate the costs or investments required for any mitigation pathway, and neither does MEECC allow doing so.

On point (4): for decades, the scenario literature has explored carbon budget allocations to describe possible future trajectories, also using IAMs: both using benefit-cost IAMs and process-based IAMs (e.g., Rose et al. 1998, Berk and Den Elzen 2001, Den Elzen and Schaeffer 2002, Luderer et al. 2012, Tavoni et al. 2015, Bauer et al. 2020, Pelz et al. 2025a). This includes ongoing joint coordinated model experiments with a broad set of IAMs participating (Pelz et al. 2025b). The same holds for studies analyzing national commitments or proposed policies (e.g., Rogelj et al. 2010), and possible policy packages both for global solutions and sectoral–specific analyses (e.g., Mastrucci et al. 2025).

In fact, the actual number of departures from state-of-the-art IAMs is far larger. MEECC carries more resemblance to the Kaya Identity than to integrated models, both in structure and in the types of insights that can be obtained with it. MEECC has no energy technology representation, no sectoral disaggregation, no endogenous economic model, no climate module, no land-use or carbon-cycle component, no bioenergy with carbon capture and storage (BECCS) or other carbon dioxide removal (CDR) technologies, and no mechanism for commodity price signals or investment dynamics. KJL argue that the core of the development-climate nexus can be captured by just three variables (primary energy, CO2 (excl. land use), and GDP). We disagree. The comparison of MEECC and process-based IAMs in Table S2 captures the scope of this gap.

Table S2. *Comparison of model components between MEECC_V.1 and process-based IAMs.*

Model component	MEECC	Process-based IAM
GDP/cap	User-specified growth trajectory lacking representation of the determinants of growth	SSP trajectories are based on empirically estimated growth models with conditional convergence dynamics; exogenous to the IAM. They include price-induced changes of economic growth as well as endogenous treatment of economic productivity
Representation of process technologies	Absent	100+ technologies
Transport sector	Absent	Detailed
Industry sector	Absent	Detailed
Buildings sector	Absent	Detailed
Energy supply representation (aggregate)	Only aggregate, no modelling of coal, oil, gas, biomass, solar, or wind	Detailed
Land use modelling	Absent	Detailed
Non-CO2 GHG emissions	Absent	Detailed
Aerosol emissions	Absent	Detailed
Carbon Dioxide Removal options	Absent	Detailed
Demographic dynamics	Own projections	Demographic model
Ability to audit internal consistency and feasibility through process and system-information	Absent (e.g., feasibility implemented as 10-year minimum from peak to net-zero CO2 per country)	The modelling of processes in detail ensures that transitions are physically traceable, permitting to understand feasibility and sustainability challenges. (this includes e.g., representation of technological change, resources, material and energy flows, etc.)
Country-level granularity	Present	One or more dozens of regions

These omissions and simplifications limit the extent to which MEECC can provide information for transition research. The omissions include the fundamental analytical components that enable assessing the feasibility and desirability of transition pathways. Feasibility assessment requires modelling technology diffusion, resource constraints, investment dynamics, and physical limits on the rate of system change. For instance, KJL project one scenario where Germany reaches net-zero CO2 in 2032 (Table 6, p. 9), with no way to ask whether that is achievable. Similarly, to decide whether a scenario is desirable, one requires the capacity to evaluate trade-offs across sectors, regions, and time. One requires the ability to project end-use services to know whether needs and aspirations can be met across, for instance, housing and mobility, as well as industrial development. MEECC provides no ground for such feasibility of desirability assessments. Its authors' characterization of this limitation as choosing not to "miss the wood of energy access and climate equity for the trees of granularity and complexity" obscures the fact that the granularity in question allows policymakers to distinguish physically achievable transitions from purely arithmetically consistent ones. A model that cannot determine whether a projected energy system transition is technically feasible, nor whether it implies welfare gains or losses, is not an adequate alternative to IAMs. Presenting it as an alternative integrated assessment framework overstates its analytical scope and risks shifting the substantive discussion of equity in climate modelling to a platform that does not represent many of the key determinants of equity within the systems assessed.

Furthermore, process-based IAMs can be downscaled to the national level, where system-level structure is adapted to local conditions and used to design sector-specific transition strategies. This is not possible with a framework such as MEECC that provides no sectoral or technological resolution. The claim that MEECC's country-level granularity exceeds that of standard IAMs mischaracterizes the difference: MEECC assigns countries to development groups but provides no within-country or within-sector analytical depth, while IAMs provide both regional aggregation and the capacity for country-level downscaling with full sectoral and technological detail. At the same time, IAMs are commonly applied in national modelling contexts in all major economies allowing for much increased national detail and alignment with national policy objectives the National Scenario Protocol or the recent Nationally Determined Contribution (NDC) of Brazil). It is also possible to link national and global scenarios (i.e. Roelfsema et al. 2020). Similarly, hybrid approaches to develop global emission trajectories consistent with national emission pathways have also been proposed (Zhong et al. 2025).

