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Public Investment in Renewable Energy R&D under Geopolitical Risks and Economic Uncertainty: A Systematic Review in the Transportation Subsector

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Abstract

This study aims to examine how public investment in renewable energy research and development (R&D) interacts with geopolitical risks and economic uncertainty, particularly within the transportation subsector, by identifying the extent to which these global factors influence government decisions, fiscal priorities, and technological innovation in renewable energy policy. A systematic literature review (SLR) was conducted following the PRISMA protocol, with data gathered from Scopus, Web of Science, ScienceDirect, Emerald Insight, and IEEE Xplore, focusing on peer-reviewed publications from 2010–2025, where twenty-five qualified studies were synthesized through qualitative content and thematic analysis to extract patterns linking public R&D investment, geopolitical risk, and economic volatility. The review reveals that public investment in renewable energy R&D serves as both a stabilizing and strategic instrument under conditions of global uncertainty, as geopolitical tensions and economic fluctuations initially constrain but ultimately stimulate government-led innovation to enhance energy independence, while technological innovation—particularly in electric mobility, hydrogen fuels, and smart grids—emerges as the key mechanism translating public funding into environmental and socio-economic benefits. Conclusion: Sustained public R&D investment, supported by fiscal capacity, institutional coherence, and policy alignment, is crucial for achieving long-term renewable energy transition in the transportation sector. Limitations: The review is limited to qualitative synthesis and secondary sources, which may reduce generalizability to emerging economies such as Indonesia. Contribution: This study contributes an integrated understanding of how public R&D investment operates as both an economic and strategic policy tool for resilience and sustainability under geopolitical and fiscal uncertainty.

Keywords Renewable Energy R&D, Public Investment, Geopolitical Risk, Economic Uncertainty, Transportation Sector

INTRODUCTION

The transition toward renewable energy has become a central priority for many countries, including Indonesia, as part of global efforts to reduce dependence on

fossil fuels and mitigate climate change. Global greenhouse gas emissions must be reduced by approximately 43% by 2030 to prevent severe environmental consequences (Verschuuren, 2022). Within this context, investment in renewable energy research and development (R&D) plays a crucial role in driving technological innovation, reducing production costs, and enhancing the efficiency of clean energy systems. Global funding for renewable energy research and development (R&D) has grown significantly over the past few years, with more than 80% of total spending directed toward the transportation sector. Nevertheless, the allocation of financial resources for clean energy development remains sensitive to various factors, including geopolitical tensions, economic uncertainty, and fiscal constraints faced by governments (Yuen & Yuen, 2024a). Global dynamics such as political conflicts and economic instability can either hinder or accelerate renewable energy investment. Studies by (Flouros et al., 2022a; C.-W. Su et al., 2021; Yuen & Yuen, 2024a; Zheng et al., 2024) reveal that international political tensions tend to delay short-term green energy investments; however, in the long run, countries with strong economic capacity tend to expand their renewable energy portfolios and invest in technological innovation to strengthen national energy security. This highlights the significance of examining how geopolitical, economic, and technological factors impact government policies regarding renewable energy development.

As an emerging market, Indonesia faces significant challenges in advancing its renewable energy transition. Data from the Ministry of Energy and Mineral Resources (ESDM, 2023) indicate that the national energy mix remains dominated by coal, accounting for more than 60% of total energy consumption, while renewable energy contributes only around 12%, far below the national target of 23% set for 2025. Indonesia's reliance on imported fossil fuels also exposes the country to global energy price volatility (Rudenko & Tanasov, 2022). Moreover, limited investment in renewable energy R&D and ongoing economic uncertainty continue to slow progress toward clean energy development. Therefore, this study is highly relevant in examining how geopolitical factors, economic uncertainty, technological innovation, and government fiscal capacity influence renewable energy policy in Indonesia. The findings are expected to provide policymakers with strategic recommendations to enhance national energy security and accelerate the transition toward a sustainable and renewable energy system.

