

Driving Zero-Carbon Development through Green Innovation and Environmental Regulation

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Abstract

The global imperative for a zero-carbon transition has catalyzed a fundamental restructuring of industrial frameworks, yet the link between renewable energy adoption and systemic productivity remains empirically fragmented. While decarbonization is often framed as a technical substitution, its success is deeply dependent on the structural and institutional readiness of diverse economic landscapes. This research aims to synthesize the pathways through which energy transitions influence green total factor productivity (GTFP) across varying developmental contexts. Employing a qualitative research design, the study utilizes a comparative thematic synthesis of secondary data derived from peer-reviewed empirical literature published between 2014 and 2025. Data were analyzed using a standardized extraction matrix to identify mediating variables, including green innovation efficiency, regulatory stringency, and institutional quality. The study employs source triangulation and a rigorous trustworthiness framework to ensure the validity of the synthesized findings. The results demonstrate that the energy-productivity nexus is non-linear and conditional, where advanced economies leverage "innovation compensation" while emerging markets often face structural bottlenecks that hinder green growth. The study concludes that achieving carbon neutrality requires a synchronized integrative mechanism where digital infrastructure and institutional signals align to drive industrial evolution. This research contributes to the field by providing a tiered structural model that explains the geographic and developmental heterogeneity of sustainable development outcomes.

Keyword

Energy Transition; Green Productivity; Environmental Regulation; Sustainable Development.

1. Introduction

The global pursuit of net-zero emissions has initiated a fundamental restructuring of energy systems and industrial frameworks. Governments worldwide are increasingly adopting energy transition policies that aim to shift production towards renewable sources while maintaining economic momentum (Adelekan et al., 2024). This transition is viewed as a critical pathway for enhancing green total factor productivity and achieving environmental sustainability (Jiang et al., 2024). Many nations are now transitioning from traditional development models to sustainable growth paradigms where innovation plays a central role (Lee et al., 2021). Policy narrative intensity has also been identified as a significant driver for accelerating renewable energy innovation in



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transition contexts (Zheng et al., 2025). Furthermore, technological advancements in solar and hydropower have demonstrated their potential to significantly improve energy productivity (Wang et al., 2023). This systemic shift requires a coordinated approach involving infrastructure investment and regulatory oversight (Ahmed et al., 2025). Consequently, the integration of green technologies and renewable energy has become a primary objective for modern industrial policy.

However, the path toward a zero-carbon economy is complicated by the fact that intensive industrialization often escalates the national carbon footprint (Rasheed et al., 2024). In many emerging economies, the competitive pursuit of industrial excellence can lead to environmental degradation that offsets the benefits of energy efficiency. Significant barriers, such as inadequate infrastructure and weak institutional frameworks, continue to hinder a just energy transition in many developing regions (Ahmed et al., 2025). There is also evidence suggesting that increased human development and foreign investment do not always lead to enhanced sustainability outcomes (Rasheed et al., 2024). These conflicting results create a significant policy challenge regarding the universal effectiveness of energy transition strategies. Market maturity and saturation further differentiate the success rates of green energy investments between established and developing economies (Murugan et al., 2025). Without a clear understanding of the structural conditions that facilitate green productivity, nations may struggle to meet their climate commitments. The persistent dichotomy between industrial output and carbon neutrality represents a critical hurdle for global sustainable development.

Existing research provides substantial evidence that renewable energy optimization and green innovation are key drivers of sustainable growth. Studies indicate that green technological innovation significantly promotes renewable energy generation and improves total factor productivity (Alfalih, 2025; Jiang et al., 2024). In the manufacturing sector, environmental regulations have been found to effectively enhance energy efficiency and stimulate innovation (Yuan & Xiang, 2018). Furthermore, the synergy between green finance and technological advancement has been shown to accelerate the transition toward low-carbon productivity (Jiakui et al., 2022). Innovation efficiency is also recognized as a positive contributor to green productivity, provided that financial constraints are sufficiently managed (Zhang & Vigne, 2021). The implementation of digital economy strategies and energy-consuming rights trading further strengthens the contribution of firms to green development (Wang et al., 2024). Additionally, technological innovation in the industrial sector acts as a primary contributor to improving ecological performance across various subsectors (Wang et al., 2020).

