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A Fairness–Efficiency Matrix for Navigating Carbon Neutrality Transitions[#]

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ABSTRACT

The Shared Socioeconomic Pathways (SSPs) provide an essential exogenous hypothesis for the Integrated Assessment Models (IAMs) to explore long-term energy transitions and low-carbon trajectories. Nevertheless, their global orientation often neglects national heterogeneities that are critical for effective policymaking. Here, this study proposes the fairness–efficiency challenges as a new research paradigm for redefining SSP narratives at the national level. The socioeconomic governance framework situates energy transition pathways along two normative dimensions: fairness, denoting the equitable distribution of costs and benefits across various regions, social groups, and generations; and efficiency, denoting the technological, institutional, and economic capacity to achieve carbon neutrality in a timely and cost-effective manner. It preserves the original SSP logic while contextualizing it within unique regional governance, developmental, and socioeconomic system structures. The resulting scenario narratives not only supports heterogenetic vision, but also provides carbon neutrality modelers with a transparent, replicable framework for scenario parameterization, uncertainty and risk management, and policy evaluation, strengthening policy relevance of national low carbon energy system projections.

Keywords: Fairness–Efficiency Matrix, Archetypal Quadrants, Alternative Pathway Typology, Carbon Neutrality, Socioeconomic future, Transition Governance

NONMENCLATURE

Abbreviations	
SSPs	Shared Socioeconomic Pathways
IAMs	Integrated Assessment Models

1. INTRODUCTION

In the era of accelerating global shift toward carbon *neutrality*, scenario analysis has emerged as a crucial tool for navigating uncertainty in long-term transitions. By constructing plausible futures, scenarios not only inform quantitative modeling but also facilitate structured dialogue among scholars, policymakers, and public and private sector stakeholders regarding alternative development pathways. The SSPs exemplifies this role by linking socioeconomic narratives with low carbon trajectories, thereby forming the backbone of global climate change assessments based on IAMs (O'Neill et al., 2014). However, the generalized character of global SSPs limits their direct capacity for national settings, where regional disparities, distinct development priorities, and context-specific adaptation.

In fact, national socioeconomic transitions to achieve carbon neutrality unfold within diverse political, economic, and social settings. Regional disparities, societal preferences, governance structures, and technological capabilities vary widely across countries, and shape both the pace and distributional outcomes of decarbonization efforts. As a result, conventional mitigation and adaption frameworks of SSPs, often neglects to incorporate nationally specific dynamics, creating a gap between higher-level, abstract global narratives and the realities of policymaking within countries and regions (Frame et al., 2018; Chen et al., 2020). Therefore, to bridge this gap, this study introduces a fairness–efficiency challenges Matrix as a framework for rebuilding SSP narratives (McCauley & Heffron, 2018).

By creating a fairness-efficiency topology, this study establishes a governance framework for socioeconomic system modeling at the national and regional levels. Conceptually, it demonstrates how global frameworks like the SSPs can be adapted to reflect national or even

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provincial-level realities without compromising any methodological rigor. Practically, the resulting scenario narratives support carbon neutrality transition modelers and policymakers to identify feasible pathways, evaluating socio-economic futures, clarifying exogenous assumptions and delineating logical boundaries. Thus, the study strengthens the feasibility and policy alignment of carbon neutrality objectives within each country while highlighting how national scenario narratives design can noy only complement, but also extend global foresight frameworks (Sovacool & Dworkin, 2015).

2. SCENARIO TYPOLOGIES

2.1 Redefining the Axes: Fairness and Efficiency

Socioeconomic transitions are not just technological shifts or economic adjustments, but also the normative process of justice issue to achieve carbon neutrality. Hence, to confront this need, we offer a new framework structured around two normative axes: *Fairness* and *Efficiency*, to capture the dual imperatives of just and effective socioeconomic transitions.

