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Scaling Green Innovation for Sustainable Industrial Energy Transitions

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Abstract
The global imperative to mitigate climate change has accelerated the transition from carbon-intensive energy systems to renewable sources, placing Green Total Factor Productivity (GTFP) at the center of sustainable development agendas. Despite various policy initiatives, the empirical relationship between energy transitions and productivity gains remains fragmented and highly contingent upon localized structural factors. This research aims to identify the patterns of consistency and divergence in the impact of energy transitions on GTFP across various national contexts. Employing a qualitative research design based on a comparative thematic synthesis, this study analyzes a wide range of secondary data from peer-reviewed literature and high-impact reports. The methodology utilizes a case study approach to deconstruct the "how" and "why" behind disparate productivity outcomes, focusing on analytical dimensions such as innovation capacity and regulatory stringency. Trustworthiness is ensured through investigator triangulation and the systematic comparison of structural patterns across multiple developmental stages. The principal results indicate that the energy-productivity nexus is non-linear and relies heavily on the mediating role of green innovation and the moderating influence of institutional readiness. The study concludes that achieving zero-carbon development is not a guaranteed outcome of energy policy but a result of synchronized structural pathways. This research contributes to the field by providing a unified conceptual framework that explains the conditional prerequisites for successful decarbonization.

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

1. Introduction
The global imperative to mitigate climate change has catalyzed an unprecedented shift toward decarbonization, placing the energy transition at the forefront of international policy agendas. As nations strive to meet net-zero emissions targets, the transition from fossil-based systems to renewable energy sources is no longer viewed merely as an environmental necessity but as a fundamental driver of economic restructuring. Increasing Green Total Factor Productivity (GTFP) is now considered one of the most significant indicators of sustainable economic growth (Lee et al., 2021). Achieving zero-carbon development requires a decoupling of economic growth from carbon-intensive inputs, necessitating a structural pathway that balances energy security with ecological

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sustainability. Consequently, the pursuit of green productivity has become the primary benchmark for evaluating the success of national energy transitions in the 21st century.

Despite the proliferation of green policies, a significant problem persists regarding the inconsistent impact of energy transitions on actual productivity gains across different global regions. In many industrial economies, growth often comes at the expense of resources and the environment, requiring strict environmental intervention to improve efficiency (Chen et al., 2018). While some nations report a "double dividend" of emissions reduction and economic efficiency, others encounter stagnant productivity or rising compliance costs that hinder industrial competitiveness. This discrepancy raises critical questions about the real-world efficacy of current decarbonization strategies, especially when institutional frameworks are poorly aligned with technological capabilities. The tension between rapid renewable energy adoption and the maintenance of industrial output suggests that the transition is not a linear process. Without a clear understanding of the underlying structural mechanisms, many nations risk implementing costly energy shifts that fail to deliver the promised green productivity growth.

Existing empirical literature has extensively documented the individual roles of renewable energy, environmental regulations, and green innovation in shaping sustainability outcomes. Studies indicate that renewable energy optimization serves as a primary channel for enhancing GTFP, particularly when supported by robust infrastructure (Jiang et al., 2024). Furthermore, environmental regulations are often cited as essential catalysts that push firms toward cleaner production methods and improved resource efficiency (Lee et al., 2021). The integration of carbon capture, utilization, and storage (CCUS) technologies has also emerged as a significant factor in promoting industrial upgrading and emissions efficiency (Dong et al., 2024). Clean technology innovation has further been shown to have a substantial positive impact on industrial GTFP, particularly when environmental regulation reaches a certain threshold (Sun et al., 2022). These findings collectively suggest that the technical components for a zero-carbon pathway are well-identified in the current academic discourse.

However, what remains largely unknown is the universal applicability of these findings across diverse developmental stages and socioeconomic contexts. While the positive correlation between green innovation and productivity is evident in certain economies, the evidence remains fragmented and often contradictory when applied to emerging markets. There is a lack of clarity on the specific thresholds where environmental regulations stop being a burden and start becoming a driver of innovation (Qiu et al., 2021). Current research often fails to explain why identical energy policies yield vastly different GTFP results in different jurisdictions. This knowledge gap suggests that the relationship between energy transition and green productivity is highly contingent upon localized structural factors that have yet to be fully synthesized.

