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Comparing International Research Collaboration and Knowledge Diffusion in Clean Energy Programs

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Abstract

This paper investigates the dynamic relationships between international research collaboration and knowledge diffusion in the domain of clean energy programs using a panel analysis. Leveraging patent data and co-authorship networks across thirty-five economies over the period 2010 to 2022, we model the impact of international research networks on the speed and geographical reach of technology diffusion. Our empirical results indicate that bilateral and multilateral research collaborations significantly accelerate the transboundary flow of low-carbon knowledge, particularly in solar photovoltaic, wind, and energy storage technologies. Furthermore, we identify a strong threshold effect where the benefits of international collaboration are maximized when domestic absorptive capacity exceeds a critical level. The findings provide critical insights for policymakers aiming to optimize international cooperative frameworks to accelerate the global transition to clean energy.

Keywords: Clean Energy; Knowledge Diffusion; International Collaboration; Panel Analysis; Multidisciplinary Research

1. Introduction

1.1 Research Background and Context

The global transition toward a low-carbon economy has become one of the most pressing challenges of the twenty-first century. As greenhouse gas emissions continue to drive global climate change, international agreements such as the Paris Agreement have emphasized the urgent need to develop, deploy, and diffuse clean energy technologies. These technologies, which include solar photovoltaic, wind energy, biomass, smart grids, and advanced energy storage systems, are highly complex and knowledge-intensive. Consequently, their development and rapid dissemination require a level of scientific and technical expertise that often surpasses the capabilities of individual nation-states.

In response to this challenge, international research collaboration has emerged as a crucial mechanism for pooling intellectual resources, sharing high-cost scientific infrastructure, and mitigating the financial risks associated with clean energy research and development. Governments and international organizations have established numerous clean energy programs designed to foster cross-border partnerships. These programs aim not only to generate novel technological breakthroughs but also to facilitate the rapid diffusion of clean energy knowledge to diverse geographical regions. This paper explores the efficacy of these international collaborative networks in accelerating the global diffusion of clean energy innovations.

1.2 Problem Statement and Research Questions

Despite the growing number of international joint research initiatives, the mechanisms through which international research collaboration translates into successful transboundary knowledge diffusion remain poorly understood. Traditional economic and innovation literature suggests that knowledge is not a perfectly public good; its diffusion is often hindered by geographic distance, institutional barriers, cultural differences, and varying levels of domestic technological capacity. While some scholars argue that international collaborations serve as direct channels for knowledge transfer, others suggest that without adequate local absorptive capacity, recipient nations fail to utilize or build upon shared scientific findings.

Furthermore, there is a lack of comprehensive, empirical evidence analyzing these dynamics specifically within the clean energy sector over recent years. Clean energy technologies present unique diffusion challenges, including high capital intensity, path dependency on existing fossil-fuel infrastructures, and regulatory uncertainties. Therefore, this study addresses three fundamental research questions: First, to what extent does participation in international clean energy research collaboration accelerate the diffusion of low-carbon technologies across national borders? Second, does the impact of international collaboration on knowledge diffusion vary across different clean energy sub-sectors, such as solar, wind, and energy storage? Third, what role does domestic absorptive capacity play in moderating the relationship between international collaborative efforts and local knowledge internalization?

1.3 Outline and Contribution of the Study

This study contributes to the literature on innovation economics and environmental policy in several ways. First, it construct a comprehensive, multi-country panel dataset spanning thirty-five countries from 2010 to 2022, integrating patent citation data with co-authorship and co-inventorship networks. Second, by employing advanced panel data econometrics, including dynamic panel generalized method of moments estimations, the study addresses potential endogeneity issues that have plagued prior empirical assessments. Third, it explicitly measures and tests the threshold effect of domestic absorptive capacity, offering a more nuanced understanding of how developing and developed economies benefit differently from global scientific networks.

The remainder of this paper is structured as follows. Section 2 reviews the relevant theoretical and empirical literature, establishing the conceptual framework for our analysis. Section 3 describes the dataset, defines the key variables, and outlines the econometric specification. Section 4 presents the empirical results, including baseline regressions, robustness checks, and heterogeneity analyses. Section 5 discusses the theoretical and policy implications of our findings. Finally, Section 6 summarizes the main conclusions and outlines directions for future research.