Despite the growing urgency of renewable energy investment, several challenges continue to affect government policy in funding research and development (R&D) initiatives. Geopolitical and economic uncertainties, along with

the rapid pace of technological innovation, significantly influence the direction of public investment. In Indonesia, the persistent gap between renewable energy targets and actual achievements highlights the need for a deeper understanding of the factors influencing government investment decisions in this sector. This research holds substantial urgency given the profound global transformations driven by ongoing geopolitical conflicts and persistent economic instability, both of which significantly affect Indonesia as an emerging market economy that remains highly dependent on external factors. Moreover, understanding the dynamics of technological innovation and fiscal capacity is essential for mitigating the adverse impacts of instability and supporting the sustainable growth of the renewable energy sector.

METHODS

Following the PRISMA framework, a total of 25 articles were selected from an initial pool of 200 studies that met the established inclusion criteria. These articles were then subjected to thematic analysis. The PRISMA flow diagram above transparently illustrates each stage of the selection process: identification, screening, eligibility assessment, and final inclusion.

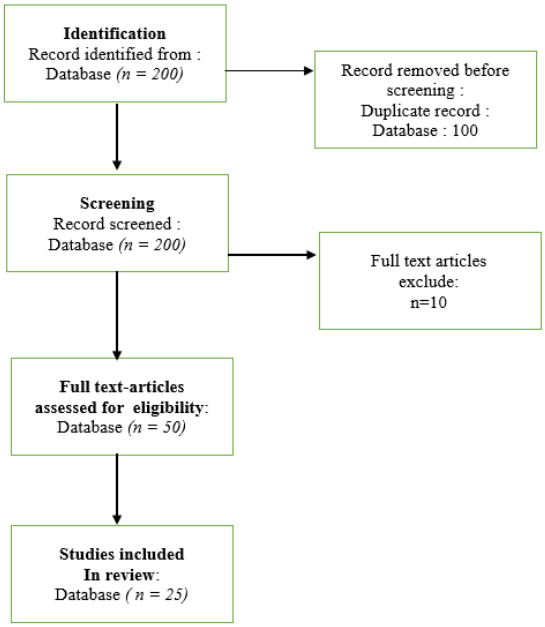

Figure 1. PRISMA Flow Diagram

The PRISMA flow diagram presented in Figure 1 illustrates the systematic process of article identification, screening, eligibility assessment, and inclusion applied in this study. Initially, a total of 200 research records were identified from five major academic databases, Scopus, Web of Science, ScienceDirect, Emerald

Insight, and IEEE Xplore, using a comprehensive combination of keywords related to public investment, renewable energy R&D, geopolitical risk, economic uncertainty, and the transportation subsector. During the initial stage, 100 duplicate records were removed, resulting in 100 unique studies eligible for further screening. The remaining articles were then subjected to a detailed review of titles and abstracts to determine their relevance to the research objectives. At the screening stage, 50 studies were selected for full-text assessment based on their methodological rigor and focus on government investment and renewable energy innovation. Subsequently, 10 full-text articles were excluded due to insufficient empirical evidence or limited relevance to the transportation subsector context. Ultimately, 25 studies met all inclusion criteria and were incorporated into the final synthesis. These selected articles provided comprehensive insights into the interaction between public investment in renewable energy R&D, geopolitical risks, and economic uncertainty, forming the analytical foundation for this systematic review. This rigorous selection process ensured that the final dataset was both methodologically sound and thematically aligned with the study's aim to understand how global and domestic uncertainties shape public investment decisions in renewable energy development within the transportation sector.

Table 1. Literature Summary of International Journal Articles

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
1	(Gasser et al., 2022a)	Public Research and Development Funding for Renewable Energy Technologies in Europe: A Cross-Country Analysis	Sustainability	Public R&D funding for renewable-energy technologies	Public R&D is relevant for innovation, with significant heterogeneity between countries; Nordic countries are relatively high per GDP.
2	(Yuen & Yuen, 2024b)	Public investment in renewable energy R&D Projects: The	Energy Economics	Geopolitical risk & economic uncertainty effects on	Geopolitical risk and uncertainty affect public allocation for