The identification of these research gaps reveals a profound fragmentation in empirical findings, where the effects of renewable energy are variously described as positive, non-significant, or even non-linear. Most studies adopt a narrow lens, focusing on single-country or regional analyses, which precludes a broader understanding of how different levels of innovation capacity moderate the energy-productivity nexus. The relationship between innovation and productivity can also differ significantly depending on the type of patents and the level of human capital involved (Liu et al., 2020). Furthermore, there is a distinct lack of structural integration; renewable energy, regulation, and innovation are frequently analyzed as isolated variables. This siloed approach overlooks the complex interplay where energy transitions trigger regulatory shifts that, in turn, necessitate innovation to maintain productivity.

Justifying a deep dive into these gaps is essential because the current lack of a unified conceptual model prevents policymakers from designing adaptive strategies. Without a comparative assessment, emerging economies may erroneously adopt models from developed nations that do not account for their specific industrial constraints or technological baselines. Understanding the conditions under which energy transitions successfully translate into GTFP is vital for preventing "green-washing" and ensuring that decarbonization leads to genuine economic resilience. By synthesizing existing literature, this research can move beyond simple estimations to identify the structural pathways that define successful zero-carbon development. Filling these gaps provides a roadmap for integrating environmental goals with the economic realities of diverse global actors.

The primary objective of this research is to identify the patterns of consistency and divergence in empirical findings regarding the impact of energy transitions on GTFP across various national contexts. Specifically, this study aims to analyze the institutional and technological conditions that moderate this relationship, such as innovation capacity and regulatory efficiency. By conducting a comparative literature-based assessment, the research seeks to develop a conceptual structural model that illustrates the pathways toward zero-carbon development. The study will address whether the transition-productivity link is universal or contingent upon specific structural prerequisites. Through this synthesis, the research intends to clarify how green innovation and environmental regulation act as mediating or moderating forces within the energy transition.

The urgency of this research stems from the rapidly closing window to achieve global climate targets without compromising economic stability. As the transition to zero-carbon systems accelerates, the need for a theoretically grounded and empirically synthesized understanding of green productivity becomes paramount. This study contributes to the field by shifting the academic debate from a binary "success or failure" perspective to a more nuanced "under what conditions" analysis. By offering a comparative synthesis of structural pathways, it provides a comprehensive framework that connects energy policy, innovation, and productivity. Ultimately, this research offers a vital contribution to the theoretical discourse and provides a foundation for more effective, context-specific policy interventions in the global pursuit of sustainable development.

2. Research Method

This research employs a qualitative research design centered on a comparative thematic synthesis to evaluate the structural pathways of the energy transition. By utilizing a multi-case study approach based exclusively on secondary data, the study examines diverse national and regional experiences to identify recurring patterns in green productivity outcomes (Rashid et al., 2019; Ruggiano & Perry, 2017). A qualitative approach is fundamentally justified for this research as it allows for a deep, contextualized exploration of the "how" and "why" behind the inconsistent results found in existing empirical literature. Unlike quantitative meta-analyses that prioritize statistical aggregation, this design facilitates the deconstruction of complex institutional mechanisms and technological moderating factors that define zero-carbon development (Gephart & Saylors, 2020). Consequently, this qualitative framework is uniquely suited to synthesizing disparate findings into a coherent conceptual model that accounts for structural heterogeneity across different levels of economic development.

The primary data sources for this assessment consist of peer-reviewed empirical articles and high-impact reports indexed in reputable global databases such as Scopus and Web of Science. The units of analysis are the individual empirical studies that test the relationships between renewable energy, environmental regulation, and Green Total Factor Productivity (GTFP) over the last decade. Data collection procedures involve a systematic screening process to ensure the relevance and methodological rigor of the included literature, focusing on studies that provide detailed insights into industrial or national transitions (Cheong et al., 2023). The analytical dimensions used as instruments for categorization include geographical location (developed vs. emerging economies), industrial structure, and the stringency of regulatory frameworks. These variables serve as the foundational pillars for the thematic synthesis, allowing for the classification of findings based on positive, negative, or non-linear impacts on green productivity (Kiger & Varpio, 2020).

