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Editorial

Progress and Policy Considerations to Achieve Energy Transition and Carbon Mitigation

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1. Introduction

The global paradigm shift toward carbon neutrality represents one of the most complex and consequential socioeconomic transformations of the twenty-first century. This transformation is shaped by a multitude of multi-dimensional factors, encompassing institutional and regulatory frameworks, technological innovation, market mechanisms, financial flows, and the behavioral economics of diverse stakeholders. This Special Issue focuses on six key scientific questions related to the research progress and policy considerations of global energy transition and carbon mitigation. The collection brings together the work of twenty leading experts and scholars, offering insights into emerging methodologies, empirical findings, and policy-relevant frameworks. Collectively, the studies illuminate both the milestones achieved in decarbonization and the persistent gaps that must be addressed to meet the Paris Agreement targets, highlighting the importance of integrated, multi-scalar, and interdisciplinary approaches.

Global coordination and regional differentiation in energy transition have long been central topics in sustainable development research. Econometric and longitudinal analyses indicate that historical investment decisions, entrenched technological choices, and institutional inertia create strong path dependencies that constrain the adoption of low-carbon technologies and reinforce reliance on high-carbon energy systems [1–3]. In regions with weak governance or insufficient regulatory oversight, fossil fuel dominance is further entrenched, slowing the deployment of renewables and low-carbon infrastructure. Fossil energy consumption and primary energy supply exhibit significant co-evolutionary patterns. While broad trends point toward a gradual shift to low-carbon energy structures, substantial regional disparities exist [4,5]. These dynamics underscore the necessity of designing differentiated transition strategies that account for both global coordination imperatives and local socioeconomic contexts.

In response to these complex transition challenges, scholars have increasingly explored more refined analytical tools and methodologies to enhance the scientific rigor and operational feasibility of decarbonization pathways. Open-source energy system models, such as pymedeas [6], EMPIRE [7], and EnergyScope TD [8], support multi-regional, multi-sectoral, and cross-temporal optimization of energy systems. These models integrate real-world constraints—including biophysical limits, raw material availability, infrastructure capacity, and climate impacts—providing critical guidance for policy design and investment planning. By enabling scenario analysis across spatial and temporal scales, these tools help identify tailored transition pathways for regions with diverse resource endowments, industrial structures, and policy landscapes. Beyond system-level modeling, the application of

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evolutionary game theory and conflict analysis frameworks, such as the Graph Model for Conflict Resolution (GMCR) and multi-agent evolutionary games, enables the systematic study of strategic interactions among governments, corporations, and communities [9–11]. These approaches reveal equilibrium states, conflict evolution pathways, and potential mediation mechanisms, offering insights into how cooperative strategies, negotiation, and incentive alignment can facilitate decarbonization in complex socio-political environments. Collectively, these methodological advances challenge the traditional top-down policy-centric perspective, emphasizing the need for adaptive, participatory, and context-sensitive governance strategies.

Building on these methodological foundations, researchers have investigated the multi-dimensional drivers of energy consumption and emissions, seeking to elucidate the causal networks that shape decarbonization. The integration of machine learning with econometric models allows quantification of the effects, as well as the sensitivities, of variables such as economic growth, energy consumption, industrial structure, trade openness, and urbanization on carbon intensity [12–15]. Cross-national studies have further clarified these patterns. For example, empirical evidence from Belt and Road countries suggests that energy efficiency improvements, rather than shifts in energy structure alone, are the primary drivers of differences in emissions intensity, providing a nuanced perspective for developing country decarbonization policies [16,17]. At the micro level, resource endowments are identified as a key determinant of urban energy efficiency, while industrial restructuring and policy tools such as environmental information disclosure significantly enhance efficiency in metropolitan regions [18]. These findings highlight that effective decarbonization strategies require attention not only to technological availability but also to socioeconomic context, institutional capacity, and governance mechanisms.

Understanding the drivers of energy transition also shifts attention to the key actors responsible for implementing decarbonization strategies, particularly the behavior and interactions of stakeholders. Multi-level, sustained engagement, including co-creation processes, collaborative initiatives, and structured dialog, has been shown to foster shared visions, improve policy feasibility, and enhance social acceptance, facilitating implementation of low-carbon interventions [19,20]. Within firms, internal pressures from employees, management teams, and shareholders often drive substantive decarbonization actions, whereas external pressures from governments, consumers, and civil society organizations may result in symbolic or hybrid strategies, especially in non-family firms [21,22]. Advanced participatory modeling techniques and digital twin technologies provide tools for real-time monitoring, information sharing, and collaborative decision-making among stakeholders. These technologies strengthen decarbonization governance by aligning incentives, enhancing transparency, and improving coordination across urban systems, industrial sectors, and regional networks [23]. Collectively, these insights demonstrate that stakeholder behavior and multi-actor interactions are central to effective energy transition planning and implementation.