Lastly, one of the reasons that scenarios developed with the help of process-based IAMs are prominent in assessment reports, is because of their ability to quantify the required information to enable consistent integration of assessments across fields of climate science (Pirani et al. 2024). This includes global concentrations of all climatically relevant GHGs, sectoral coverages of 10 different emissions species crucially including aerosols and aerosol and ozone precursors for climate models, which in turn provide information for regional and local climate impact models.

2. Methodological concerns and internal inconsistencies

2.1 Unprecedented GDP growth rates

The model's development threshold scenario requires all countries to reach $28,000 GDP per capita by 2050. Because no economic model generates these trajectories, the required growth rates are computed mechanically from the gap between 2019 incomes and the target, which may lead to macroeconomic inconsistencies. There is no underlying growth model that would explain how these growth rates are achieved. For 31 countries, 26 of which are in sub-Saharan Africa, this implies growth more than 9% per year sustained continuously for 31 years (see Figure S1). This is similar to the assumed 8.5% annual growth rate for G5 countries in the GDP_UHigh scenario (stated in the paper as 7%). Sustained growth at such rates is virtually without precedent in the historical record. China's GDP growth of roughly 10% over three decades in the period 1980s-2010s comes closest, and was a historical outlier under catch-up conditions that may not apply to other structurally constrained low-income economies (e.g., Bosworth and Collins, 2008). Compared to the user-defined assumptions in MEECC, the SSP GDP projections are produced using several macro-economic growth models, in which the GDP growth is primarily a function of physical and human capital and total factor productivity which captures technological change and institutional quality (Crespo Cuaresma, 2017; Dellink et al., 2017, Leimbach et al., 2023, Koch and Leimbach, 2023). Within the SSP framework scenarios, only for SSP5 and only for three countries out of 216 do we see growth rates of between 9 and 10% per year over the 2025-2050 period (Guyana, Mozambique and Solomon Islands). Following the SSP5 storyline of fossil-fuel powered growth, these could be interpreted as the result of extractive resource projects (oil, gas, or mining) landing on a very small GDP base, hardly expandable to many more countries. As shown in Fig. S2, SSPs exhibit a significant negative relationship between present-day income and projected growth, reflecting the conditional convergence dynamics embedded in the underlying SSP socioeconomic modelling. It is also worthwhile noting that population projections, themselves scenario-specific and driven by changes in fertility, mortality and migration, feed directly both in the labor supply and the per-capita scaling of GDP, thereby providing an internally consistent picture of socioeconomic development.

It is also worthwhile highlighting that the socioeconomic development trajectories represented by the SSPs are widely used as inputs in models estimating future climate impacts, exposure, vulnerability, including capacities of countries to invest in mitigation and adaptation (O'Neill et al., 2020, Brutschin et al., 2021, Andrijevic et al., 2023). This is where minimum standards of empirical and theoretical grounding need to be met. Growth trajectories that are neither anchored in established growth theories nor consistent with observed historical dynamics are, at best, pure thought experiments, and, at worst, a source of systematic bias in downstream applications. For example, presenting the KJL income growth rates to adaptation planners to indicate when they might gain sufficient financial capacity to implement certain measures could introduce unfounded optimism and risks of misguided policy.

Below is a comprehensive comparison of historical GDP growth rates from the World Bank, aggregated as averages over a 25-year observed period (1975-2000; 2000-2025), compared to the averages across all SSPs from 2025 until 2050 and the MEECC growth rates for the G1-G5 country groups as well as the rates assumed for countries to reach the $28000 per capita by 2050.