To ensure the rigor of the findings, the study maintains trustworthiness through the principles of credibility, transferability, and dependability (Bingham, 2023). Validity is addressed through investigator triangulation and the systematic comparison of findings across multiple independent studies to verify the consistency of the identified structural patterns (Schlunegger et al., 2024). Reliability is further reinforced by the implementation of a transparent and reproducible literature search protocol, ensuring that the synthesis is grounded in a stable and audit-worthy selection of secondary data (Assarroudi et al., 2018). Regarding ethical considerations, this research adheres to the highest standards of academic integrity and intellectual property rights. Since the study relies solely on publicly available secondary data, traditional informed consent from human subjects is not applicable; however, the ethical handling of data is maintained through accurate citation practices and the objective representation of original authors' findings to prevent any misinterpretation or breaches of confidentiality regarding the primary datasets (Ruggiano & Perry, 2017).

3. Result and Discussion

3.1 Structural Mechanisms of Energy Transition and Green Productivity

The transition toward a zero-carbon economy is fundamentally anchored in the theoretical premise that environmental constraints can trigger a structural evolution in industrial productivity, a concept commonly examined through the lens of Green Total Factor Productivity (GTFP). This analytical framework suggests that the shift from fossil-based energy to renewable sources is not merely a technical substitution but a catalyst for systemic efficiency gains. By applying the principles of the Porter Hypothesis, this study interprets the energy transition as a mechanism that necessitates innovation to offset the potential costs of environmental compliance. The following analysis utilizes dimensions such as innovation capacity, regulatory stringency, and energy optimization to deconstruct the complex pathways through which nations navigate the decarbonization process. These conceptual indicators serve to guide the interpretation of empirical findings, moving beyond isolated variables to understand the integrative nature of green productivity. This theoretical grounding ensures that the discussion addresses the core problem of how structural alignment determines the success of the transition-productivity nexus.

Empirical assessments consistently identify renewable energy optimization as a primary driver of environmental sustainability and green productivity growth (Jiang et al., 2024). However, the narrative of success is heavily dependent on the presence of supportive infrastructure and favorable economic conditions. Studies show that renewable energy development yields the greatest benefits when combined with high levels of economic activity and technological advancement (Li et al., 2023). In many cases, the transition provides a "double dividend" by reducing emissions while simultaneously upgrading the industrial energy structure. Yet, for countries with a high dependency on traditional fossil fuels, the initial shift can create temporary productivity bottlenecks if not managed through a gradual structural adaptation. This suggests that the energy transition is most effective when integrated into a broader macroeconomic strategy rather than treated as a localized environmental policy. Therefore, the adoption of clean energy acts as a foundational pillar that requires systemic readiness to fully realize its productivity potential.

The role of environmental regulation within this structural pathway is characterized by a complex, often non-linear relationship with industrial output. Findings indicate that dual environmental regulations—encompassing both formal mandates and informal social pressures—promote green productivity through a distinct threshold effect (Ma et al., 2022). Initially, stringent environmental laws may increase the cost of compliance, potentially hindering short-term growth in less innovatively capable regions. However, as regional development increases, the impact of these regulations on GTFP becomes significantly more positive and stable (Sun, 2022). It is also observed that while industrial intelligence can enhance productivity, intensified regulation may sometimes dampen these positive effects if not aligned with firm-level innovation capabilities (Xie et al., 2025). This highlights the necessity of a balanced regulatory design that encourages efficiency without imposing prohibitive costs on emerging industrial sectors. Consequently, the regulatory environment must evolve alongside the technological landscape to sustain long-term green growth.

Green technology innovation serves as the critical mediating mechanism that translates energy transition efforts into tangible productivity gains. Both environmental regulations and innovation capabilities have been found to effectively promote GTFP, with innovation acting as the bridge that connects policy to performance (Lee et al., 2021). The leading role of innovation is particularly evident when comparing different types of patents, where invention-based advancements provide more robust long-term growth than non-invention patents (Liu et al., 2020). Proper stringency in environmental regulation is further identified as a prerequisite for maximizing the influence of innovation on a nation's green growth trajectory. Without a strong internal innovation ecosystem, the transition to renewable energy remains a cost-intensive endeavor rather than a value-creating one. This confirms that the transition-productivity nexus is highly sensitive to a nation's ability to generate and implement cleaner production technologies. Thus, fostering an innovation-driven environment is essential for bypassing the potential "compliance traps" of the energy transition.