Despite these insights, several critical aspects of the energy-productivity relationship remain unresolved. It is not yet clear whether the positive impact of renewable energy is universal or if it depends on specific national income levels and developmental stages. While some findings suggest that technological innovation improves green growth, other results remain mixed or even negative in certain geopolitical contexts (Lu et al., 2025). The precise role of environmental regulations is also disputed, with some evidence suggesting they may hinder labor productivity while improving energy efficiency (Yuan & Xiang, 2018). There is a lack of understanding regarding the nonlinear effects and threshold levels required for energy transitions to yield net productivity gains. Furthermore, the interplay between policy narrative intensity and actual innovation outcomes across diverse regions is not fully explored. The extent to which institutional quality acts as a prerequisite for the effective adoption of green technologies remains an open question. Consequently, the conditional factors that

determine the success of structural pathways to zero-carbon development require a more systematic evaluation.

The existing literature is characterized by fragmented empirical findings that prevent the development of a unified theory of green productivity. Some studies prioritize the role of renewable energy production, while others emphasize the detrimental impacts of industrialization and foreign direct investment on sustainability (Rasheed et al., 2024). There is a notable lack of comparative studies that explain the divergent results between emerging and mature economies. Most research focuses on single-country analyses or regional panels without a comprehensive cross-comparison of structural pathways. Additionally, the integration of energy transition, innovation, and regulation as a single structural mechanism is frequently overlooked. While bibliometric reviews exist, they often fail to synthesize the underlying institutional conditions that moderate productivity outcomes (Sharma et al., 2025). The exclusion of configurational perspectives in many econometric models further limits the understanding of multifactor-synergy pathways (Lu et al., 2025). Addressing these gaps is essential for harmonizing the global discourse on zero-carbon development.

Conducting a comparative literature-based assessment is necessary to reconcile the inconsistencies observed in previous empirical research. By synthesizing various studies, this research can identify common patterns and structural bottlenecks that are not visible in individual datasets. This approach allows for a deeper exploration of the institutional and technological conditions that dictate the success of energy transitions. Furthermore, moving beyond new data estimations toward a thematic synthesis provides a more robust conceptual framework for policymakers. A comparative analysis justifies the focus on structural pathways by highlighting how different industrial configurations respond to green policies. This method also facilitates a better understanding of the trade-offs between environmental compliance and industrial productivity. Effectively, this synthesis bridges the gap between theoretical green growth models and the complex realities of global industrial transformation. It provides the necessary evidence to move from general recommendations toward context-specific energy strategies.

The central objective of this research is to identify the patterns of consistency and divergence in empirical findings concerning the energy transition and green productivity. This study aims to analyze the specific institutional and technological factors that moderate the relationship between renewable energy adoption and ecological efficiency. A primary goal is to determine why some economies successfully improve their productivity while others experience environmental degradation during industrialization. The research also seeks to develop a comprehensive structural model that synthesizes the interactions between energy shifts, regulation, and innovation. Another objective is to evaluate the differences in transition outcomes between advanced nations and emerging economies. By mapping these structural pathways, the study provides a nuanced perspective on the feasibility of achieving net-zero targets. Ultimately, these objectives are designed to provide a conceptual roadmap for sustainable development.

This research is increasingly urgent as nations face the challenge of meeting ambitious climate goals within a limited timeframe. The study contributes to the academic field by shifting the focus from simple energy substitution to a more complex understanding of structural transformation. By providing a comparative synthesis, it offers a more globally representative perspective than previous single-region studies. The research highlights the critical importance of aligning innovation capacity and institutional quality with energy policy. This work provides a foundation for more

effective policy designs that account for national development stages and industrial structures. It also adds value by identifying the specific conditions under which zero-carbon transitions lead to tangible productivity gains. The findings are expected to assist global organizations and national governments in refining their strategies for a just and sustainable future. This contribution is vital for ensuring that the transition to a low-carbon economy is both effective and resilient.

2. Research Method

This study employs a qualitative research design centered on a comparative thematic synthesis of secondary data (Ruggiano & Perry, 2017). This design is selected to facilitate an in-depth exploration of the structural pathways and institutional nuances that govern the relationship between energy transitions and green productivity across diverse economic landscapes. A qualitative approach is justified as it allows for the identification of complex, non-linear mechanisms and contextual variables that purely quantitative meta-analyses may fail to capture (Elbardan & Kholeif, 2017). This design is particularly effective for this research because it moves beyond statistical correlation to provide a holistic interpretation of how different policy configurations and innovation capacities influence environmental outcomes (Rashid et al., 2019). By constructing an analytical framework based on the synthesis of existing empirical literature, the study can reconcile fragmented findings and develop a cohesive structural understanding of zero-carbon development pathways.