Fairness embodies the distributive and procedural justice of decarbonization. It addresses how benefits and burdens are allocated across regions, social groups, and generations. A fair transition is therefore one that minimizes inequities while ensuring that stakeholders are acknowledged and empowered in shaping the transition process.

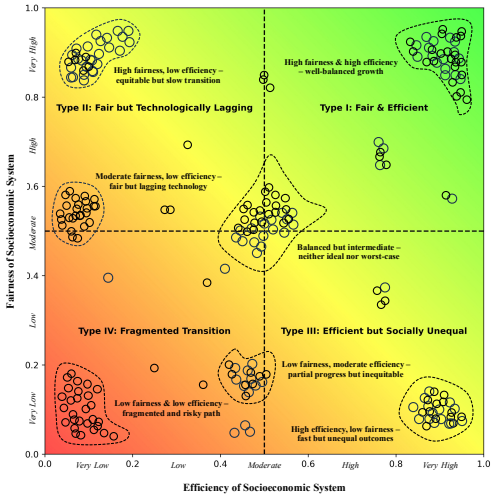
Efficiency, on the contrary, reflects the capacity of technological, institutional, and economic systems to achieve carbon neutrality in a timely, cost-effective, and resilient manner. It moves beyond a narrow concern with cost-minimization to include the pace of technological innovation, the adaptability of governance institutions, and the feasibility of socioeconomic systems. Efficient transition is thus one that leverages innovation and coordination to meet decarbonization goals without compromising stability.

By explicitly articulating these axes (see Tab. 1), the new transform framework scenario thinking from descriptive speculation into normatively structured and executable evaluation, making visible the synergy and antagonism, trade-offs between speed and just that often remain implicit in the global mitigation and adaption frameworks.

2.2 Archetypal Quadrants

As shown in Fig. 1, when plotted along the axes of systemic fairness and efficiency challenges, the matrix yields four archetypal pathway outcomes. These archetypes illustrate contrasting logics of transition pathways and provide a normative compass for interrogating the diversity of plausible futures.

Fig 1. Fairness-Efficiency Matrix for Alternative Archetypal Pathway Typology



Tab 1. Dimensions of the Fairness–Efficiency Matrix

Dimension	Core Definition	Key Components	Indicative Questions
Fairness	Equity in the distribution of benefits and burdens, and inclusivity in governance processes.	Social fairness (inter- and intra-generational equity, regional balance) Procedural fairness (participation in decision-making) Recognition justice (acknowledging vulnerable/ marginalized groups) Resource access (affordability and availability of energy)	Who gains and who bears the costs of the transition? Are vulnerable groups recognized? Do all regions have equitable access to benefits?
Efficiency	Capacity to achieve carbon neutrality effectively, coherently, and at pace.	Technological efficiency (rate of innovation, deployment of renewables, storage systems) Economic efficiency (cost-effectiveness, competitiveness)	How quickly and effectively can the system decarbonize? Can the system remain resilient under uncertainty?

The four archetypal transition quadrants emerging from the fairness–efficiency matrix are discussed as follows, each highlighting distinct opportunities as well as trade-offs in future sustainable transformation.

Fair & Efficient – This quadrant represents the most desirable outcome: an inclusive transition that achieves both social fairness and rapid decarbonization through technological and economic efficiency. Here, fairness is not treated as a constraint but as a driver of stability, fostering social acceptance and reducing resistance to change. Benefits and burdens are distributed equitably across various groups, regions, and generations, while technological innovation, governance, and adaptable institutions will ensure that the progress is both swift and resilient. Additionally, efficiency is reinforced by fairness: when energy access, affordability, and environmental quality are shared broadly, public trust strengthens, and policy continuity becomes more secure. These pathways maximize both legitimacy and feasibility, but they hinge on long-term coordination, consistent political will, and investment strategies that balance near-term costs with durable social and environmental returns.