Specialized technological pathways, such as carbon capture, utilization, and storage (CCUS), offer a more targeted approach to achieving industrial upgrading within the zero-carbon framework. Research demonstrates that CCUS technology innovation significantly improves green productivity by enhancing carbon emission efficiency and facilitating the modernization of industrial structures (Dong et al., 2024). This specialized innovation works in synergy with environmental regulations to create a positive moderating effect on the energy-productivity relationship. Furthermore, the development of green technology has been shown to boost energy productivity specifically by upgrading industrial structures in various regional contexts (Wang et al., 2021). These findings suggest that the transition is most successful when it targets high-impact sectors through niche technological interventions. The integration of these advanced systems allows industries to bridge the gap between heavy-resource reliance and sustainable production. As such, specialized pathways provide a strategic route for maintaining competitiveness during the shift to a net-zero economy.

The effectiveness of these structural pathways is also deeply influenced by regional disparities and the maturity of innovation networks. Clean technology innovation has been shown to have a more profound impact on industrial GTFP in regions where environmental regulation has already reached a specific threshold value (Sun et al., 2022). In contrast, regions with lower innovation capacity or weaker institutional frameworks often experience negative or non-significant outcomes from similar energy policies. Furthermore, the position of a city or region within a green innovation network significantly dictates its ability to enhance urban green productivity (Jiao et al., 2025). These spatial variations suggest that a "one-size-fits-all" approach to energy transition is likely to fail in diverse economic landscapes. The evidence points to the need for decentralized strategies that account for the unique industrial baselines of different geographical areas. Understanding these contextual dynamics is vital for ensuring that the transition does not exacerbate existing regional inequalities.

The findings derived from this synthesis refine the "weak" version of the Porter Hypothesis by clarifying that while regulations improve energy efficiency, they may simultaneously challenge labor productivity (Yuan & Xiang, 2018). This critical interpretation challenges the assumption that the energy transition is a purely win-win scenario, highlighting instead the trade-offs that occur in the absence of technological compensation. The study extends current theories by documenting the specific institutional and innovation thresholds required to turn environmental constraints into productivity drivers. These contextual dynamics explain the "productivity paradox" seen in many emerging economies where green investments have not yet translated into efficiency gains. By integrating disparate empirical findings, this analysis fills the identified gap regarding the lack of a unified structural model for zero-carbon development. It demonstrates that the transition is a holistic transformation that depends on the successful alignment of energy, regulation, and innovation variables.

Ultimately, this comparative assessment confirms that the pathway toward zero-carbon development is a contingent process rather than a guaranteed outcome of energy policy. The research clarifies that the energy-productivity nexus is mediated by innovation capability and moderated by the efficiency of regulatory design (Lee et al., 2021; Dong et al., 2024). It addresses the fragmented nature of previous literature by identifying the structural conditions that explain why some regions succeed while others encounter economic friction. This synthesis provides a robust framework for understanding the interplay between policy mandates and industrial reality in the quest for sustainability. By focusing on the structural mechanisms of the transition, the study offers a clearer understanding of how nations can achieve a resilient, low-carbon industrial base. This contribution is essential for shifting the global discourse from simple emissions reduction to a more comprehensive model of sustainable economic evolution.

3.2 Divergent Pathways: Comparative Synthesis of Transition Outcomes across Economic Contexts

The theoretical viability of an energy transition is often viewed through a universalist lens, yet the actual realization of green productivity is deeply contingent upon a nation's specific developmental baseline and industrial maturity. From a structural perspective, the "path dependency" of an economy determines its ability to absorb the shocks of transitioning from fossil-intensive inputs to renewable systems. This subsection evaluates how the transition-productivity nexus diverges between advanced and emerging economies, using the principles of technological readiness and institutional capacity as guiding indicators. By deconstructing these differences, the analysis identifies why identical green policies yield heterogeneous results, thereby addressing the gap concerning the non-universal nature of zero-carbon development. This comparative framing allows for a more nuanced understanding of the structural barriers that prevent a seamless global transition.

Empirical evidence suggests that in advanced economies, the energy transition is significantly more stable due to high levels of economic activity, superior social conditions, and advanced technological baselines (Li et al., 2023). In these contexts, renewable energy development acts as a robust driver of GTFP because the existing infrastructure can readily integrate decentralized energy sources without compromising industrial output. Furthermore, the high quality of innovation in developed regions allows for a more efficient "innovation compensation" effect, where the costs of energy shifts are quickly offset by gains in resource efficiency. This confirms that for mature economies, the energy transition is less of a disruptive shock and more of an evolutionary structural upgrade. Consequently, the correlation between renewable adoption and green growth in these nations is consistently positive and significant.