The data sources for this research consist exclusively of peer-reviewed empirical articles published in reputable international journals indexed in Scopus and Web of Science between 2014 and 2025 (Sharma et al., 2025). Data collection procedures followed a systematic identification process using targeted keywords such as "renewable energy," "green total factor productivity," "environmental regulation," and "green innovation" (Sharma et al., 2025). The units of analysis are the individual empirical studies that provide evidence on the drivers of sustainable growth in both advanced and emerging economies. The primary instrument used for data organization is a standardized extraction matrix, which facilitates the systematic classification of research variables and analytical dimensions. These dimensions are structured around the core components of the energy-productivity nexus, including renewable energy adoption rates, regulatory stringency, innovation efficiency, and the mediating role of institutional quality.

To ensure the validity and reliability of the synthesis, this study adopts a rigorous trustworthiness framework involving source triangulation and peer-debriefing (Elbardan & Kholeif, 2017). Trustworthiness is further established through the application of transparent inclusion and exclusion criteria, ensuring that the synthesized evidence is derived from high-quality, methodologically sound research. Reliability is maintained by consistently applying the extraction matrix across all units of analysis to minimize researcher bias and ensure the comparability of findings. Ethical considerations are strictly upheld through the principles of academic integrity, ensuring accurate representation and proper citation of all secondary sources. Although this study does not involve direct interaction with human subjects, ethical standards regarding data handling are maintained by utilizing anonymized, publicly available findings from the primary studies (Ruggiano & Perry, 2017). Consequently, the requirements for informed consent and confidentiality are addressed by the ethical protocols implemented in the original research, which this assessment respects and upholds.

3. Result and Discussion

3.1 Structural Dynamics of Energy Transition and Green Productivity: A Synthesis of Decarbonization Pathways

The analytical evaluation of the energy-productivity nexus is fundamentally grounded in the Porter Hypothesis and Ecological Modernization Theory, which posit that stringent environmental governance can catalyze technological shifts that offset compliance costs. To interpret the findings within this subsection, we utilize the conceptual indicators of "innovation compensation" and "efficiency-driven growth," where green total factor productivity (GTFP) serves as the primary metric for systemic decoupling of economic output from carbon intensity. This theoretical framing allows for an assessment of whether the transition to zero-carbon energy functions as a disruptive burden or a structural stimulus for industrial modernization. By viewing the energy transition through the lens of structural path dependency, we can analyze how the integration of renewable sources interacts with institutional quality to redefine the efficiency frontier. These principles guide the subsequent interpretation of empirical evidence by highlighting the conditions under which decarbonization strategies transform from environmental mandates into drivers of holistic productivity. Consequently, the analysis focuses on the synergy between technological maturity and regulatory design as the decisive mechanism for green development.

The synthesis of empirical evidence suggests that the impact of renewable energy on green productivity is predominantly positive but highly contingent upon the existing technological infrastructure and market maturity. Research indicates that renewable energy optimization acts as the most effective channel for improving GTFP, particularly when supported by green technology innovation and efficient infrastructure (Jiang et al., 2024). In regions where solar and hydropower technologies are well-integrated, the resulting energy productivity gains facilitate a smoother transition toward zero-carbon pathways (Wang et al., 2023). However, this positive relationship is often non-linear, as the initial stages of energy substitution can impose significant financial strains on industrial sectors with high fossil fuel dependency. The findings reveal that for renewable energy to bolster productivity, there must be a threshold level of green finance and legislative support to mitigate the risks associated with capital-intensive energy projects (Jiakui et al., 2022). Thus, the transition is not merely a technical substitution but a structural shift that requires the simultaneous evolution of financial and energy markets to sustain green growth.

Environmental regulation plays a dual role in this transition, acting as both a catalyst for innovation and a potential constraint on short-term labor productivity. Empirical data suggests that well-designed environmental policies encourage firms to adopt cleaner technologies, leading to long-term gains in energy efficiency (Yuan & Xiang, 2018). The "innovation compensation" effect is most visible in economies where regulatory stringency is balanced by institutional support for green research and development (Lee et al., 2021). Nevertheless, the findings also highlight a critical tension: while regulation improves environmental performance, it can temporarily hinder labor productivity if industrial sectors are unable to adapt their operational structures rapidly enough. This suggests that the effectiveness of the energy transition is deeply embedded in the "regulatory design," where the focus must shift from punitive measures to incentive-based mechanisms. Market-oriented tools, such as energy-consuming rights trading, have demonstrated a superior ability to enhance green productivity by leveraging digital economy frameworks to reduce transaction costs (Wang et al., 2024).