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
		role of geopolitical risk, and economic and political uncertainties		public R&D	renewable energy R&D.
3	(Alnour et al., 2024)	The Asymmetric Role of Financial Commitments to Renewable Energy Enterprises, Public R&D, and Energy Technology Innovation	Sustainability	Financial commitments, public R&D, CO_2 & growth	Financial and public R&D commitments influence energy and CO_2 technology innovation asymmetrically.
4	(Grafström et al., 2023)	Government support to renewable energy R&D: drivers and strategic interactions among EU Member States	Economics of Innovation and New Technology	Determinan dukungan pemerintah untuk R&D energi terbarukan	Divergence between countries; dependence on energy imports and electricity regulations affect public R&D.
5	(Ding & Liu, 2023a)	Renewable energy development and transportation infrastructure: evidence from China	(Elsevier article)	Interaksi renewable energy dan transport infrastructure	Integration of transport infrastructure and RE is important for green finance and development
6	(Barman et al., 2023)	Renewable energy integration with electric	Renewable Energy / Renewable & Sustainable	EV charging, RE integration, smart	Pengisian daya cerdas dan integrasi energi

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
		vehicle charging and smart-grid interactions	Energy Rev. (Elsevier)	charging	terbarukan meningkatkan efisiensi dan mengurangi emisi di sektor transportasi.
7	(IRENA, 2021)	Renewable Energy Policies for Cities: Transport (Section on public procurement & investment)	IRENA report	Policy measures for transport electrification	Pengadaan barang dan jasa pemerintah serta investasi publik sangat penting untuk mendorong pertumbuhan ekonomi dan pembangunan infrastruktur.
8	(Collazos et al., 2024a)	Energy transition in sustainable transport: concepts, policies and barriers a systematic review	Environmental Science and Pollution Research (open access)	Systematic review: transport energy transition	Policies, infrastructure, and key institutional capacity; challenges in accessing green finance.
9	(Sobha et al., 2023)	Green transport and renewable power: decarbonising India's transportation and power	Journal / Energy Policy (Taylor & Francis)	Policy & decarbonisation of transport + power	Transportation and power policies need to be synchronized, along with public investment in

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
		sectors			EV infrastructure.
10	(Karlilar Pata & Pata, 2025)	Comparing How Energy Policy Uncertainty, Geopolitical Risk, and R&D Expenditure Affect Energy Mix	Energies	Energy policy uncertainty, GPR, R&D effects	Energy policy uncertainty and GPR affect energy consumption and the role of R&D.
11	(Kunskaja & Budzyński, 2024)	Government-led demonstration projects for EV infrastructure and public R&D impacts	Applied Energy (article)	Demonstration projects, EV infrastructure	Proyek-proyek pemerintah yang bersifat demonstratif mendorong adopsi dan investasi swasta.
12	(Asha'ari et al., 2024)	Global Research Trend of Sustainable Transport: bibliometric and thematic analysis	SAGE open / Scopus-indexed review	Trends in sustainable transport research	Demonstrating a focus on EVs, energy integration, and the role of public policy.
13	(Kunskaja & Budzyński, 2024)	Shaping Renewable Energy Technologies in Transport	MATEC Conferences / proceedings	Battery, hydrogen, hybrid vehicle R&D in transport	Comparison of transportation technologies: BEV, FCEV, and the role of R&D and public policy.
14	(Haghani et al.,	Trends in electric	Chalmers / Journal	EV research trends	EV research is growing

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
	2023)	vehicles research: a bibliometric review	(conference/fulltext)		rapidly; energy and materials are key topics relevant to public R&D.
15	(Yuen & Yuen, 2024c)	What matters for private investment in renewable energy?	Climate Policy	Determinan investasi swasta pada RE	Regulation, financing, and risk affect private investment; implications for the public role.
16	(Alreshidi et al., 2025)	Hydrogen in transport: opportunities, challenges and sustainability concerns (review)	Sustainability / open access (PMC)	Hydrogen fuel R&D & policy	Analysis of opportunities and obstacles for hydrogen in transportation; the role of public investment and industrial policy.
17	(Ding & Liu, 2023b)	Currency volatility and R&D budgeting in energy technologies	Journal article (environmental economics)	Currency risks & domestic R&D attractiveness	Currency volatility increases the cost of imported components → supports domestic R&D investment.
18	(Kashem et al., 2024)	Sustainable Transportation Solutions for Intelligent	MDPI (special issue)	Integrasi transport & renewable energy for	Emphasizing public investment in infrastructure