In contrast, emerging economies often face a "productivity paradox" where the push for a green transition does not immediately translate into efficiency gains. For these nations, environmental regulations have a more limited impact on agricultural and industrial green productivity when regional economic development levels are low (Sun, 2022). As these economies grow, the impact of regulation becomes more pronounced, but the initial phase is often characterized by high compliance costs and low technological return. The reliance on foreign direct investment (FDI) further complicates this dynamic; while FDI can provide capital, it requires strong domestic environmental regulations to prevent a "pollution haven" effect that could undermine GTFP (Qiu et al., 2021). Thus, for emerging markets, the energy transition is a high-stakes balancing act between maintaining rapid growth and building the necessary innovation capacity to sustain a low-carbon trajectory.

A critical structural difference lies in the spatial distribution of green innovation and its impact on regional productivity. In developing contexts, industrial green total factor productivity is highly sensitive to regional thresholds; for instance, clean technology innovation shows greater efficacy in central and western regions only after environmental regulation reaches a specific intensity (Sun et al., 2022). This suggests that the energy transition in emerging nations is not just a national challenge but a geographically fragmented one, where some regions leapfrog into green development while others remain trapped in carbon-intensive structures. This spatial heterogeneity highlights that the success of a zero-carbon pathway is predicated on the ability to synchronize regional policies with localized industrial strengths. Without this synchronization, the transition risks widening the productivity gap between advanced hubs and underdeveloped peripheries.

The findings from this comparative synthesis challenge the notion of a "one-size-fits-all" decarbonization strategy, extending prior research that highlighted regional variations in energy efficiency (Wang et al., 2021). By identifying the developmental thresholds required for a positive energy-GTFP link, the analysis refines our understanding of the "preconditions for success" in zero-carbon development. These findings confirm that emerging economies cannot simply replicate the trajectories of advanced nations without first addressing their specific innovation and regulatory bottlenecks. This critical interpretation explains why fragmented empirical findings exist in current literature: researchers are often measuring different stages of the same structural evolution.

Ultimately, this subsection contributes to filling the research gap regarding the lack of conditional interpretation by providing a clear distinction between the "innovation-led" transition of advanced economies and the "regulation-driven" transition of emerging ones. It demonstrates that the energy transition is a conditional process where the starting point—defined by economic maturity and infrastructure—dictates the available structural pathways. By documenting how regional development levels moderate the impact of both innovation and regulation (Sun, 2022; Lee et al., 2021), this study provides a more realistic framework for global policy alignment. This perspective is vital for ensuring that zero-carbon strategies are inclusive and account for the structural realities of the diverse global governance setting.

3.3 The Structural Mediation Chain: Integrating Energy Transition, Regulation, and Innovation

The theoretical coherence of a zero-carbon pathway depends on the successful integration of energy shifts, regulatory frameworks, and technological progress into a singular structural mechanism. Central to this integration is the role of innovation as a mediator that facilitates the transition from carbon-intensive production to green efficiency. This subsection employs the conceptual indicators of mediation and moderation to examine the "Energy Transition-Regulation-Innovation" chain, illustrating how these variables interact to drive Green Total Factor Productivity (GTFP). The analysis frames the energy transition not as an independent driver, but as a catalyst that triggers regulatory responses, which in turn necessitate innovation to maintain industrial competitiveness (Lee et al., 2021). By exploring this chain, the study addresses the gap regarding the lack of structural integration in current literature. This approach provides a holistic explanation for the systemic changes required to achieve zero-carbon development.

Empirical evidence confirms that green technology innovation acts as a critical bridge, allowing environmental regulations to effectively promote green total factor productivity. Specifically, research indicates that innovation capability plays a significant mediating role between environmental mandates and productivity growth, where regulations promote GTFP primarily by forcing firms to enhance their internal innovation levels (Lee et al., 2021). Without this mediating effect, the energy transition would likely manifest as a purely economic burden, as seen in sectors where technological adaptation lags behind regulatory stringency. Furthermore, the leading role of innovation in driving green growth is corroborated by findings that patent applications, particularly invention-based ones, are the primary engine for sustained productivity improvements (Liu et al., 2020). This structural chain demonstrates that a successful energy transition is inherently an innovation-driven process, where the quality of the technological response determines the overall economic outcome.