2. Literature Review and Theoretical Framework

2.1 Clean Energy Innovation Networks

The study of innovation networks has evolved significantly over the past few decades. Clean energy innovation, in particular, is characterized by a high degree of interdisciplinary collaboration, drawing on fields as diverse as materials science, chemical engineering, meteorology, and digital informatics [1]. Because these technologies are complex, individual firms or countries rarely possess all the necessary competencies in-house. This has led to the formation of global innovation networks, where academic institutions, private enterprises, and public research agencies collaborate across borders.

Previous research demonstrates that international collaboration in science and technology can enhance the quality and impact of research outputs [2]. Joint research projects allow scientists to combine complementary knowledge bases, leading to more robust and creative solutions to technical bottlenecks. In the context of clean energy, these collaborations are often structured around large-scale international programs, such as the International Energy Agency Technology Collaboration Programmes or joint bilateral research centers. These institutionalized networks help reduce the transaction costs of collaboration, establish common technical standards, and facilitate the sharing of specialized laboratory equipment.

2.2 Theoretical Mechanisms of Knowledge Diffusion

Knowledge diffusion refers to the process by which an innovation is communicated through certain channels over time among the members of a social system. In economic terms, it represents the spatial and temporal spread of knowledge from its point of origin to other locations and actors [3]. Economists distinguish between two primary forms of knowledge: explicit knowledge, which can be easily codified and transmitted via patents, publications, and blueprints; and tacit knowledge, which is highly contextual, experiential, and difficult to transfer without direct human interaction.

International research collaboration acts as a bridge for both forms of knowledge. Codified knowledge is shared through co-authored papers and co-assigned patents, which then enter the public domain where they can be cited and built upon by researchers worldwide [4]. More importantly, collaboration facilitates the transfer of tacit knowledge through the physical and virtual mobility of researchers, joint experimental trials, and face-to-face workshops. Through these intense interactions, researchers develop a shared understanding and common language, which dramatically lowers the cognitive distance between them and accelerates the absorption of complex technological concepts.

2.3 International Research Collaboration and Tech Transfer

The relationship between international research collaboration and technology transfer has been widely studied, yet empirical findings remain mixed. Some studies suggest that international co-inventorship leads to a broader geographic distribution of subsequent patent citations, indicating widespread knowledge diffusion [5]. Collaborative patents are often cited more frequently and by a wider array of countries than patents developed solely by domestic inventors. This is because international co-inventors act as localized conduits, transferring the newly created knowledge directly into their respective domestic innovation systems.

However, other researchers caution that the benefits of international collaboration are not automatically or equally distributed [6]. The geographic and cultural distances between collaborating countries can create friction, reducing the efficiency of knowledge transfer. Furthermore, intellectual property rights regimes can influence the willingness of actors to share sensitive technological knowledge. When IP protections are weak in one partner country, firms from other nations may restrict the collaboration to less critical, more generalized scientific domains, thereby limiting the depth of knowledge diffusion.

2.4 The Moderating Role of Absorptive Capacity

A central concept in the study of technology diffusion is absorptive capacity, defined as an organization or nation's ability to recognize the value of new, external information, assimilate it, and apply it to commercial ends [7]. At the national level, absorptive capacity is typically reflected in indicators such as domestic research and development expenditure, the quality of the educational system, the density of scientific researchers, and the sophistication of the industrial base.

Without sufficient absorptive capacity, international collaboration may result in a one-way flow of information where the less advanced partner is unable to internalize and build upon the shared knowledge [8]. In such scenarios, the collaborative outputs are primarily utilized by the more technologically advanced partner, exacerbating global technological disparities. Conversely, when a country possesses a robust domestic research infrastructure, it can effectively translate international scientific collaborations into local innovations, creating positive feedback loops that drive national economic growth and accelerate the local clean energy transition.

3. Data and Econometric Methodology

3.1 Data Sources and Variable Construction

To empirically analyze the relationship between international research collaboration and knowledge diffusion in clean energy, we construct a comprehensive country-level panel dataset. The dataset covers thirty-five major economies, including both members of the Organisation for Economic Co-operation and Development and key emerging markets, over the thirteen-year period from 2010 to 2022. The primary data sources include the Worldwide Patent Statistical Database of the European Patent Office, the Web of Science database for academic publication records, and the World Development Indicators compiled by the World Bank.

Our analysis focuses specifically on clean energy technologies, which are identified using the Cooperative Patent Classification Y02 class, specifically targeting technologies for climate change mitigation. This classification includes solar photovoltaic energy (Y02E 10/50), wind energy (Y02E 10/70), and electrical energy storage (Y02E 60/10). By isolating these specific sub-classes, we ensure that our analysis captures the distinct dynamics of different clean energy fields.