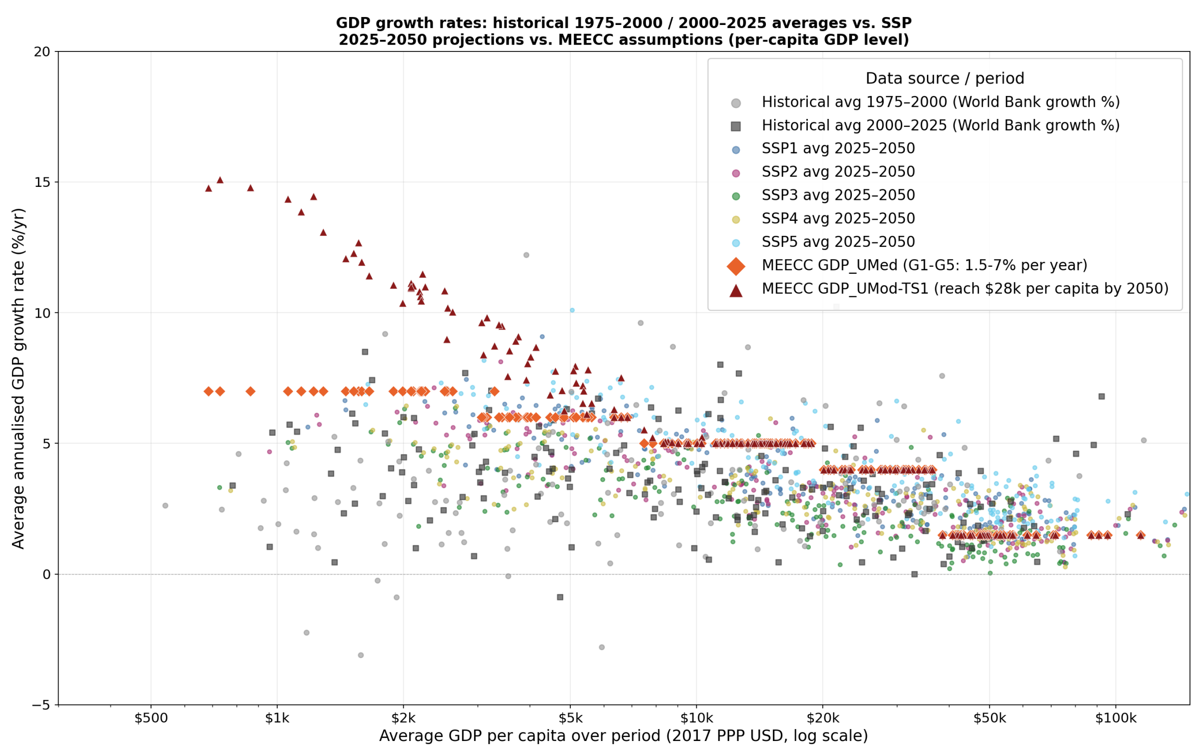

Figure S1. *Average annual GDP growth rates assumed in MEECC (scenarios GDP_UMed and GDP_UMod-TS1, as reported in the code), SSP projections and observed in historical data, plotted against levels of GDP per* *capita. Each point represents one country. Grey points show average annual GDP growth rates observed over 1975-2000 and 2000-2025 (World Bank data), plotted against average GDP per capita over the same period. Annotated are examples of countries with unique historical circumstances. We also show average annualized growth rates projected for 2025-2050 under SSPs 1 to 5 (IIASA SSP database v3.1), plotted against average GDP per capita over the same period. The orange diamonds show the fixed GDP growth rates assigned to each MEECC country group, as reported in the code. Red triangles show the country-specific rates under the threshold scenario TS1, in which each country's growth rate is raised to the level required to reach $28,000 per capita by 2050.*

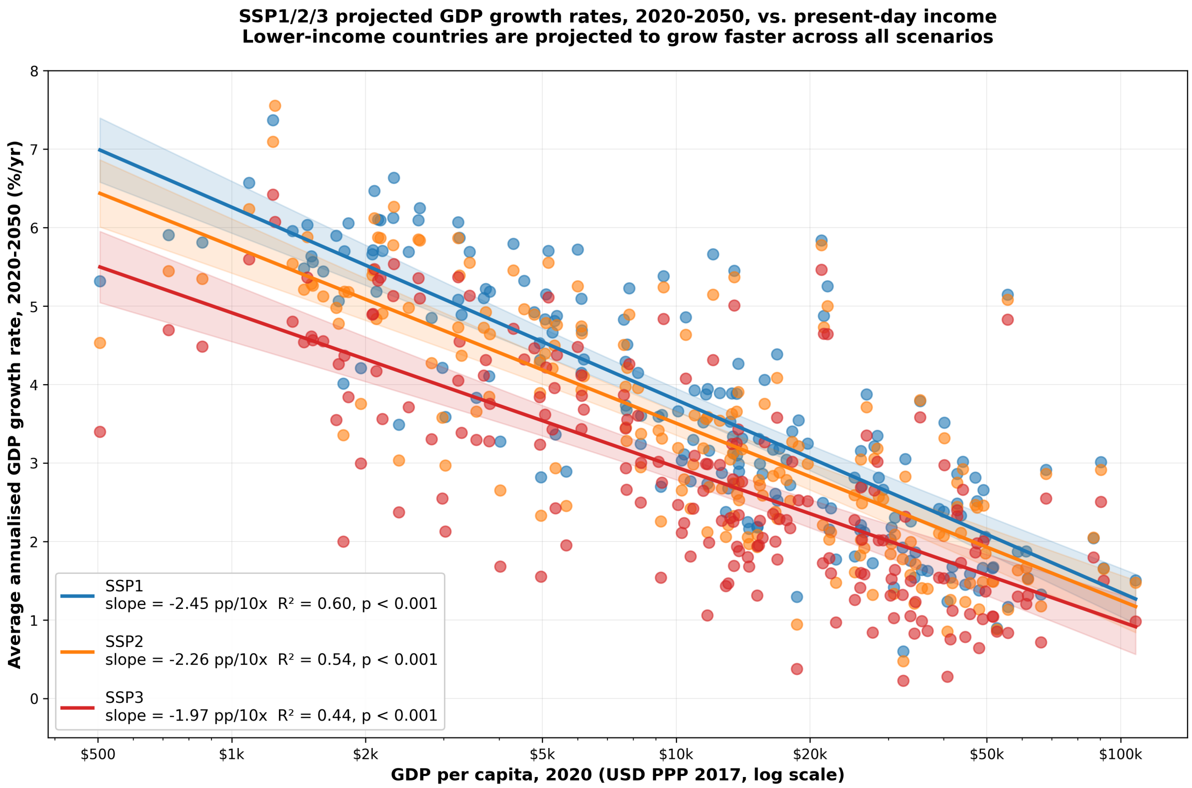

Figure S2. *Relationship between present-day income and projected GDP rates under SSPs 1 to 3. Lines show ordinary least squares regression fits on log-transformed per capita GDP (x-axis). Shaded bands indicate 95% confidence intervals.*