Given this complex behavioral landscape, designing an appropriate policy architecture is crucial for advancing energy transitions. Evidence suggests that technological innovation systems, carbon pricing mechanisms, and just transition frameworks must operate synergistically and complementarily to achieve both green transition goals and multiple policy objectives [24–26]. Technological innovation systems encompass R&D investment, industrial incubation, and infrastructure development, and can accelerate the diffusion of low-carbon technologies through standards, subsidies, and public procurement [27]. Carbon pricing mechanisms internalize the cost of emissions, guide mitigation efforts, and direct investments toward low-carbon alternatives, but must be combined with innovation policies and social protection measures to provide both market signals and fiscal

support [28,29]. Just transition frameworks focus on social equity and inclusion, including income redistribution, employment transition support, and regional compensation [30,31]. Only through the integrated and dynamic adjustment of these policy instruments can multi-stakeholder coordination be mobilized to achieve effective and sustained decarbonization.

The global transition toward clean energy systems and carbon neutrality is not merely a technological challenge; it is a deeply systemic and multi-dimensional process. Achieving meaningful decarbonization requires coordinated innovation in technological development, financial and market mechanisms, policy architecture, and stakeholder engagement. The research compiled in this Special Issue (Part II), along with complementary studies across the global scholarly landscape, provides a robust knowledge base for navigating this transformation.

2. An Overview of Published Articles

2.1. Advancing the Global Energy Transition: A Systematic Review of Policy, Stakeholder, and Technological Determinants

Contemporary scholarship underscores evidence-based policymaking as the cornerstone of effective energy transitions. Gałecka and Pyra's (2024) (contribution 1) longitudinal study employing vector error correction models (VECMs) demonstrates significant path dependence in global energy markets (2011–2023), where fossil fuel consumption exhibits cointegration with total primary energy supply. Their findings confirm an emerging structural shift toward low-carbon sources, albeit with notable regional heterogeneities. Complementing this macro perspective, Brodny et al.'s (2024) (contribution 2) policy evaluation framework applied to Poland's transition (2004–2021) reveals paradoxical outcomes: While achieving 38% renewable penetration in electricity generation (vs. 7% baseline), the nation's persistent coal dependence highlights systemic challenges in industrial decarbonization. These case studies collectively emphasize the nonlinear nature of energy transitions, where policy effectiveness is contingent upon localized institutional capacities and stakeholder alignment.

2.2. Forward-Looking Methodologies in Energy Transition Research

Cutting-edge research employing computational modeling approaches provides critical foresight into decarbonization pathways. Fields et al. (2023) (contribution 3) conducted a groundbreaking scenario analysis using the Open-Source Energy Modeling System (OSeMOSYS) to evaluate six distinct renewable energy transition trajectories for Kenya, establishing an evidence-based framework for strategic energy planning in developing economies. Their work demonstrates how integrated assessment models can inform national energy policy formulation.

The political economy of coal phase-outs presents particular complexities in emerging economies. Kou et al.'s (2022) (contribution 4) innovative application of evolutionary game theory reveals structural barriers to China's coal transition, identifying that stakeholder incentives—particularly for coal-dependent enterprises and affected communities—must be fundamentally realigned to enable meaningful decarbonization. This finding challenges conventional assumptions about top-down energy transitions in state-led economies.

Complementing this national perspective, Li et al. (2023) (contribution 5) advanced provincial-level energy system modeling through their seven-scenario analysis of Guangxi's 2050 energy landscape. Their integrated assessment, incorporating technoeconomic parameters and carbon constraints, demonstrates the province's potential to achieve 57% emission reductions alongside 70% non-fossil penetration—a finding with significant implications for regional energy planning in developing regions.

2.3. Multi-Dimensional Drivers of Energy and Emission Dynamics

Contemporary research employs sophisticated analytical frameworks to disentangle complex decarbonization drivers. Chahuán-Jiménez et al. (2023) (contribution 6) pioneered a novel integration of machine learning clustering techniques with generalized linear modeling, establishing robust correlations between macroeconomic indicators (GDP, trade flows) and carbon intensity across diverse national contexts. Their work highlights the embeddedness of emission patterns within broader economic structures.

The Belt and Road Initiative has emerged as a critical laboratory for studying transnational decarbonization patterns. Li et al.'s (2022) (contribution 7) application of the Theil Index and Logarithmic Mean Divisia Index (LMDI) decomposition across 60 participating nations revealed energy efficiency as the dominant factor (contributing 42–58% of variance) in emission intensity differentials, surpassing even energy mix considerations.