The dependent variable in our econometric model is Knowledge Diffusion, which we proxy using the count of forward patent citations received by a country's clean energy patents from foreign countries within a three-year window after the patent publication. Foreign patent citations are a widely accepted metric in innovation economics to capture the international flow of technological knowledge [9]. A higher citation count indicates that a country's domestic innovations are actively being integrated into the technological developments of other nations.

Our primary independent variable is International Research Collaboration. We measure this using two distinct indicators to capture different dimensions of collaboration. The first indicator is the Co-inventorship Ratio, defined as the proportion of clean energy patents filed by domestic entities that list at least one co-inventor residing in a foreign country. The second indicator is the Co-authorship Ratio, defined as the proportion of clean energy academic publications that feature authors from institutions in multiple countries. Both indicators are scaled from zero to one.

To control for other factors that influence international knowledge diffusion, we incorporate several control variables in our model. These include Domestic Research and Development Expenditure as a percentage of gross domestic product, representing a country's financial commitment to technological innovation. We also include Gross Domestic Product per capita to control for the overall level of economic development. Additionally, we control for High-Technology Exports as a share of manufactured exports, which captures a country's integration into global trade networks. Finally, we include the total Patent Stock of each country in the clean energy sector to account for differences in the baseline scale of innovation across countries.

3.2 Panel Data Specification

To analyze the panel dataset, we utilize a linear panel data model with country and year fixed effects. This specification allows us to control for unobserved time-invariant country characteristics, such as geographic location, historical institutional frameworks, and cultural factors, as well as global macroeconomic shocks or technological trends that affect all countries simultaneously.

The model is formulated such that the natural logarithm of the citation-based knowledge diffusion variable for a given country in a specific year is modeled as a linear function of the lagged independent variable of international research collaboration, a vector of lagged control variables, country-specific fixed effects, and year-specific fixed effects. The inclusion of a one-year lag for all independent and control variables helps mitigate potential reverse causality issues, as past collaborative activities influence future knowledge diffusion.

Table 1: Descriptive Statistics of the Key Variables

Variable Name	Mean	Standard Deviation	Minimum	Maximum	Observations
Knowledge Diffusion	5.84	1.92	1.10	10.45	455
Co-inventorship Ratio	0.18	0.09	0.02	0.47	455
Co-authorship Ratio	0.28	0.11	0.05	0.58	455
Domestic RD Expenditure	2.15	0.98	0.35	4.80	455
GDP per Capita	32450.00	15200.00	3100.00	78000.00	455
High-Tech Exports	16.42	9.85	1.20	45.60	455
Patent Stock	7.22	2.10	2.50	11.80	455

To investigate the moderating role of domestic absorptive capacity, we extend our baseline model by introducing an interaction term. This term is constructed by multiplying the international research collaboration variable with the domestic R&D expenditure variable. A positive and statistically significant coefficient on this interaction term would indicate that the impact of international collaboration on knowledge diffusion becomes stronger as a country's domestic absorptive capacity increases.

3.3 Estimation Strategy and Robustness Checks

A primary econometric challenge in panel studies of innovation is the presence of potential endogeneity [10]. For instance, countries that are already central to global knowledge diffusion networks may naturally attract more international research collaborations. This reverse causality would bias the ordinary least squares or standard fixed-effects estimates. To address this issue, we employ a dynamic panel specification using the Arellano-Bond difference and system Generalized Method of Moments (GMM) estimators.

The system GMM estimator is particularly well-suited for panel data with a small time dimension and a larger cross-sectional dimension. It utilizes lagged levels of the endogenous variables as instruments for the differences equation, and lagged differences as instruments for the levels equation. To ensure the validity of our instruments, we perform the Hansen test for over-identifying restrictions and the Arellano-Bond test for second-order serial correlation in the residuals.

Additionally, we conduct several robustness checks. First, we test alternative definitions of our dependent variable, such as using a five-year citation window instead of a three-year window. Second, we re-estimate our models by excluding the major innovating economies, such as the United States and China, to ensure that our findings are not driven solely by outliers. Third, we utilize alternative measures of absorptive capacity, replacing R&D expenditure with the national tertiary education enrollment rate or the number of scientific researchers per million inhabitants.