Additionally, the GDP growth rates hard-coded in the published model file are systematically up to 2.5 percentage points higher for G2-G5 countries (resulting in growth rates of 8.5% for G5 countries), than those stated in the paper's own Table 9 (see Table S4 for the full comparison). That the published rates differ from the archived code for all five non-threshold scenarios, is a problematic and consequential mismatch.

2.2 Overreliance on a single demographic trajectory without justification or contextualization

The single demographic trajectory used by KJL appears inconsistent with high development. While the main paper and supplementary information provide no information about this trajectory, the code repository reads *"Documentation for MEECC_V.1_dashboard_updated.docx"*, Version MEECC-V.1.3: *"The population by country data from 2019 to 2050 were collated from the data and estimates* *from HYDE (2023); Gapminder (2022); UN WPP (2024) – with major processing by Our World in Data. Further, the country level population between 2051 and 2100 was projected at the rate of last five years till 2100."*

Figure S3. *Annual population growth rates for selected countries, and the world, obtained from KJL (red line), and the UN World Population Prospects (green, blue and violet lines for the lower 95th, medium and upper 95th percentile respectively).*

Comparing the population numbers used in United Nations World Prospects 2024 (WPP2024; United Nations, Department of Economic and Social Affairs, Population Division 2024) provides useful context (Figure S3). UN WPP low, medium, and high variants diverge, but all UN variants continue to see declining global population growth rates. KJL, without substantiation, keep growth rates constant for 2050–2100, per country. Such an assumption does not appear internally consistent on the global level, where it represents an exceptionally high population growth projection especially due to high continued population growth in lower income countries.

This omission is particularly consequential given the paper's equity framing. Population growth is itself not unrelated to development: a substantial body of demographic research documents that fertility rates decline with rising incomes and improved education, and declining mortality (Kebede et al. 2019, Lorentzen et al. 2008, Lutz et al. 2019), which are the developmental outcomes MEECC's GDP threshold scenario is designed to achieve. The model's assumption of rapid income convergence seems internally inconsistent with the high population growth projected.

2.3 A primary energy convergence target of 75 GJ per capita is an inadequate metric of wellbeing

The paper's central assumption on the energy convergence target of 75 GJ per capita primary energy is not a well-defined physical quantity: it conflates accounting convention, generation technology and end-use technology in ways that make cross-country and cross-scenario comparisons problematic.

For example, primary energy needs are much higher in fossil-fuel dominated energy systems because most of the fuel's primary energy is lost as waste heat in combustion engines and thermal power plants, whereas an electricity-dominated system uses much more efficient end-use technologies (like heat pumps and electric vehicles) that deliver the same useful energy, and as a consequence the same energy service, with far less input.

In other words, the same amount of primary energy can result in very different energy services that matter for human well-being (Kalt et al. 2019). While applied as an illustrative number, it should be noted that it also rests on a misapplication of the sources the paper cites. While KJL indicate that users can choose between a range of 60-95 GJ/cap/year, they apply the 75 GJ/cap/year primary energy use as a constant over the full 21st century citing Jackson et al. (2022). Jackson et al. (2022) stress that their findings are correlational, with the nine well-being metrics used in the study representing a cross-section for the state of the world in 2018, and caution against causal interpretations. More explicitly, Ranjan and Kanitkar (2025) show in their main results (Table 4) an empirical decline from 1990 to 2017. Contrasting this trend, to reach a number for 2050, they extrapolate specific variables, noting that their thresholds can change over time. Such an extrapolation approach is highly sensitive to its specifications. For example, when extrapolating to 2050 based on shorter time periods (2012-2017), thresholds using their method can grow to 329 GJ/cap/yr in 2050 for primary education (SI table S.6; up from 28 for 1990-2017, SI Table S.2; or finding 78 for 2050 if extrapolating based on 1990-2017). The safe sanitation energy threshold is also 28 GJ/cap/year for 1990-2017 (SI Table S.2) but declines to 9 GJ/cap/year in 2050 under the 2012-2017 based extrapolation (SI Table S.6). Together, this questions the extent to which a constant primary energy threshold may approximate a certain level of development from now until 2050.

A broader literature review reinforces this point. Steinberger & Roberts (2010) showed that the primary energy threshold for achieving high Human Development Index (HDI) values has been falling over time, with some countries achieving HDI above 0.8 below 75 GJ per capita and write "Rather than insisting that a high level of energy and carbon are a prerequisite for high living standards, …, it would seem that they are ever less necessary". In recent years, many countries have shown marked increases in the HDI while per capita primary energy has declined (Figure S4, for countries with GDP/cap below 28,000 in 2013). This includes middle- and low- income countries at low primary energy per capita consumption like Pakistan (~15 GJ/cap/yr) and Egypt (~35 GJ/cap/yr). Additionally, Kikstra et al. (2025), expanding upon previous work by e.g. Rao et al. (2019) and Millward-Hopkins et al. (2020), show how the energy requirements (here expressed in final energy per capita) for a set of living standards could decline substantially well before 2050, especially in scenarios with climate mitigation policies.