China's urban systems provide particularly rich insights into subnational decarbonization dynamics. Miao et al.'s (2024) (contribution 8) enhanced Epsilon-Based Measure (EBM) analysis of 270 Chinese cities established energy endowment as the primary determinant ($p < 0.01$) of municipal energy efficiency variations. Parallel research by Zeng et al. (2023) (contribution 9) employing system dynamics modeling identified industrial structure as the key emission driver ($\beta = 0.67$) in the Beijing–Tianjin–Hebei megaregion, while energy mix optimization showed greatest mitigation potential. Tan et al.'s (2024) (contribution 10) quasi-experimental study further demonstrated that mandatory environmental disclosure policies improved manufacturing energy efficiency by 12–18% ($p < 0.05$), highlighting the importance of transparency mechanisms in industrial decarbonization.

2.4. Stakeholder Dynamics in the Energy Transition Paradigm

The behavioral economics of stakeholders constitute a pivotal determinant in achieving Paris-aligned energy transition trajectories. Pylak et al.'s (2024) (contribution 11) longitudinal analysis of EU NUTS-2 regions (2021–2027) reveals significant path dependence in regional commitments to the Green Deal, with pre-existing decarbonization infrastructure correlating strongly ($\beta = 0.72$, $p < 0.01$) with policy compliance, while carbon-intensive regions demonstrate institutional lock-in effects.

Industrial decarbonization presents particular behavioral complexities. Cherepovitsyna et al.'s (2023) (contribution 12) ESG benchmarking of Fortune 500 oil majors exposes a pronounced ambition–action gap, where declared net-zero commitments outpace actual Scope 1–3 emission reductions by 38–62%. Parallel research by Finnie et al. (2024) (contribution 13) identifies five systemic barriers to embodied carbon reduction in New Zealand's construction sector through structural equation modeling (SEM), with knowledge deficits (loading factor = 0.81) and supply chain limitations (loading factor = 0.79) emerging as primary constraints.

2.5. Behavioral Heterogeneity Across Stakeholder Groups

Zhang et al.'s (2021) (contribution 14) application of the Knowledge–Attitude–Practice (KAP) framework to 1335 Chinese households challenges conventional wisdom, revealing nonsignificant correlations ($r = 0.12$, $p > 0.05$) between climate literacy and energy conservation behaviors. Contrastingly, Szel et al.'s (2024) (contribution 15) discrete choice experiments demonstrate generational cleavages in sustainable FMCG adoption, with Gen Z consumers exhibiting 3.2× greater willingness-to-pay for circular products compared to Baby Boomers.

Sentiment analysis by Xiang et al. (2021) (contribution 16) leveraging NLP techniques on Twitter/X data ($n = 2.4$ M tweets) reveals evolving socio-political dimensions, where

developing nation sentiment polarity remained stable ($\mu = 0.43$) despite growing negative sentiment in developed economies ($\Delta = -0.29$, 2019–2021).

2.6. Policy Architecture for Effective Decarbonization

Elshkaki and Shen's (2022) (contribution 17) systematic review establishes three pillars for effective transition policies: (1) technology innovation systems, (2) carbon pricing mechanisms, and (3) just transition frameworks. Muhirwa et al. (2021) (contribution 18) advance the resource nexus paradigm through Tapio decoupling analysis, exposing Africa's persistent resource–emission coupling (decoupling index < 0.4 in 13/15 nations).

Comparative policy analysis yields critical insights. Using OSeMOSYS simulations for DRC, Dalder et al. (2024) (contribution 19) demonstrate that optimal policy mix requires $16 \pm 2\%$ renewable subsidies coupled with $70 \pm 5\%$ fossil taxes to achieve 83% clean energy penetration by 2065. The event study of China's ETS by Paraschiv et al. (2024) (contribution 20) reveals significant abnormal returns (+7.3%, $p < 0.01$) for renewable equities post-policy implementation, validating the efficacy of market mechanisms.

3. Conclusions

This collection of studies aims to examine the multifaceted pathways driving the global energy transition, highlighting both the technological innovations and socio-institutional processes that shape decarbonization outcomes. The twenty contributions collectively demonstrate that achieving deep, systemic decarbonization necessitates a comprehensive framework that integrates evidence-based policy design, cutting-edge technological development, strategic stakeholder coordination, and adaptive governance mechanisms. The research emphasizes that energy transitions are inherently nonlinear and complex, influenced not only by technological feasibility but also by institutional capacities, regional disparities, behavioral heterogeneity, and the distinctive socioeconomic structures of different countries and regions. Importantly, these studies show that effective decarbonization strategies require the simultaneous consideration of multiple interacting dimensions: economic incentives, regulatory frameworks, market mechanisms, social norms, and infrastructure planning. By exploring these interactions across diverse sectors and scales, the research highlights the necessity of integrating bottom-up behavioral insights with top-down policy interventions, fostering collaboration among governments, industry, and civil society, and designing flexible, resilient systems capable of responding to uncertainty. Overall, this body of work provides a nuanced understanding of the drivers, barriers, and mechanisms that underpin effective global energy transitions.