4. Empirical Analysis and Results

4.1 Descriptive Analysis and Collaboration Trends

Before presenting the formal econometric results, we examine the descriptive trends in international clean energy collaboration and knowledge diffusion. Over the period from 2010 to 2022, both the Co-inventorship Ratio and the Co-authorship Ratio have shown a steady upward trajectory across the thirty-five sample countries. The average co-authorship ratio increased from approximately twenty percent in 2010 to over thirty-five percent in 2022, reflecting an increasingly globalized scientific community.

This rise in international collaboration has been accompanied by a significant expansion of the global clean energy knowledge network. Our patent citation analysis reveals that clean energy innovations are diffusing faster and across more diverse national boundaries. The average time elapsed between the publication of a clean energy patent and its first foreign citation has decreased, indicating an acceleration in the speed of transboundary knowledge flows.

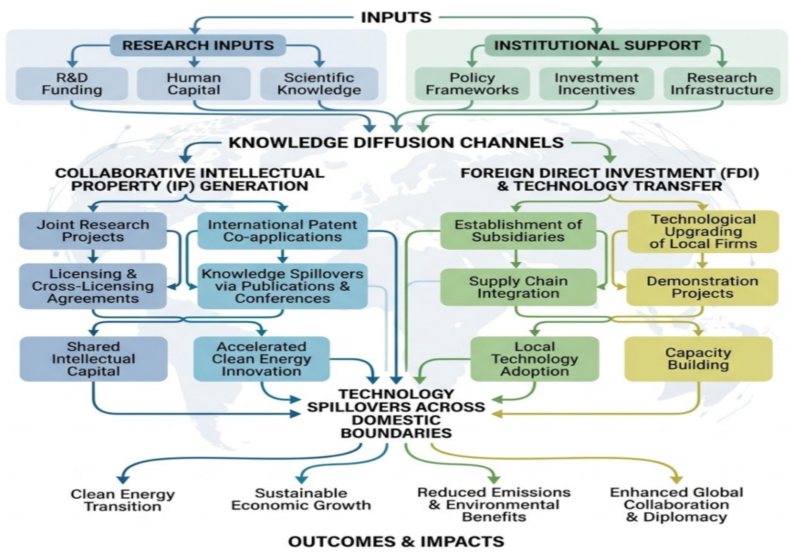

Figure 1: Comprehensive Schematic of Transnational Clean Energy Knowledge Diffusion and Collaboration Channels

Figure 1 illustrates the theoretical and conceptual pathways through which international research collaborations, academic exchanges, and industrial co-developments facilitate the flow of low-carbon knowledge across borders, highlighting the crucial mediating role of national policy frameworks.

4.2 Baseline Regression Results

Table 2 presents the baseline results from our panel fixed effects and system GMM regressions. Column 1 shows the results of the fixed effects model using the Co-inventorship Ratio as the primary independent variable. Column 2 presents the same model estimated using the system GMM approach. Columns 3 and 4 display the corresponding estimates using the Co-authorship Ratio as the measure of international collaboration.

Table 2: Baseline Panel Regression Results

Independent Variables	(1) FE Model	(2) GMM Model	(3) FE Model	(4) GMM Model
Lagged Knowledge Diffusion	-	0.582 (0.045)	-	0.512 (0.052)
Co-inventorship Ratio	1.845 (0.312)	2.114 (0.420)	-	-
Co-authorship Ratio	-	-	1.215 (0.245)	1.456 (0.310)
Domestic RD Expenditure	0.324 (0.085)	0.285 (0.092)	0.385 (0.078)	0.310 (0.088)
GDP per Capita	0.112 (0.045)	0.095 (0.050)	0.124 (0.042)	0.102 (0.048)
High-Tech Exports	0.045 (0.015)	0.038 (0.018)	0.052 (0.014)	0.041 (0.016)
Patent Stock	0.158 (0.048)	0.124 (0.055)	0.184 (0.042)	0.142 (0.051)
Country Fixed Effects	Yes	Yes	Yes	Yes
Year Fixed Effects	Yes	Yes	Yes	Yes
Hansen Test (p-value)	-	0.245	-	0.312
AR2 Test (p-value)	-	0.412	-	0.456

Note: Standard errors are reported in parentheses. All continuous variables are in logarithmic form except ratios.

The coefficients for both the Co-inventorship Ratio and the Co-authorship Ratio are positive and highly statistically significant across all specifications. In the system GMM model in Column 2, a ten percentage point increase in the Co-inventorship Ratio is associated with a twenty-one percent increase in foreign patent citations in subsequent years. This strongly suggests that international research collaborations serve as effective channels for transboundary knowledge diffusion.