Fair but Technologically Lagging – Transitions in this quadrant place fairness and inclusivity at the center, ensuring that the costs and benefits of change are widely and equitably shared. These pathways strengthen social legitimacy, safeguard vulnerable groups, and reduce the risk of political backlash. However, limited technological innovation, fragmented governance, and high transition costs slow progress, raising the danger of missing climate targets. Fairness, in this case, economic stability but can also mask systemic weaknesses: if societal systems remain inefficient, the long-term credibility of a just transition may erode. This quadrant highlights the tension between immediate justice and long-term effectiveness, showing that social support alone is not enough without parallel investment in technological innovation and institutional strength. Ultimately, narratives in this space warns that equity without efficiency risks creating transitions that are morally compelling but practically unsustainable.

Efficient but Socially Unequal – Pathways in this region deliver rapid and cost-effective decarbonization, often powered by technological breakthroughs, strong centralized governance, or market-driven mechanisms. On the surface, these societal transitions appear highly successful. The carbon neutrality targets are met, economic competitiveness is maintained, and innovation thrives. Yet beneath this rapid efficiency lies a fragile foundation. Vulnerable groups may be excluded from these benefits, regions left behind, or costs unevenly distributed in ways that entrench inequality. Efficiency without fairness risks produces transitions that are materially effective but in fact socially brittle. Legitimacy erodes as excluded groups mobilize against policies perceived as unjust, leading to political resistance, reversals, or even stalled transitions. The deeper insight here is that efficiency achieved at the expense of fairness can undermine its own durability. The technically optimal transition fails to secure broad consent may collapse under the weight of its inequities.

Fragmented Transition – This quadrant represents the least desirable (most severe) outcome, where weak governance structures, institutional incoherence, and stagnant innovation prevent both fairness and efficiency from taking hold. Transition gains are disproportionately captured by elites or politically dominant regions, while vulnerable groups are left with higher burdens, reduced access to resources, and fewer opportunities, deepening inequality across social and regional lines. The absence of coherent direction may erode trust in institutions and weaken social contract, making collective action become increasingly difficult, reinforcing a vicious cycle of delay and disengagement. The fragmentation does slow progress toward climate goals and it actively destabilizes societies, deters technological investment, weaken resilience, and fuels political contestation. In this sense, a fragmented transition is not merely ineffective but dangerously unstable—one where disunity magnifies inequities and exposes both the transition and broader societal systems to systemic risk and long-term fragility.

Altogether, the four quadrants reveal that national socioeconomic transitions hinge as much on normative choices as on technological feasibility. Two quadrants (B and C) embody imperfect trade-offs: prioritizing fairness may slow down innovation, while prioritizing efficiency risks exclusion, and only their alignment produces pathways that are both legitimate and effective. *Fragmented Transition,* however, stands apart not as a trade-off but as systemic failure, where weak governance and vested interests stall progress on both fronts. Overall, these transitions demonstrate that the fairness–efficiency matrix exposes the normative dimensions of transition strategies that are obscured by technical modeling or narrow economic analysis. It challenges the illusion of value-neutral planning and enables a more systematic, accountable exploration of

socioeconomic futures, and places legitimacy and justice on equal footing with cost and performance.

Table 2. Archetypal Transition Pathways in the Fairness–Efficiency Paradigm

Archetype	Core Features	Opportunities	Risks/Challenges
Fair & Efficient	Equitable distribution of costs and benefits; strong technological innovation; adaptive and coherent governance; resilient energy systems.	Aligns legitimacy with effectiveness; maximizes social buy-in and climate ambition; enhances long-term stability.	Requires sustained political will, resource mobilization, and coordination; risk of high transaction costs.
Fair but Technologically Lagging	Strong equity and justice principles; inclusive governance; but weaker innovation, institutional capacity, or higher costs.	Builds legitimacy and avoids deepening inequalities; enhances social cohesion.	Risk of delayed decarbonization; may undermine climate targets if efficiency gaps persist.
Efficient but Socially Unequal	Rapid decarbonization; strong technological and institutional performance; but inequitable outcomes across regions/groups.	Accelerates emissions reductions; cost-effective in the short term.	Social exclusion, resistance, legitimacy crises; potential backlash undermining long-term stability.
Fragmented Transition	Weak governance, low innovation, incoherent institutions; highly uneven distribution of costs/benefits.	Limited—may preserve short-term stability for select groups.	Fails both fronts; risks lock-in of high-emissions systems and social fragmentation.