The role of green innovation emerges as the primary mediating mechanism that bridges the gap between energy transition and productivity enhancements. Technological innovation not only reduces carbon dioxide emissions but also significantly facilitates the adoption of renewable energy across large-panel economies (Han et al., 2025). The findings underscore that innovation efficiency is a positive contributor to green growth, though its impact is often constrained by financial bottlenecks in less developed regions (Zhang & Vigne, 2021). Furthermore, the industrial sector's transition toward zero-carbon development is heavily reliant on technological advancements in specific subsectors, which act as the backbone for regional ecological performance (Wang et al., 2020). This implies that a "one-size-fits-all" innovation policy is insufficient; instead, structural pathways must be tailored to the specific innovation capacities of different industrial ecosystems. The synergy between human capabilities and technological adoption is therefore essential for ensuring that green energy supplies translate into tangible productivity dividends (Alfalih, 2025).

Contextual dynamics reveal that the success of decarbonization pathways is significantly moderated by the developmental stage and institutional quality of the nation. In emerging economies, the competitive pursuit of industrialization often results in a "pollution halo" or "pollution haven" effect, where industrial growth temporarily exacerbates the carbon footprint (Rasheed et al., 2024). This indicates that the energy transition does not automatically yield productivity gains if the institutional framework is weak or if there is an over-reliance on foreign direct investment that lacks green technological spillovers. Findings suggest that in such contexts, human development and foreign investment might actually correlate with reduced sustainability unless specifically aligned with green growth objectives (Rasheed et al., 2024). Consequently, the governance setting must prioritize the strengthening of institutions to ensure that the transition to renewable energy is not undermined by industrial inefficiencies. This structural reality necessitates a synchronized approach where energy policy is integrated with broader macroeconomic and institutional reforms to facilitate a just transition.

Ultimately, these findings refine the existing theoretical discourse by challenging the assumption of a universal, linear benefit from renewable energy adoption. While confirming the foundational tenets of the Porter Hypothesis, the analysis extends this theory by demonstrating that "innovation compensation" is conditional upon institutional maturity and the presence of green financial mechanisms. This assessment fills the identified research gap by providing a comparative synthesis that explains why similar energy policies yield divergent productivity outcomes across different structural contexts. By highlighting the missing link between policy narrative intensity and actual innovation outcomes, the study clarifies how governance frameworks can either accelerate or stall the zero-carbon transition (Zheng et al., 2025). The results contribute to a more nuanced understanding of GTFP, shifting the academic focus from simple energy substitution to a multi-dimensional structural transformation. This synthesis provides a robust empirical foundation for future research to explore the specific threshold effects that define the tipping point for green productivity in diverse economic landscapes.

3.2 Institutional and Technological Moderators of the Energy-GTFP Nexus

The theoretical investigation of energy transitions must account for the institutional and technological contexts that mediate the relationship between policy inputs and productivity outputs. Institutional Theory suggests that the efficiency of green mandates is determined by the quality of governance and the robustness of legal frameworks that protect innovation and market competition. Simultaneously, Technological Transition

Theory emphasizes the role of path dependency and the necessity of an existing technological base to absorb new renewable energy solutions. By utilizing indicators such as innovation capability, institutional quality, and financial development, this subsection frames the analytical problem of why identical energy policies produce heterogeneous results across different regions. These theoretical dimensions serve as a lens to evaluate the "absorptive capacity" of an economy, determining whether it can successfully convert green investments into total factor productivity gains. The following analysis explores how these moderating factors interact to define the structural boundaries of the zero-carbon transition. This framing ensures that the discussion remains conceptually grounded in the dynamics of systemic transformation rather than isolated variable correlations.

A critical finding from the literature suggests that the effectiveness of the energy transition is fundamentally tied to a nation's internal innovation capability and its human development levels. Empirical evidence indicates that green technological innovation significantly promotes the supply of renewable energy, particularly in countries that have prioritized the development of human capabilities (Alfalih, 2025). This synergy highlights that without a base level of technical expertise, the mere installation of renewable infrastructure may fail to yield significant productivity dividends. Furthermore, the ability of environmental regulations to improve green total factor productivity is often contingent upon the pre-existing innovation capacity of the industrial sector (Lee et al., 2021). When innovation capability is high, firms are more likely to respond to regulatory pressures through technological upgrading rather than simple compliance. Conversely, in regions with low innovation efficiency, the costs of the energy transition can become a significant drag on overall industrial performance. This relationship underscores the importance of technological readiness as a structural prerequisite for sustainable development. Consequently, the transition to a zero-carbon economy must be viewed as an innovation-led process rather than a simple resource substitution.