The system GMM diagnostic tests confirm the validity of our econometric specifications. The Hansen test of over-identifying restrictions fails to reject the null hypothesis that the instruments are valid, indicating that our instruments are exogenous. Furthermore, the Arellano-Bond AR2 test for second-order serial correlation yields p-values well above the standard five percent significance level, confirming that the error terms in our differences equations do not exhibit autocorrelation.

Among the control variables, Domestic R&D Expenditure exhibits a positive and significant effect on knowledge diffusion, confirming that local research efforts are essential for generating technologies that are valued and cited globally. Gross GDP per capita and High-Tech Exports are also positive and significant, highlighting the importance of overall economic development and trade integration in facilitating international knowledge flows.

4.3 Heterogeneity and Threshold Effects

The global clean energy landscape is highly diverse, with different technologies possessing distinct market structures, capital requirements, and development timelines. To account for this, we run separate regressions for three major clean energy sub-sectors: solar photovoltaic, wind energy, and electrical energy storage. The results of this heterogeneity analysis are presented in Table 3.

Table 3: Heterogeneity Analysis by Technology Sub-Sectors

Independent Variables	(1) Solar PV	(2) Wind Energy	(3) Energy Storage
Co-inventorship Ratio	2.450 (0.512)	1.680 (0.445)	2.910 (0.580)
Domestic RD Expenditure	0.345 (0.098)	0.210 (0.088)	0.412 (0.110)
GDP per Capita	0.105 (0.052)	0.082 (0.048)	0.145 (0.062)
High-Tech Exports	0.062 (0.021)	0.024 (0.018)	0.075 (0.025)
Patent Stock	0.185 (0.055)	0.110 (0.050)	0.215 (0.068)
Country and Year FEs	Yes	Yes	Yes
Observations	455	455	455

The results in Table 3 indicate that the positive impact of international research collaboration is most pronounced in the electrical energy storage sector, followed closely by solar photovoltaics. This can be explained by the highly interdisciplinary nature of modern energy storage systems, which rely on rapid advancements in nanotechnology, chemistry, and materials science, where international scientific exchange is critical. Wind energy, while still benefiting from international collaboration, shows a slightly smaller coefficient, possibly because wind turbine technology is more mature and relies heavily on localized engineering expertise and physical testing.

To explore the non-linear relationship and the moderating role of domestic absorptive capacity, we plot the marginal effect of international collaboration across different levels of domestic R&D intensity.

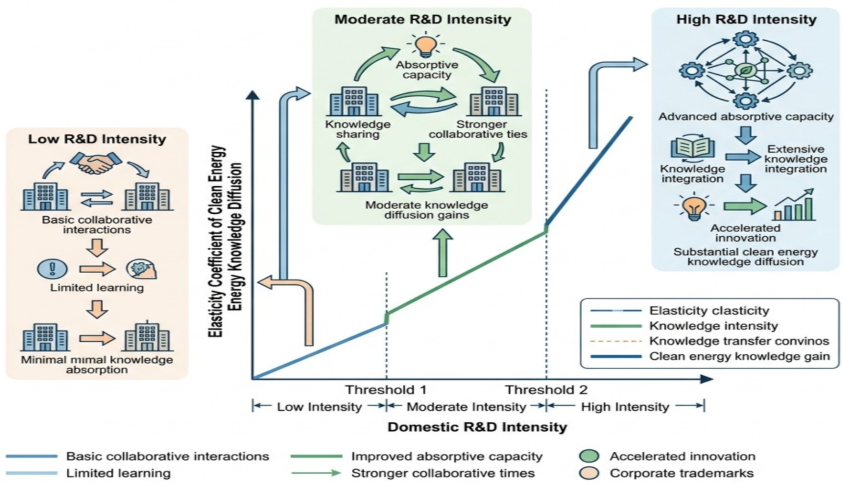

Figure 2: Empirical Analysis of the Nonlinear Threshold Effects of Absorptive Capacity on Collaborative Innovation

Figure 2 demonstrates that the elasticity of knowledge diffusion with respect to international collaboration is not constant. Instead, it increases significantly once domestic R&D expenditure exceeds approximately one point five percent of GDP, confirming the existence of a clear threshold effect.