The relationship is further refined by specialized technological pathways that act as accelerators within the mediation chain. For instance, carbon capture, utilization, and storage (CCUS) technology innovation significantly improves GTFP by promoting both industrial structure upgrading and carbon emission efficiency (Dong et al., 2024). In this context, environmental regulation plays a positive moderating role, creating a policy environment where investments in specialized green technologies yield higher productivity returns. This synergy suggests that for high-emission industries, the mediation chain is most effective when it is supported by targeted technological interventions that address the specific limitations of renewable energy alone. The integration of CCUS into the structural model confirms that the pathway to zero-carbon development is multi-faceted, requiring a blend of energy substitution and advanced mitigation technologies.

Furthermore, the strength of the mediation chain is contingent upon the collaborative nature of the innovation ecosystem. Stronger network positions within a green innovation network have been shown to significantly enhance urban green productivity, particularly when amplified by supporting mechanisms like green finance (Jiao et al., 2025). This highlights that the "innovation" component of the chain is not merely a firm-level variable but a collective regional asset. In areas with dense innovation networks, the spillover effects of green technology are more pronounced, allowing the energy transition to catalyze growth across entire industrial clusters. Conversely, isolated firms or regions may find the mediation process more difficult, as they lack the collaborative resources necessary to offset the costs of regulatory compliance. This reinforces the principle that the structural pathway to sustainability is a networked phenomenon.

The findings presented here extend the theoretical understanding of the Porter Hypothesis by demonstrating that innovation is not just a possible outcome of regulation, but a necessary mediator for the energy transition's success. This study refines prior empirical models by documenting how the mediation effect varies according to the type of innovation and the stringency of the regulatory environment (Liu et al., 2020; Lee et al., 2021). By identifying CCUS as a specific moderating factor, the analysis challenges the idea of a generic transition pathway and highlights the importance of sector-specific innovation strategies (Dong et al., 2024). These contextual dynamics explain why some industrial sectors experience rapid green growth while others face stagnation despite identical regulatory pressures. The results clearly show that the "structural chain" is only as strong as its weakest link, which in many cases is the internal innovation capacity of the industrial base.

Ultimately, this subsection contributes to filling the research gap regarding the lack of structural integration by providing a unified model that connects the previously isolated variables of energy, regulation, and innovation. It addresses the fragmented findings in existing literature by showing that variations in GTFP results are often due to differences in how successfully this mediation chain is established. The analysis clarifies that a zero-carbon development strategy must simultaneously manage energy substitution, regulatory evolution, and innovation enhancement to be effective. By documenting the critical mediating role of innovation (Lee et al., 2021) and the moderating role of environmental policy (Dong et al., 2024), the study offers a comprehensive roadmap for achieving sustainable productivity. This integrated perspective is essential for moving the global energy discourse toward a more robust and theoretically sound framework for action.

3.3 Policy Synergy: Aligning Industrial Capacity with Decarbonization Targets

The theoretical efficacy of a zero-carbon pathway depends not only on the availability of technology or the stringency of regulation in isolation but on policy synchronization that aligns with domestic industrial capacity. A primary issue identified in the literature is the mismatch between ambitious emission targets and the readiness of infrastructure and human capital across various sectors (Chen et al., 2018). The theoretical approach in this subsection emphasizes the principle of "Policy Mix," where economic incentives and environmental mandates must work complementarily to prevent productivity declines. Without such alignment, the energy transition may instead become a cost burden that hinders global competitiveness, particularly for labor-intensive industries with low innovation flexibility (Yuan & Xiang, 2018). Consequently, policy synchronization acts as a key indicator in determining whether a nation can transcend the transition phase without experiencing economic stagnation.

Secondary data analysis indicates that the optimization of renewable energy only yields maximum impact when supported by massive infrastructure development and investment in human capital (Jiang et al., 2024). In many regions, failures to increase GTFP are often caused by policies that focus too heavily on upstream aspects (energy generation) without considering downstream efficiency at the industrial level. When environmental regulations are tightened without adequate green financing schemes, industries tend to experience efficiency drops due to limited funds for technological upgrades (Jiao et al., 2025). This synchronization is vital in a global context where supply chains are highly integrated; a single nation's policy that is misaligned with international standards can isolate its domestic industry from global green markets.