Financial development and the availability of green credit act as vital moderators that facilitate the capital-intensive shift toward renewable energy systems. The transition toward a low-carbon development model is significantly accelerated when green finance is integrated with technological innovation (Jiakui et al., 2022). Without robust financial mechanisms, even the most ambitious energy policies may struggle to achieve the scale necessary to alter national productivity trajectories. Findings suggest that green finance not only provides the necessary capital but also reduces the investment risks associated with long-term renewable energy projects. This financial moderation is particularly relevant in emerging economies where traditional credit markets may be biased toward fossil fuel-intensive industries. Moreover, the digital economy has emerged as a supportive framework that enhances the effectiveness of energy-consuming rights trading systems (Wang et al., 2024). This integration suggests that the technological moderator is not limited to energy hardware but extends to the digital and financial infrastructures that manage energy consumption. Therefore, the structural pathway to green productivity is heavily dependent on a synchronized evolution of the financial sector.

The quality of institutions and the intensity of policy narratives serve as overarching moderators that determine the pace and stability of the energy transition. Research highlights that policy narrative intensity plays a significant role in fostering renewable energy innovation by providing clear signals to investors and industrial actors (Zheng et al., 2025). When institutions are strong, they can effectively enforce environmental regulations and manage the transaction costs associated with green

transitions. However, the literature also reveals that heightened industrial competitive performance and rapid industrialization can sometimes exert a greater influence on the carbon footprint than the adoption of renewables (Rasheed et al., 2024). This implies that if institutional governance fails to balance industrial growth with ecological goals, the benefits of the energy transition may be negated. Furthermore, the role of human development in sustainability outcomes is complex, as some findings suggest that human development does not always correlate positively with carbon neutrality (Rasheed et al., 2024). This divergence indicates that institutional frameworks must be specifically designed to align social development with environmental sustainability. Strong governance thus acts as a filter that ensures energy transition efforts are translated into lasting productivity gains.

The specific design and stringency of environmental regulations function as a moderating dimension that can either stimulate or stifle industrial efficiency. Empirical analysis shows that environmental regulations are capable of enhancing green total factor productivity by incentivizing firms to optimize their resource allocation (Jiang et al., 2024). However, the "Porter Hypothesis" is not universally applicable, as the impact of regulation on labor productivity can vary significantly depending on the sector and the regulatory tool used (Yuan & Xiang, 2018). In some cases, the cost of compliance may exceed the innovation benefits, particularly in industries with low technological flexibility. The findings suggest that market-oriented regulations, such as emissions trading or energy-rights markets, often yield better productivity outcomes than rigid command-and-control measures (Wang et al., 2024). This moderating effect of "regulatory design" implies that the success of the zero-carbon transition depends on the government's ability to craft policies that promote innovation compensation. Thus, the transition pathway is shaped by the delicate balance between environmental protection and industrial competitiveness. Effective regulation must therefore be viewed as a strategic instrument for structural transformation rather than a mere punitive tool.

These findings critically extend and refine the Porter Hypothesis by identifying the institutional and technological boundaries of its applicability. While the hypothesis suggests that regulation drives productivity through innovation, our synthesis demonstrates that this relationship is fundamentally filtered by the economy's innovation capacity and financial development. This study challenges the notion of a universal "win-win" scenario, illustrating that the productivity gains from the energy transition are conditional upon specific structural prerequisites. By confirming that green finance and institutional quality are essential moderators, the research provides a more sophisticated theoretical framework for zero-carbon development (Jiakui et al., 2022; Zheng et al., 2025). This refinement highlights that the transition is a path-dependent process where initial technological conditions dictate the eventual productivity outcome. Furthermore, the analysis reveals that human development and industrial performance can act as counter-productive forces if not managed by robust environmental governance (Rasheed et al., 2024). Consequently, the theory of green growth must be updated to incorporate these context-specific moderating variables. This theoretical evolution is necessary for a more realistic assessment of global decarbonization strategies.

The synthesis effectively fills the theoretical and empirical gaps concerning the conditional interpretation of the energy-productivity nexus. By categorizing the success of energy transitions according to innovation capacity and regulatory design, the research provides the clarity that previous fragmented studies lacked. The contextual dynamics identified here explain why emerging economies often face a disconnect between renewable adoption and GTFP gains compared to advanced economies. This study moves

the academic discussion from "whether" the transition is effective to "under what conditions" it becomes a driver of green productivity. The findings emphasize that a lack of financial support and weak innovation systems are the primary reasons for the failure of energy policies in certain regions (Zhang & Vigne, 2021). Furthermore, by integrating energy, regulation, and innovation into a single analytical framework, the research addresses the previous lack of structural integration in the literature. This comprehensive approach provides a more resilient roadmap for countries navigating the complex trade-offs of the zero-carbon transition. Ultimately, this subsection clarifies the structural boundaries that define the global landscape of green development.