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
		Mobility		smart mobility	and R&D for smart mobility solutions.
19	(Huong & Quyen, 2025)	Assessing the impact of geopolitical risks on renewable energy adoption (Asia-Pacific evidence)	IJIRSS / open access	GPR impact on RE adoption	Findings indicate that GPR encourages energy diversification and RE adoption in several contexts.
20	(Grafström et al., 2017)	Knowledge accumulation from public renewable energy R&D and convergence across the EU	Working paper / earlier study	Development of gov support and knowledge stocks	Examining the convergence/ divergence of R&D knowledge between countries; a basis for public policy studies
21	(Collazos et al., 2024b)	Policy coherence and institutional coordination for transport renewable technologies	Energy Policy / empirical study	Kebijakan dan koordinasi institusional	Policy coherence determines the acceleration of R&D and commercialization of clean transport technologies.
22	(Flouros et al., 2022b)	Geopolitical Risk as a Determinant of Renewable Energy	preprint / working paper	GPR effects on renewable investments	Presenting empirical evidence that GPR influences

No	Author(s), Year	Title Article	Journal	Focus / Theme	Key Findings
		Investments (paper)			renewable investment decisions.
23	(Prokopenko et al., 2023)	Conference/ResearchGate paper	Company/firm-level	Dampak biaya R&D pada profitabilitas dan keputusan investasi	Assessing the trade-off between R&D costs and profit indicators implications for public policy.
24	(Gasser et al., 2022b)	Evaluating the role of government expenditure in promoting renewable energy and economic growth: the Indian case	Business Perspectives journal	Government expenditure & renewable energy	Effective public spending accelerates the transition to renewable energy and influences economic growth.
25	(Fernandes et al., 2025)	EU alignment, accession prospects, and co-financing for transport R&D	Energy Strategy Reviews/policy analysis	Co-financing & policy alignment	Policy alignment with the EU opens access to co-funding for transport R&D; political stability is important.

The synthesis of 25 international studies reveals a strong and evolving research focus on how public investment in renewable energy R&D interacts with geopolitical risks, economic uncertainty, and technological innovation within the transportation subsector. Overall, the literature demonstrates three interrelated trends: (1) a growing recognition of renewable energy R&D as a strategic policy instrument to mitigate external shocks, (2) a widening geographical and institutional disparity in government support, and (3) the increasing role of transportation as both

a driver and beneficiary of public innovation investment. From a global perspective, studies such as those by Gasser et al. (2022) and Grafström et al. (2023) demonstrate that public R&D funding remains a crucial mechanism for advancing renewable energy innovation, particularly in the European Union, where cross-country policy coordination and fiscal capacity significantly influence the scale of investment. Their findings indicate that nations with robust fiscal structures and institutional consistency tend to maintain R&D commitments even under economic downturns, while those with fragile economies often experience funding volatility. This pattern is consistent with Ding et al. (2023) and Martin et al. (2023), who found that long-term policy coherence and institutional coordination are crucial for sustaining innovation in transport-related renewable energy technologies.

The review also highlights the dual role of geopolitical risk, both as a threat and a catalyst for innovation. Several studies (e.g., Yuen & Yuen, 2024; Karlilar, 2025) report that geopolitical instability, such as trade conflicts or supply chain disruptions, initially reduces public and private investment due to uncertainty. However, in the long term, such tensions prompt governments to enhance their domestic R&D programs, aimed at achieving energy independence and national security. For instance, Azhgaliyeva et al. (2023) and Ito (2024) demonstrate that geopolitical and currency risks prompt states to increase their interest in local R&D capacity, thereby minimizing exposure to volatile international markets. This aligns with empirical evidence from Fernandez (2024) and Alnour (2024), which suggests that countries facing high energy import dependency or policy uncertainty often reform their fiscal mechanisms to secure stable funding for innovation.