3. DISCUSSIONS

3.1 Normative Clarity

Our fairness–efficiency topology sharpens the view on equity–effectiveness tension that is often obscured in techno-economic analyses of national energy transitions. By situating calculated transition pathways within a two-dimensional normative space, this framework compels stakeholders to question: who benefits, who carries the burden, and how decarbonization targets are effectively met? This reframing underscores that energy futures are not merely technological projections but are also deeply contested moral and distributive choices.

3.1.1 Uncovering Hidden Assumptions

Many of the scenario tools implicitly treat efficiency and justice as harmonious, sidelining normative conflicts. However, our topology disrupts this veneer of neutrality by exposing trade-offs: for example, pathways optimized for rapid decarbonization may inadvertently exacerbate regional inequities if the distribution of costs, benefits, or decision-making power is neglected.

3.2 Policy Relevance

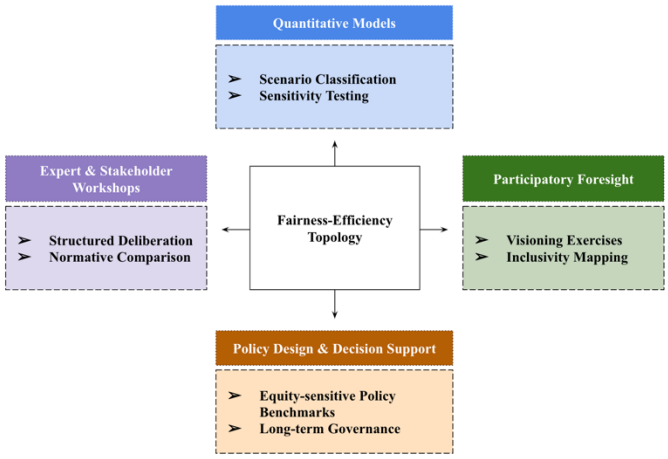
The national and regional socioeconomic governance face the dual imperative of achieving rapid decarbonization while maintaining social legitimacy and inclusivity. The socioeconomic transition pathway topology responds directly to this challenge by offering a structured evaluative lens that allows policymakers to classify strategies not only on their technological outcomes but also on their normative underpinnings.

By explicitly placing transition policies within a two-dimensional space, the framework highlights the political and institutional stakes of socioeconomic transitions. Pathways that lean too heavily on efficiency may deliver short-term emissions gains but risk triggering distributional backlash if vulnerable groups are excluded—examples range from energy affordability strikes in the EU to resistance against rapid coal phase-outs in Asia. Conversely, strategies that emphasize fairness without attention to efficiency may foster social cohesion yet falter in accomplishing energy transition targets. This study hence makes visible the tensions and trade-offs that policymakers must navigate, clarifying when policies are likely to reinforce trust and cohesion versus when they risk exclusion, resistance, or fragmentation.

3.3 Methodological Versatility

A strength of the topology lies in its methodological versatility (Fig. 2). Unlike frameworks that are bound to quantitative, the topology is intentionally designed to be applied across a wide range of methodological practices, and institutional settings. Its flexibility makes it equally relevant to research and policy design.