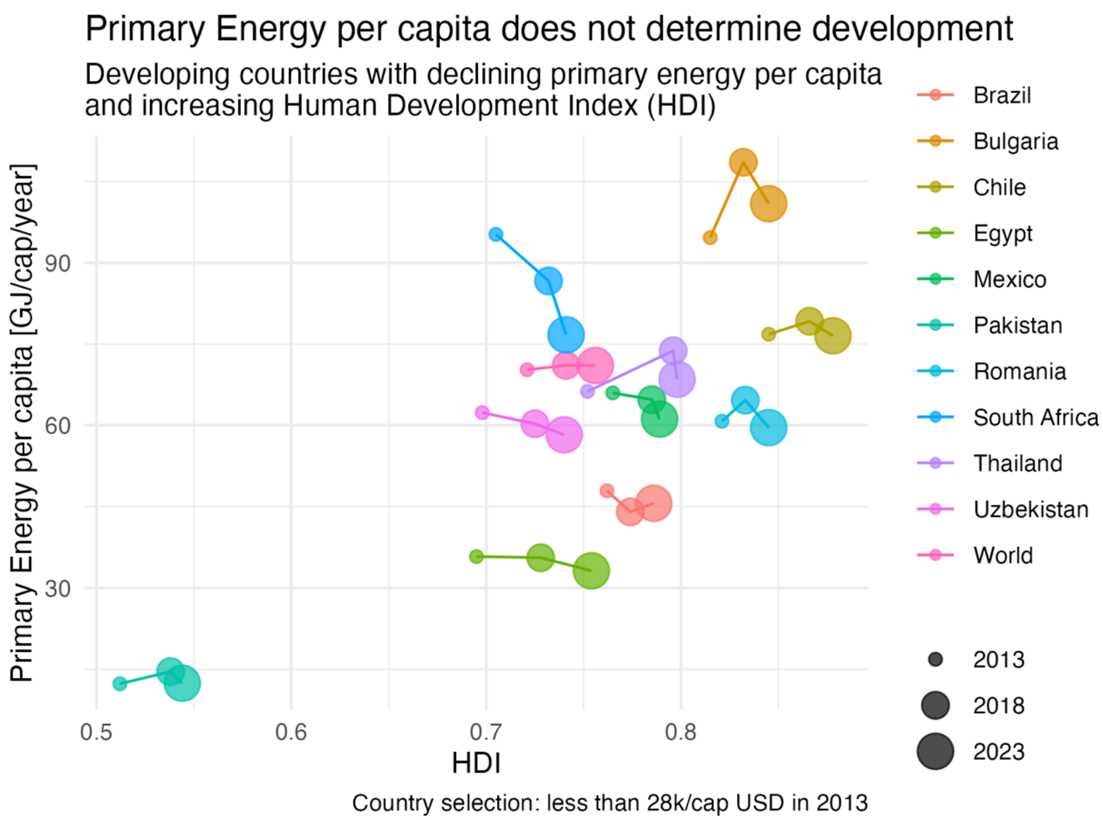

Figure S4. *Illustration that for increasing development, primary energy per capita growth is not a necessary requirement. Available countries with <28kUSD/cap in 2013 that have seen periods of five or ten years where primary energy per capita declined while the HDI increased.*

The lack of accounting for the conversion-loss problem itself is a major methodological flaw. A target expressed in primary energy provides little useful information without specifying the energy system, because identical primary energy totals yield very different amounts of service levels and living standards, depending on the source mix. Under a coal-dominated system, 75 GJ per capita primary energy delivers approximately 17–19 GJ per capita worth of useful energy services. Under a renewable-electricity-dominated system, in which electric motors dominate and heat pumps deliver three to four units of thermal energy per unit of electrical input, the same 75 GJ per capita primary energy delivers more than double: approximately 53–73 GJ per capita of useful energy services. By specifying convergence in primary energy rather than final energy, useful energy or energy services, the model embeds a strong implicit assumption about the energy mix that is never acknowledged. It does not recognize the possible pathways that deliver higher services at lower levels of primary energy use. A 75 GJ per capita target is not a technology-neutral development threshold.

For illustrative purposes, Table S3 below provides a comparison of the differences in the efficiency of energy conversion and the final energy produced by different configurations of energy systems. The effect of the primary energy accounting convention and energy requirements for equivalent services in different contexts are provided in Tables S5 and S6, respectively.