3.2 Comparative Synthesis of Developmental Pathways: Advanced vs. Emerging Economies

The comparative evaluation of zero-carbon transitions necessitates a theoretical framework that accounts for the "Developmental Gap" and the "Pollution Haven Hypothesis." Ecological Modernization Theory often assumes a linear progression toward green growth, yet dependency theories suggest that emerging economies may face structural constraints that advanced nations have already bypassed. To interpret these findings, we utilize dimensions such as industrial competitive performance, foreign direct investment (FDI) inflows, and national income levels as conceptual indicators. This analytical framing addresses the problem of why global energy policies often result in divergent environmental outcomes, focusing on whether energy transitions lead to "green decoupling" or merely shift carbon burdens across borders. By examining the structural differences in energy infrastructure and industrial maturity, this subsection clarifies how developmental stages moderate the effectiveness of sustainability mandates. These principles guide the narrative toward understanding the geographic heterogeneity of green total factor productivity (GTFP).

A primary distinction revealed in the synthesis is that advanced economies generally exhibit an "innovation-driven" pathway where energy transitions are positively correlated with productivity gains. In these contexts, the integration of renewable energy and green innovation acts as a catalyst for systemic efficiency, allowing for a simultaneous reduction in carbon intensity and an increase in economic output (Jiang et al., 2024). To provide a systematic overview of these structural differences, the following table summarizes the main dimensions that distinguish the transition pathways of the two economic groups:

Table 1. Comparative Analysis of Energy Transition Pathways and Structural Dynamics between Advanced and Emerging Economies

Dimension	Advanced Economies (Innovation-Driven)	Emerging Economies (Resource-Driven)
Primary Pathway	Green decoupling and efficiency gains	Pollution-intensive industrialization
Innovation Role	Technological frontier and compensation	Adoption bottleneck and dependency
Regulation Impact	Stimulates "Innovation Compensation"	High compliance costs; "Pollution Havens"
Financial Context	Mature green credit and digital markets	Financial constraints; traditional bias
Sustainability	Positive correlation with GTFP	Trade-offs with industrial performance
Institutional Quality	High stability; narrative-driven	Focused on growth-ecology balance

Source: Processed by the Author, 2026

According to the above classification, the success of developed countries is largely attributed to the maturity of their green financial markets and the high efficiency of their technological innovation systems (Zhang & Vigne, 2021). Findings show that developed countries have reached a threshold where environmental regulations stimulate "innovation compensation," which effectively transforms compliance costs into competitive advantages. This confirms that in high-income settings, the energy transition follows the optimistic projections of the Porter Hypothesis, where the shift to renewable energy complements existing industrial advantages. Consequently, the transition in advanced economies is characterized by a "virtuous cycle" of policy rigor and technological evolution.

In stark contrast, emerging economies often experience a "pollution-intensive" industrialization phase where the pursuit of economic growth temporarily degrades environmental sustainability. Research indicates that in these regions, heightened industrial competitive performance and rapid industrialization continue to have significant detrimental impacts on the carbon footprint (Rasheed et al., 2024). The empirical outcomes suggest that even as these nations adopt renewable energy, the sheer scale of industrial expansion often offsets the ecological benefits of cleaner energy sources. Furthermore, in many emerging markets, foreign direct investment (FDI) and human development have been found to paradoxically reduce sustainability levels (Rasheed et al., 2024). This suggests a "pollution haven" effect, where global industrial production is relocated to regions with less stringent environmental governance, complicating the local transition to zero-carbon pathways. Thus, the pathway for emerging economies is not a simple replication of Western models but a complex struggle between industrial survival and ecological compliance.

The role of green technological innovation also manifests differently across these developmental tiers, serving as a primary driver in the North while remaining a significant bottleneck in the South. While innovation efficiency is a positive contributor to GTFP in advanced economies, it is often hindered by financial constraints and low human capability in developing regions (Alfalih, 2025; Zhang & Vigne, 2021). The findings underscore that without the "absorptive capacity" provided by high-quality human development and technical infrastructure, emerging nations struggle to domesticate green energy technologies effectively. This gap creates a technological dependency that can slow down the overall pace of the global energy transition. Moreover, the industrial sector's transition toward zero-carbon development is heavily reliant on subsector-specific advancements that are often absent in less diversified economies (Wang et al., 2020). Consequently, the global landscape is divided between "innovation leaders" who define the green frontier and "innovation followers" who face structural barriers to entry.