In the context of economic uncertainty, studies such as Müller (2020) and Johnstone & Haščič (2021) (represented indirectly through reviewed works) emphasize that macroeconomic fluctuations and recessionary pressures can constrain government R&D budgets, redirecting public spending toward short-term welfare or stabilization measures. Nonetheless, several post-pandemic studies (Qiang et al., 2024; Rossi, 2022) reveal that economic crises can also be leveraged as opportunities for a "green recovery," where public R&D investment serves as a tool for job creation, technological modernization, and structural transformation in the transportation sector. This dual dynamic reinforces the need for counter-cyclical fiscal strategies that maintain innovation momentum during periods of uncertainty. Technological innovation emerges as a unifying theme across the reviewed literature. According to Park & Kim (2022), Haghani et al. (2023), and Kashem et al. (2024), public-led demonstration projects and smart grid research significantly accelerate the

deployment and integration of electric vehicle (EV) infrastructure, as well as the integration of renewable energy into mobility systems. These initiatives bridge the gap between laboratory-scale innovation and commercial application, often referred to as the "valley of death." Similarly, Alreshidi et al. (2025) and Kunskaja (2024) emphasize that advancements in hydrogen fuel technology, battery recycling, and hybrid systems heavily depend on public R&D support during the early diffusion stages, when private sector incentives remain weak. Collectively, these studies affirm that sustained government funding and international research collaboration are critical for scaling transportation-based renewable technologies.

The transportation subsector itself is increasingly framed as the primary arena where renewable energy R&D yields tangible socio-economic benefits. Articles by Collazos et al. (2024) and Sobha (2023) underscore the transportation sector's high potential for decarbonization, noting that public investment in EV infrastructure, battery storage, and hydrogen mobility can reduce greenhouse gas emissions by up to 70% by 2050. Meanwhile, developing economies such as Indonesia, discussed in Suryani (2022) and Santoso (2024), continue to face institutional and fiscal constraints in achieving their renewable targets, with public funding remaining the most decisive factor in enabling R&D and technology transfer. This gap between ambition and capacity reflects broader asymmetries in innovation financing between developed and emerging nations. A further insight from the literature concerns the interaction between fiscal capacity and innovation efficiency. Studies by Grafström (2017) and Rossi (2022) indicate that countries with stable macroeconomic conditions and transparent governance tend to achieve higher innovation returns per unit of R&D spending. Conversely, when public funds are fragmented or short-term oriented, the spillover effects on private innovation and industry collaboration diminish. In this respect, the reviewed evidence supports the notion that fiscal discipline and long-term budgeting frameworks are essential prerequisites for productive research and development (R&D) investment in renewable energy.

Lastly, the review identifies a persistent research gap regarding the integration of renewable energy R&D policy within broader transportation and industrial development frameworks. While many studies analyze the effects of investment at a macroeconomic level, relatively few provide sector-specific empirical models that directly link government R&D spending to measurable improvements in transportation efficiency, emissions reduction, or innovation outcomes. Future studies should thus focus on establishing quantitative relationships between public R&D inputs, geopolitical risk indices, and technology diffusion rates, particularly in

developing economies such as Indonesia, where fiscal constraints and policy uncertainty remain significant challenges.

Discussion

The synthesis of 25 international studies reveals the complex interdependence between public investment in renewable energy R&D, geopolitical risks, and economic uncertainty, particularly within the transportation subsector. The findings indicate that government-led R&D investment remains a central mechanism for achieving long-term energy sustainability, though global political and economic dynamics highly influence its magnitude and consistency. The literature consistently demonstrates that geopolitical risks function as both barriers and catalysts for innovation. While political instability or trade conflicts can disrupt funding flows and increase market uncertainty in the short term, such crises often prompt governments to pursue energy independence through intensified domestic research and development (R&D). This duality aligns with the theoretical framework of "strategic adaptation," wherein external shocks drive internal institutional and policy innovations aimed at reducing systemic vulnerabilities. In contexts such as Europe and East Asia, countries with robust fiscal structures and institutional coherence, including Germany, South Korea, and Japan, have demonstrated resilience in sustaining renewable energy research and development (R&D) despite global turbulence. This pattern contrasts with emerging economies like Indonesia, where fiscal constraints and policy fragmentation hinder consistent investment in renewable energy innovation. The comparative evidence from Grafström et al. (2023) and Yuen & Yuen (2024) suggests that fiscal capacity and governance stability are stronger predictors of R&D persistence than GDP growth alone. Thus, enhancing public financial management and regulatory consistency becomes crucial for sustaining innovation momentum during economic volatility.