Fig 2. The Fairness–Efficiency Interface across Methods



For scholars, this interface offers several functions. First of all, it can serve as a classification tool, enabling researchers to map existing scenarios onto the fairness–efficiency grid. This process reveals underlying trade-offs that might be obscured in more technocratic or purely descriptive scenario frameworks. Second, it can function as a deliberative device, structuring expert workshops by providing a shared vocabulary to compare divergent visions of the future. Third, it can be employed as an evaluative benchmark, enabling comparison across various studies, modeling exercises, or national contexts while maintaining transparency about the assumptions embedded in each.

In terms of policymakers, this interface operates as a decision-support heuristic. It helps to guide the design and transition pathways that extend beyond economic metrics to include considerations of equity, legitimacy, and institutional resilience. In this sense, it does not simply assess whether a policy is cost-effective or technologically feasible, but whether it is also socially robust and politically sustainable. By embedding both dimensions into the evaluative frame, this framework encourages policymakers to anticipate potential sources of exclusion, resistance, or fragmentation, and to design strategies that are not only effective in meeting carbon neutrality targets, but also inclusive in their distribution of costs and benefits.

3.4 Limitations and Caveats

The strength of this topology lies in its parsimony, yet this simplicity also defines its limitation. By distilling complex sociotechnical dynamics into two simple axes, this method inevitably abstracts away multidimensional interactions, including any synergies and trade-offs that extend beyond fairness and efficiency. Furthermore, the benchmarks for assessing fairness and efficiency are not just universal constants but deeply context-dependent, reflecting political priorities, institutional legacies, as well as cultural norms. What one society interprets as just or effective may diverge sharply from another's view. Thus, these caveats imply that our devised topology should not be misconstrued as a predictive model or prescriptive blueprint, rather, it can be best understood as a heuristic device, a structured lens that provokes critical reflection, sharpens awareness of normative stakes, and allows for comparative dialogue across diverse transition contexts.

4. CONCLUSION

The fairness–efficiency matrix is more than an analytical pathway framework. By forcing every imagined future to declare, simultaneously, how much carbon it removes and also how much justice it delivers, this typology truly dissolves the long-standing asymmetry between those who design green transitions and those who live through them (Carley & Konisky, 2020). In doing so, it moves national carbon neutral governance from a technocratic exercise in least-cost optimization to a reflexive process in which societies interrogate the moral content of their collective choices before the choices become irreversible infrastructures, sunk costs, and stranded communities.

At a planetary scale, the topology reveals an uneasy truth: the IPCC's "carbon logic", and the SDGs' "justice logic" have advanced on parallel tracks, each governed by their own metrics, constituencies, and timelines. Our two-axis space renders their collision and their potential reconciliation unavoidable. A pathway that ranks high on efficiency but low on fairness may still satisfy the 1.5 °C targeted by the IAMs, yet it simultaneously undermines SDG—10 (*Reduced Inequalities*) and SDG—16 (*Peaceful Institutions*), eroding the very social foundations which durable decarbonizations depends (IPCC, 2023; United Nations, 2015). Conversely, a pathway that elevates fairness but nevertheless falters on speed jeopardizes SDG—13 (*Climate Action*) and risks entrenching fossil infrastructures that will devastate the very communities it sought to shield. This topology thus punctures the false signal of "sustainable development" rhetoric that treats justice and carbon as additive rather than co-constitutive imperatives.

Finally, the fairness-efficiency matrix performs a democratizing function that orthodox climate economics has systematically evaded. By translating complex model outputs into a visual grammar legible to mayors, labor unions, indigenous representatives, and also community energy co-ops, it reclaims scenario planning from the

epistemic enclosures of modelers and consultants. In this way, it operationalizes the principle embedded in SDG—17, *Partnerships for the Goals*, by providing a shared coordinate system in which disparate actors can locate their interests, articulate their grievances, and negotiate the terms of consent. In short, this framework does not merely help societies decarbonize; instead, it helps them decarbonize equitably. Without this equitable anchoring, neither national carbon neutrality nor any other forms of sustainable aspiration can endure the turbulent century ahead.

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