Institutional quality and policy narrative intensity further differentiate the success rates of transition strategies between the two groups. In advanced economies, strong institutions provide the stability needed for long-term renewable energy innovation and the effective enforcement of energy-rights trading (Zheng et al., 2025; Wang et al., 2024). However, in emerging economies, the institutional framework may be more focused on managing the trade-offs between poverty reduction and environmental protection. The findings suggest that when institutional governance is weak, the energy transition can become fragmented, with green policies failing to produce the desired "innovation-driven" growth (Jiang et al., 2024). This structural discrepancy implies that the global zero-carbon transition is not a uniform movement but a tiered process where the "governance setting" dictates the feasibility of sustainability goals. Without

addressing these institutional voids, the transition in emerging markets may remain limited to symbolic adoption rather than structural transformation.

These findings critically challenge the universalist assumptions of many global climate policies by highlighting the divergent impacts of industrialization on sustainability. While prior studies often aggregate global data, this synthesis refines the existing literature by identifying the "detrimental impacts" of industrial competitive performance in emerging contexts (Rasheed et al., 2024). The analysis confirms the "Pollution Haven Hypothesis" in specific regions while simultaneously validating the "Porter Hypothesis" in more advanced settings, effectively reconciling these seemingly contradictory theories. This comparative interpretation explains the contextual dynamics of why FDI and human development do not universally support green growth. By providing this tiered perspective, the study fills the empirical gap concerning the non-linear relationship between development stages and green productivity. This refinement is essential for developing a more equitable global climate framework that acknowledges the structural burdens of industrialization in the Global South.

Ultimately, this subsection addresses the theoretical gap by establishing that developmental maturity is a primary determinant of energy transition success. The findings demonstrate that for the energy transition to be effective in emerging economies, policymakers must prioritize a resilient approach to competitive industrial performance rather than just energy substitution (Rasheed et al., 2024). This synthesis provides a clear response to the research problem regarding the inconsistencies in global GTFP outcomes, attributing them to variations in "innovation-driven" versus "resource-driven" pathways. The analysis underscores that the zero-carbon transition requires a fundamental restructuring of industrial policy to ensure that green technologies do not become a new source of economic inequality. By mapping these divergent pathways, the research offers a more realistic roadmap for achieving global carbon neutrality. This comparative clarity is the final step toward a comprehensive understanding of the structural requirements for a just and sustainable energy future.

3.2 Integrative Structural Mechanism: Transition, Regulation, and Innovation

The final stage of the analytical synthesis requires an integrative theoretical framework that conceptualizes the zero-carbon transition not as a series of isolated policy interventions, but as a synchronized structural mechanism. Systems Theory and the Multi-Level Perspective (MLP) on socio-technical transitions provide the necessary foundation for this interpretation, suggesting that sustainability is achieved through the co-evolution of technology, regulation, and industrial behavior. In this subsection, we utilize the conceptual dimensions of "structural synergy" and "feedback loops" to explain how renewable energy adoption, environmental mandates, and innovation efficiency converge to redefine the efficiency frontier. This analytical problem addresses the previous fragmentation in literature by clarifying the causal sequence and interdependencies of these variables. By framing the transition as an integrated mechanism, the study can interpret findings in a way that demonstrates how regulatory pressure acts as the kinetic force that drives energy inputs through the filter of innovation to produce green productivity outcomes.

The synthesis of empirical data confirms that the most resilient pathways to zero-carbon development are those that achieve a high degree of integration between energy-rights trading and digital infrastructure. Market-oriented tools, specifically energy-consuming rights trading, have demonstrated a superior ability to enhance green total

factor productivity when embedded within a digital economy framework (Wang et al., 2024). This integrative mechanism reduces transaction costs and information asymmetry, allowing the regulatory "push" to translate more efficiently into technological "pull." The findings suggest that the digital economy acts as a catalyst that accelerates the diffusion of green innovations across industrial sectors, thereby magnifying the impact of renewable energy optimization (Jiang et al., 2024; Wang et al., 2024). This demonstrates that the structural mechanism is not merely linear but operates as a network where digital maturity enhances the elasticity of the energy-productivity nexus. Consequently, the transition is most effective when policy design acknowledges these cross-sectoral synergies.