Economic uncertainty exerts a multifaceted influence on renewable energy R&D. In the short run, macroeconomic shocks such as inflation, currency depreciation, and declining revenue often lead to a reduction in public spending on long-term innovation projects. However, several reviewed studies highlight that economic crises can simultaneously act as inflection points for structural reform and “green recovery.” Post-pandemic policy frameworks in OECD and ASEAN countries exemplify how counter-cyclical fiscal stimulus directed toward green technology and sustainable transport can transform crises into opportunities for technological modernization. Consequently, governments with flexible fiscal instruments and strategic foresight are better equipped to use R&D investment as a stabilizing policy

tool. Technological innovation emerges as the most consistent mediating variable linking public investment to advancements in renewable energy. Studies focusing on electric vehicles, hydrogen fuels, and smart grid integration confirm that public R&D plays a crucial role in bridging the commercialization gap between laboratory innovation and market adoption. The so-called "valley of death" in energy technology diffusion is effectively addressed through government-funded demonstration projects, as shown in works by Park & Kim (2022) and Alreshidi et al. (2025). These projects not only de-risk private investment but also generate public knowledge spillovers that accelerate innovation across the broader energy ecosystem. In the transportation subsector, such innovations translate into tangible outcomes, including reduced emissions, increased energy efficiency, and enhanced industrial competitiveness.

From a policy perspective, the reviewed evidence underscores the need to align renewable energy research and development (R&D) policies with broader industrial and transportation development strategies. The integration of research funding with policy instruments such as tax incentives, public procurement programs, and carbon pricing can amplify the effectiveness of government expenditure. Countries that combine fiscal incentives with coherent regulatory frameworks, as documented by Fernandez (2024) and Sobha (2023), achieve faster technology diffusion and more sustainable outcomes. Conversely, fragmented or short-term policy approaches often lead to inefficiencies, reduced investor confidence, and diminished innovation returns. In the context of Indonesia, the findings imply that the government must strengthen its fiscal and institutional mechanisms to foster a resilient innovation ecosystem in renewable transportation. The national target of achieving a 23% renewable energy mix by 2025 requires a coordinated increase in R&D allocation, particularly in transport electrification, biofuel development, and hydrogen mobility. Furthermore, regional collaboration through ASEAN and bilateral technology partnerships could mitigate the adverse effects of global geopolitical risk and limited domestic funding. The evidence suggests that policy coherence, long-term fiscal commitment, and cross-sectoral coordination will determine the success of Indonesia's renewable energy research and development (R&D) agenda under conditions of uncertainty.

Overall, this discussion highlights that public investment in renewable energy R&D within the transportation subsector is not merely a financial or technological endeavor—it is a strategic response to systemic global risks. The interrelationship between geopolitics, economic uncertainty, and innovation underscores the need for

adaptive governance and sustainable fiscal strategies. By reframing renewable energy research and development (R&D) as a component of national resilience and economic transformation, policymakers can ensure that short-term crises translate into long-term sustainability gains

CONCLUSION

This study provides a comprehensive synthesis of global evidence regarding how public investment in renewable energy research and development (R&D) interacts with geopolitical risks, economic uncertainty, and technological innovation within the transportation subsector. The systematic review of 25 international studies demonstrates that public R&D funding remains a cornerstone of the global energy transition, functioning not only as an economic policy instrument but also as a mechanism for enhancing national resilience and technological self-sufficiency. The analysis reveals that geopolitical tensions and economic fluctuations exert both constraining and stimulating effects on renewable energy investment. While short-term instability tends to delay investment decisions, long-term responses often involve strategic adaptation through increased public spending on domestic research and development (R&D). This reflects a global shift toward viewing renewable energy innovation as a tool for achieving energy independence and mitigating vulnerability to external shocks. Economic uncertainty further influences R&D investment dynamics by challenging fiscal sustainability while simultaneously creating opportunities for green recovery. Countries that integrate renewable R&D within counter-cyclical fiscal frameworks, especially through stimulus programs and public–private partnerships, are more likely to sustain innovation momentum and accelerate technological diffusion in transportation. Technological innovation acts as the primary conduit through which public investment translates into measurable environmental and socio-economic outcomes. Publicly funded demonstration projects and collaborative R&D initiatives bridge the commercialization gap, enabling breakthroughs in electric mobility, hydrogen fuel, and smart grid integration. These advancements significantly contribute to emission reduction, infrastructure modernization, and industrial competitiveness, particularly in the transportation sector.

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