These findings further highlight that industrial intelligence and digitalization can mitigate the negative impacts of stringent regulation, yet this requires specific supporting policies (Xie et al., 2025). Effective policy synchronization involves the use of market instruments, such as carbon trading, which must be calibrated with the innovation levels of the manufacturing sector to avoid deindustrialization. Empirical evidence confirms that successful nations are those capable of aligning national innovation strategies with energy transition mandates, thereby creating an ecosystem that supports green productivity growth (Liu et al., 2020). This alignment ensures that every step toward zero-carbon is also a step toward strengthening the national economic structure.

Critically, these findings extend the discourse on the "Porter Hypothesis" by demonstrating that regulatory benefits do not occur automatically but are the result of policy designs responsive to market dynamics (Ma et al., 2022). This study challenges linear policy models that rely solely on regulatory coercion and instead proposes an adaptive model that prioritizes capacity readiness (Sun, 2022). Governance context dynamics show that synchronization between central and local governments is key to avoiding regulatory overlaps that often hinder clean technology investment. The primary contribution of this analysis is filling the gap regarding the importance of "structural synchronization" as a mandatory prerequisite before zero-carbon targets are established. In closing the discussion, the integration between energy transition, regulation, and innovation previously discussed will only reach its full potential through a coherent policy framework (Lee et al., 2021). This analysis successfully addresses the research questions regarding structural pathways by proving that GTFP is a result of systemic interaction, not merely an output of a single variable. By documenting the critical role of policy synchronization (Chen et al., 2018; Jiao et al., 2025), this research provides a robust foundation for designing more resilient sustainable development strategies. Zero-carbon development, therefore, must be understood as a comprehensive economic transformation process requiring total alignment between environmental ambition and productive capacity.

4. Conclusion

The comprehensive synthesis of the energy-productivity nexus reveals that the transition to a zero-carbon economy is not a linear substitution of energy sources but a complex structural transformation governed by institutional and technological thresholds. This research confirms that renewable energy optimization is a primary driver of Green Total Factor Productivity (GTFP), yet its efficacy is heavily mediated by green innovation and moderated by the stringency of environmental regulations. The analysis identifies a distinct "threshold effect" where environmental mandates transition from an initial cost burden to a catalyst for efficiency, provided that a robust innovation ecosystem is in place. Furthermore, the findings highlight a significant divergence between advanced and emerging economies, where the success of decarbonization is predicated on the alignment of infrastructure readiness and policy synchronicity. Ultimately, the study concludes that achieving sustainable productivity requires a holistic integration of energy, regulation, and innovation into a unified structural chain.

This study makes a significant contribution to the field of sustainable development by providing a theoretically grounded structural model that reconciles previously fragmented empirical findings. By moving beyond a binary "success or failure" evaluation of energy policies, the research identifies the specific socio-economic and institutional conditions under which energy transitions successfully translate into productivity gains. The integration of specialized pathways, such as CCUS technology and industrial intelligence, offers a refined understanding of how high-emission sectors can navigate decarbonization without compromising economic output. Methodologically, the use of a comparative thematic synthesis allows for a nuanced interpretation of the "Porter Hypothesis" across diverse developmental stages, offering a more realistic framework for global environmental governance. This research thus fills the theoretical gap regarding the universal applicability of green growth models in heterogeneous economic landscapes.

Despite the insights provided, future research should aim to address several emerging dimensions of the zero-carbon transition. Prospective studies could utilize longitudinal quantitative data to test the specific threshold values identified in this qualitative synthesis, particularly regarding the exact level of regulatory stringency required to trigger the "innovation compensation" effect in different industrial sectors. Additionally, there is a need for more granular investigations into the role of digital transformation and artificial intelligence as moderating variables in the green productivity chain. Research focusing on the social dimensions of the transition, such as labor market shifts and the "just transition" framework, would also provide a more holistic view of sustainable development. Finally, exploring the impact of international trade policies and global carbon border adjustments on domestic GTFP would offer valuable insights into the geopolitical challenges of achieving a coordinated global zero-carbon future.

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