The interplay between environmental regulation and innovation efficiency serves as the core engine of this structural mechanism, determining whether the transition results in economic growth or industrial stagnation. Empirical evidence supports the "innovation-driven" model, where green technological innovation acts as the primary mediator that mitigates the potential costs of carbon neutrality (Jiakui et al., 2022). The findings indicate that for the energy transition to be sustainable, innovation must move beyond simple carbon reduction to focus on systemic productivity enhancements (Sharma et al., 2025). This synergy is particularly evident in high-panel economies where innovation efficiency is high enough to offset the "compliance drag" of stringent environmental laws. However, the mechanism remains fragile in contexts where innovation bottlenecks exist, reinforcing the idea that the transition is a path-dependent process. Therefore, the structural integration of innovation policy and environmental governance is the decisive factor in achieving long-term zero-carbon goals.

A critical component of this integrative mechanism is the role of policy narrative intensity and institutional signals in shaping industrial expectations and long-term investment. Research highlights that clear and intense policy narratives regarding carbon neutrality are essential for mobilizing the capital necessary for renewable energy innovation (Zheng et al., 2025). When policy signals are consistent, they create a predictable environment that encourages firms to commit to high-risk, high-reward green technological shifts. This institutional dimension ensures that the structural mechanism is anchored in a long-term strategic vision rather than short-term political cycles. Furthermore, the synthesis reveals that human capability and technological supply must be synchronized to ensure that green energy production leads to tangible sustainability outcomes (Alfalih, 2025). This alignment suggests that the integrative mechanism is as much about social and institutional readiness as it is about technical engineering.

Ultimately, these findings refine the theoretical understanding of the Porter Hypothesis by demonstrating that "innovation compensation" is a systemic outcome of structural integration rather than a guaranteed byproduct of regulation. The analysis confirms that the synergy between energy transition and productivity is mediated by both the digital economy and institutional narrative intensity (Wang et al., 2024; Zheng et al., 2025). This study extends existing theories by showing that a failure in any single component of the mechanism—whether it be financial support, regulatory design, or innovation capacity—can lead to a breakdown of the entire green development pathway. By filling this gap, the research provides a cohesive structural model that explains the complex feedback loops between policy and performance. The findings challenge practitioners to move beyond siloed energy policies and toward an integrated governance strategy that treats decarbonization as a holistic industrial evolution. This comprehensive perspective is essential for reconciling the trade-offs between economic expansion and environmental preservation in the pursuit of a zero-carbon future.

4. Conclusion

This study has synthesized the complex structural pathways between energy transitions and green total factor productivity (GTFP), demonstrating that the shift toward zero-carbon energy is not a linear process but one moderated by institutional and technological maturity. The findings reveal that while renewable energy optimization is the most potent driver for enhancing sustainability, its success is fundamentally contingent upon high innovation capacity and robust green financial frameworks. A critical distinction was identified between advanced economies, which benefit from an "innovation-driven" virtuous cycle, and emerging economies, where rapid industrialization and "pollution haven" effects often offset the ecological benefits of cleaner energy adoption. Ultimately, the research confirms that the integrative mechanism of digital infrastructure, market-oriented regulation, and policy narrative intensity forms the necessary architecture for transforming energy inputs into long-term productivity gains.

The research provides significant contributions to the field of environmental economics and sustainability governance by refining the Porter Hypothesis within a tiered global context. By moving beyond statistical correlations to provide a qualitative thematic synthesis, this study addresses the empirical gap concerning the heterogeneous impacts of decarbonization across different developmental stages. It introduces a more nuanced "conditional interpretation" of the energy-productivity nexus, highlighting that "innovation compensation" is a systemic outcome of structural integration rather than a guaranteed regulatory byproduct. Furthermore, the development of an integrative structural model—linking energy transition, digital economy, and institutional signals—offers a cohesive framework that reconciles fragmented findings in previous literature. This contribution is essential for shifting the academic focus from simplistic energy substitution to a multi-dimensional structural transformation.

Future research directions should prioritize the exploration of specific threshold effects that determine the tipping point at which green investments consistently yield productivity dividends in emerging markets. While this study identified broad structural barriers, further empirical investigation is needed to quantify the exact levels of human development and institutional quality required to mitigate the "pollution-intensive" phase of industrialization. Additionally, longitudinal studies could examine the long-term impacts of digital energy-rights trading on industrial competitiveness across various subsectors. There is also a significant opportunity to investigate the role of green hydrogen and other emerging technologies as potential disruptors of current path dependencies. Finally, future inquiries should delve deeper into the socio-political dimensions of the zero-carbon transition to ensure that the shift toward a green frontier is inclusive and equitable across the global developmental spectrum.

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