Table S3. *Primary-to-useful energy chain by energy system: what 75 GJ per capita of primary energy delivers.*

Energy system	Primary-to-final efficiency (%)	Final energy from 75 GJ (GJ)	Final-to-useful efficiency (%)	Useful energy (GJ)	Ratio to biomass
World average (2020)	72	54	65	35	—
Traditional biomass, wood burned directly	~90	68	11–18	7–12	1×
Traditional biomass, charcoal route	19–33	14–25	18	3–4	0.4×
Coal-dominated grid	32	24	70–77	17–19	1.8×
Clean electrified grid, physical content method	91	69	77–106	53–73	6.4×
Clean electrified grid, substitution method	32	24	77–106	19–25	2.2×

Conversion efficiencies from Grubler et al. (2012); charcoal carbonisation yields from Schure et al. (2019). About 90% of biomass reaches end-use sectors without passing through central electricity and heat generation (41 of 46 EJ; Grubler et al. 2012, Fig. 1.5). Carbonisation efficiency is on an energy basis, derived from earth-kiln mass yields of 13–15% (Schure et al. 2019, p. 59) and heating values of 28–33 MJ/kg for charcoal (ibid.) and 15–19 MJ/kg for wood (Grubler et al. 2012, Table 1.B.2a). End-use efficiencies for electrified systems are the 2020 residential and commercial sector averages (Brockway et al. 2024, Fig. 11), used as a proxy for heat pumps and electric vehicles. Commercial exceeds 100% because low-temperature heating and cooling equipment delivers more useful heat than its energy input. The global average is the world primary-to-final energy efficiency for 2020 from Brockway et al. (2024), which follows the physical content method and covers direct fuel use as well as electricity generation. Grid rows include transmission losses of about 9% (Grubler et al. 2012, Fig. 1.5). Ratios are calculated against the midpoint of the direct wood-burning row.

We also not some additional inconsistencies in the code base provided. Specifically, the 'no solution' exclusion is applied to the emissions figures, while GDP and energy panels include countries that the emissions panels drop, which is not specified in the figure captions. We also note that there is a unit conversion issue for the LULUCF_Shift scenario where the code sets a maximum of 10 times the -0.005 GtCO2 by 2100 number provided in Table 11.

3. Equity assumptions out of step with recent equity literature

3.1 Unclear use of the carbon budget accounting pre-2020

MEECC distributes the remaining carbon budget (RCB) from IPCC AR6 WG1 Table SPM.2 (IPCC, 2021), which provides budgets as of the beginning of 2020. The paper was submitted in July 2025 and accepted in March 2026. At time of publication, cumulative emissions from 2020 through 2025 amount to more than 200 $GtCO_2$ (Friedlingstein et al., 2026). This renders the RCB values used by MEECC materially overstated relative to what was remaining at the time of publication: the 1.5°C 50%-probability remaining carbon budget has shrunk to approximately 130 $GtCO_2$ as of early 2025 according to updated and revised analyses (Forster et al., 2025). A model built around a carbon budget constraint that overstates remaining budget provides unreliable quantitative guidance on the urgency of near-term action.

More fundamentally, the choice to allocate only the post-2020 RCB, without accounting for pre-2020 cumulative emissions, is a non-standard way of applying the principle of historical responsibility to which the paper repeatedly appeals. In scholarly literature, accounting for national emissions starting from, e.g., 1850, 1990, or 2015 is common. The implication here is that the authors always allow some positive carbon budget to all countries, unlike other approaches which would identify negative remaining carbon budgets already to date. By starting the allocation only from 2020, MEECC effectively forgives historical emissions.

This conceptual ambiguity is further evident in inconsistent scenario labels. The Methods describe PCFS_GF as "grandfathering past emissions", apparently because it allocates only the RCB while disregarding historical emissions. Yet allocating only the RCB is neither the conventional definition of grandfathering nor distinctive to this scenario, as all scenarios allocate the RCB. By contrast, PCUS_CurrAnn allocates the RCB in proportion to current emissions and is separately classified as "inequitable grandfathering". This is not merely a label issue but conflates distinct equity operationalizations.

In a central scenario, the authors do weigh historical emissions in their solely-forward-looking approach (for "PCFS_HistCap" under "SEA-1"). However, this also includes a highly unusual calculation of capability: GDP per capita is summed across countries, which makes the allocation depend on the number of countries in the sample rather than on population-weighted capability.

In effect, the approach of what the authors name "*per capita fair share weighted by both historical responsibility and capability*" is nearly identical to an equal per capita allocation which the authors call "*per capita fair share of the RCB based on grandfathering past emissions*". In its implementation, it is largely determined by the population size of a country, hardly weighing GDP per capita or historical responsibility. Effectively, the authors implement slight variations of equal per capita splits of the remaining budget, which do not reflect historical responsibility or respective capabilities in ways that are common within the wider literature. While the authors recognize that "*The difference between countries' emissions allocation due to these varying equity-based allocation schemes is not large*", the contrasting description does not seem to match the lack of contrast in modelled quantities.