A prominent theme across this collection is the increasing importance of methodological innovation in both understanding and facilitating the complex processes of decarbonization. Traditional approaches to energy system analysis often struggle to capture the nonlinear, multi-scalar, and interactive nature of energy transitions, particularly when they involve multiple sectors, regions, and policy instruments. In response, open-source energy system models, evolutionary game theory applications, and machine learning approaches have emerged as indispensable tools for researchers and policymakers [32–34]. Open-source energy system models, for instance, allow for the simulation of multi-regional and multi-sectoral energy transitions under a wide range of economic, technological, and environmental constraints. By integrating resource availability, technology adoption rates, and climate impact assessments into scenario analysis, these models can capture both short-term operational decisions and long-term strategic pathways [35]. They provide a platform for exploring trade-offs among efficiency, equity, resilience, and sustainability, enabling decision-makers to assess the consequences of alternative transition strategies

under different assumptions about technological progress, market dynamics, and policy interventions.

Emission dynamics are influenced by a complex interplay of macroeconomic factors, including industrial structure, trade flows, urbanization patterns, and the pace of technological adoption [36]. Simultaneously, micro-level determinants such as firm-level investment decisions, corporate sustainability strategies, consumer preferences, and the availability of regional energy resources play a critical role in shaping actual emissions outcomes [37,38]. Empirical evidence from China and countries along the Belt and Road initiative indicates that improvements in energy efficiency, rather than structural changes in the energy mix alone, often constitute the primary factor driving differences in emission intensity across regions and sectors [39–41]. These insights highlight the importance of transparent reporting, systematic environmental information disclosure, and the promotion of localized technological innovation in supporting effective sectoral decarbonization. Integrating rigorous analytical methods with context-specific empirical evidence allows researchers to identify the most impactful interventions, optimize policy and regulatory frameworks, and provide targeted guidance for reducing carbon emissions. By acknowledging the heterogeneity of economic structures, institutional capacities, and resource endowments, such approaches help ensure that decarbonization strategies are both technically feasible and socially and economically sustainable across diverse regional and institutional contexts.

The collection also emphasizes the importance of stakeholder heterogeneity and behavioral complexity in transition dynamics. Institutional lock-ins, ambition–action gaps among corporations, and behavioral inconsistencies among consumers illustrate the tension between normative commitments to decarbonization and practical implementation [42,43]. In many contexts, firms may publicly commit to sustainability goals but fail to translate these commitments into operational changes without sufficient internal incentives or regulatory enforcement. Similarly, consumers may express strong environmental preferences but adopt low-carbon technologies at a slower rate due to social, economic, or informational constraints. Advances in behavioral modeling, social media analytics, and participatory policy experiments have begun to illuminate these gaps, providing actionable insights into public sentiment, behavioral inertia, and generational divides in sustainability engagement [44,45]. These findings enable policymakers and planners to craft interventions that are attuned to local social norms, cognitive biases, and community-specific characteristics, thereby enhancing both the uptake of low-carbon technologies and the sustainability of behavioral change over time.

Finally, the collection of studies converges on the need for coherent policy architectures that integrate technological innovation systems, carbon pricing, and just transition frameworks. The interaction of these policy pillars determines not only the pace but also the equity and stability of the global transition [46]. Technological innovation systems encompass research and development investment, industrial incubation, infrastructure deployment, and knowledge transfer, and they accelerate the diffusion of low-carbon technologies through standards, subsidies, and public procurement. Carbon pricing mechanisms, including emissions trading systems and carbon taxes, provide market signals that internalize the social and environmental costs of emissions, guiding investment and production decisions toward low-carbon alternatives. However, pricing alone is insufficient; it must be complemented by innovation policies, regulatory support, and social protection measures to ensure that transitions are both economically viable and socially acceptable. Evidence from existing emissions trading schemes, renewable energy subsidy programs, and fiscal incentive structures suggests that balanced and adaptive policy portfolios can simultaneously enhance economic efficiency, social legitimacy, and environmental effectiveness [47,48].

In conclusion, this collection of twenty studies collectively provides a comprehensive understanding of the challenges, opportunities, and mechanisms underpinning the global energy transition. The research highlights that decarbonization is not merely a technical problem but a deeply systemic process shaped by the interactions of technology, policy, market dynamics, and human behavior. Achieving meaningful, just, and resilient energy transitions requires a synthesis of methodological rigor, stakeholder engagement, adaptive governance, and coherent policy design. Together, these elements form the foundation for a science-informed, socially inclusive, and economically viable pathway toward global carbon neutrality. Ultimately, the collective insights from this Special Issue reinforce that a successful global energy transition is possible—but it demands coordinated, multi-level action across all dimensions of society, governance, and technology.

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