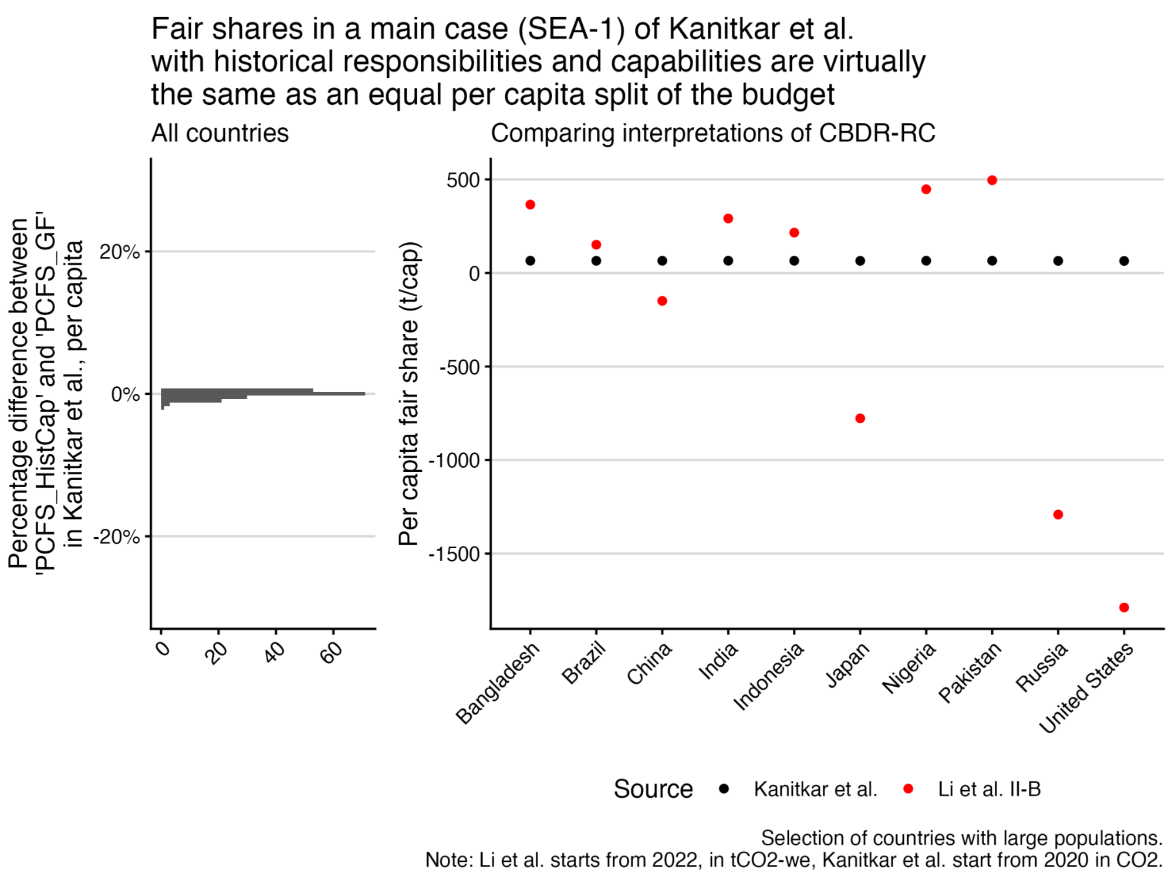

Figure S5. *Illustration showing how the KJL fair shares budget of equal per capita emissions, "PCFS_GF (i.e.,* *per capita fair share of the RCB based on grandfathering past emissions)" in KJL, is nearly identical to their variant "PCFS_HistCap, i.e., per capita fair share weighted by both historical responsibility and capability" (left). Comparing to one example from the literature, Li et al. (2025) interpretation II-B, which, like KJL, operationalises CBDR-RC using historical emissions for responsibility and GDP per capita for capability (ability to pay), showing the large differences with the methodological choices in KJL. All visualised numbers relate to a pathway of 1.5C above the pre-industrial levels.*

These two elements systematically miss the responsibility and capabilities of countries with the highest historical cumulative emissions and highest incomes. This internal inconsistency undermines the paper's central equity claims.

Finally, the model does not permit net-negative CO2-FFI emissions for any country group, on the grounds that negative emissions involve uncertain technologies. While this caution is understandable, its consequence within the MEECC framework is that the historical over-consumption of carbon budget by G1 and G2 countries cannot be represented as a debt that those countries must repay. The equity literature that the paper invokes is grounded precisely in the notion that countries which have over-consumed their fair shares of the global carbon budget owe a carbon debt to those which have not. Eliminating net-negative emissions from the model scope eliminates also the mechanism by which the possible payback of this debt could be operationalized.

Note that the MEECC pathways still do go to net zero CO_2, without any clarification of how this is achieved. Assumptions on different LULUCF scenarios will affect these outcomes and the implications of those scenarios, specifically for countries where LULUCF emissions do not provide for a sink, are not discussed in detail. The wider scientific literature implies that a certain level of CDR will be required and in its Sixth Assessment Report, WGIII SPM C.11, finds that "The deployment of carbon dioxide removal (CDR) to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO2 or GHG emissions are to be achieved (*high confidence*)." (IPCC, 2022). The equity literature is actively considering the responsibilities for deployment of CDR (e.g. Fyson et al. 2020) and it is not clear why this is not also resolved as part of the MEECC framework.

3.2 Lack of engagement with the most recent literature on equity in IAMs

MEECC presents its equity framework as a substantive departure from the existing IAM-related research. This claim is difficult to sustain. A substantial literature predating MEECC has already examined how justice can be operationalized within integrated assessment models. Rubiano Rivadeneira and Carton (2022), for example, review critiques of IAMs through distributive, procedural, and recognition lenses, showing how each dimension is variably incorporated or excluded in model-based knowledge production. Earlier, Klinsky and Winkler (2018) outlined practical approaches to embedding equity directly within 1.5 °C scenario design rather than treating it as an external evaluative layer. More recently, Zimm et al. (2024) proposed a shared justice framework alongside a Justice Model Intercomparison Project, with the explicit aim of improving coherence and comparability in how justice is represented in mitigation pathways for future IPCC assessments. Drawing on interviews with 39 experts, Low et al. (2025) identify three distinct trajectories for advancing this agenda: extending representation within IAMs, linking IAMs with complementary models and user communities, and repositioning IAMs within a broader set of analytical practices.

Two implications follow. First, the core critique motivating MEECC is widely recognized, and the disagreement centers on how to respond rather than on the existence of the problem. Second, much of the literature has focused on reforming scenario design, indicators, and reporting practices while retaining the internal consistency and feasibility assessments that IAMs provide. This body of work is not uniform. Low et al. (2025) document disagreement regarding the limits of representation and the appropriate role of mitigation scenarios. Such divergence is analytically productive. Against this background, MEECC's presentation of wholesale replacement as the only coherent response appears insufficiently justified. Its limited engagement with this literature constrains the reader's ability to assess why reform from within is dismissed rather than further developed.

Table S4. *GDP growth rates (%) inconsistencies between the manuscript and the code*

	Paper (Table 9)					Code (MEECC_V.1_revision.py)				
Scenario/Country group	G1	G2	G3	G4	G5	G1	G2	G3	G4	G5
GDP_UHigh	2	4	5	6	7	2	5	6	7	8.5
GDP_UMed*	1.5	3	4	5	6	1.5	4	5	6	7
GDP_ULow	1	2.5	3.5	4.5	5	1	3	4	5	6
GDP_DG1	0	3	4	5	6	0	3	5	7	8.5
GDP_DG2	-1	2	4	5	6	-1	3	5	7	8.5

*In the code referred to as "GDP_UMod".

Table S5. *Effect of the primary energy accounting convention on the electricity available from a 75 GJ per capita primary energy budget.*

Three conventions are in use (Grubler et al. 2012, p. 142). Under the substitution method, 1 kWh of non-combustible electricity counts as about 3 kWh of primary energy, the thermal input at the 35% global average efficiency of fossil power generation (p. 105). Under the direct equivalent method, used by UN Statistics and in several IPCC reports, 1 kWh counts as 1 kWh for every non-combustible source. The physical content method, used by the IEA, OECD and Eurostat, does the same for hydro, wind and solar PV but counts nuclear at 33% and geothermal at 10% efficiency.

Electricity generation mix	Accounting method	Electricity delivered from 75 GJ primary (GJ)	Note
Fossil-dominant	Any	24	Convention independent, including transmission losses
High-renewables system	Substitution method	24	75 GJ primary represents 24 GJ of actual electricity output including transmission losses
High-renewables system	Physical content method	69	75 GJ primary is 75 GJ at the busbar, less transmission losses
Modern gas CCGT system	Any	34	50% generation efficiency

Sources: Grubler et al. (2012).

Table S6. *Energy requirements for equivalent services in different contexts.*

Energy service	Low-income / incumbent configuration	High-income / clean configuration	Efficiency measure
Cooking	Traditional stoves: animal dung 11%, coal 14%, agricultural waste 15%, wood 18%, charcoal 18%	Improved and modern stoves: improved charcoal 25%, improved agricultural waste 35%, rocket wood	Average thermal efficiency

Energy service	Low-income / incumbent configuration	High-income / clean configuration	Efficiency measure
		38%, wood gasifier 43%, kerosene 49%, LPG 55%	
Space heating	Fuel-fired furnace, typically 70–80%; natural-gas furnace worked example 80% first law, 7% second law	Best-performing condensing furnace above 90%; electric heat pump supplies 12 units of heat per three to four units of electricity, second-law efficiency 25–33%	First- and second-law efficiency
Passenger transport	Gasoline light-duty vehicles 20%	Electric trains 75%	Final-to-useful efficiency
Illumination	Coal-fired generation to incandescent bulb: about 1% of primary energy reaches the illumination service	World average domestic electric lamps 9%	Primary-to-service and final-to-useful
Refrigeration and industry	—	Refrigerators 78%, ammonia synthesizers 77%, tractors 31%, diesel pumps 26%	Final-to-useful efficiency

Cooking and space-heating efficiencies from Grubler et al. (2012); machine efficiencies for 2020 from Brockway et al. (2024).

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