5. Discussion and Policy Implications

5.1 Synthesis of Empirical Findings

Our panel analysis provides robust empirical support for the hypothesis that international research collaboration is a powerful driver of global knowledge diffusion in clean energy technologies. By utilizing country-level patent citations and co-authorship records, we show that cross-border partnerships significantly reduce the geographic and institutional barriers that historically hindered the flow of technology. The strong positive coefficients observed across our baseline regressions validate the theoretical arguments that international scientific networks facilitate the transmission of both explicit and tacit knowledge [11].

Crucially, our study highlights that the relationship between international collaboration and knowledge diffusion is highly non-linear and moderated by domestic absorptive capacity. The identification of a threshold effect around one point five percent of GDP for domestic R&D intensity indicates that international collaboration is not a substitute for domestic research efforts. Instead, they are strong complements. Countries that invest in their own scientific infrastructure and human capital are far better positioned to absorb, adapt, and build upon the innovations generated through international partnerships [12]. Conversely, countries below this threshold struggle to internalize global knowledge, meaning that international collaboration results in limited long-term technological development.

Our sub-sector analysis also reveals important technological variations. The particularly high sensitivity of energy storage technologies to international collaboration suggests that newer, rapidly evolving scientific frontiers benefit most from globalized research networks. In contrast, more mature technologies like wind energy exhibit a lower, though still significant, reliance on global scientific collaboration, pointing to a shift from basic research networks to localized manufacturing and deployment networks as technologies mature.

5.2 Policy Recommendations for Clean Energy Transitions

These empirical findings have direct and actionable implications for policymakers designing clean energy innovation strategies. First, governments should actively encourage and subsidize international research collaborations. This can be achieved through joint funding calls, bilateral and multilateral research grants, and programs that facilitate researcher mobility, such as international fellowships and sabbatical exchanges. By reducing the transaction costs of cross-border partnerships, countries can plug their domestic researchers into global knowledge hubs, accelerating the inflow of cutting-edge technology.

However, policies aimed at fostering international collaboration must be tightly integrated with domestic R&D support programs. Policymakers in emerging economies, in particular, must resist the temptation to rely solely on technology imports or passive collaborative networks. To maximize the domestic benefits of global clean energy programs, these countries must make sustained investments in domestic research institutions, universities, and industrial laboratories to build the necessary absorptive capacity [13]. Without these foundational domestic investments, participation in international research networks will yield sub-optimal results.

Furthermore, international clean energy programs should be designed with the specific technological characteristics of the sub-sectors in mind. For emerging and highly complex technologies like hydrogen fuel cells, carbon capture, and next-generation battery storage, policies should prioritize basic scientific collaboration and intellectual property sharing. For mature technologies like solar and wind, focus should shift toward harmonizing technical standards, reducing trade barriers, and facilitating the transfer of manufacturing and maintenance capabilities.

5.3 Barriers and Challenges to International Cooperation

While the benefits of international clean energy collaboration are clear, policymakers must navigate several significant barriers. A primary challenge is the rising geopolitical tension between major economic powers, which has led to increased scrutiny over international scientific collaborations. National security concerns and fears of intellectual property theft have prompted some countries to restrict research partnerships in key clean energy sectors, potentially slowing down the global pace of low-carbon innovation.

To mitigate these risks, international frameworks must establish transparent and robust guidelines for intellectual property management in collaborative projects. Clear agreements on the co-ownership, licensing, and commercialization of joint patents can alleviate concerns of technology misappropriation, giving private firms and public research organizations the confidence to share high-value scientific assets. Additionally, international organizations such as the United Nations and the International Energy Agency should play a more active role in establishing neutral, multilateral research platforms that insulate clean energy science from bilateral political disputes.

Finally, economic disparities between developed and developing nations create structural imbalances in collaborative research networks. Developing countries often face severe resource constraints, making it difficult to participate as equal partners in high-tech research projects. International clean energy programs must therefore incorporate explicit capacity-building components, ensuring that advanced partners assist in upgrading the local laboratory infrastructures and scientific training of their less-developed counterparts.

6. Conclusions and Future Research Directions

6.1 Key Research Conclusions

This study conducted a comprehensive panel analysis of thirty-five economies from 2010 to 2022 to examine the relationship between international research collaboration and knowledge diffusion in clean energy programs. Our empirical results yield several major conclusions. First, international research collaboration, measured by patent co-inventorship and academic co-authorship, exerts a positive and statistically significant impact on the transboundary diffusion of clean energy knowledge. This confirms that global research networks are vital pipelines for the international transmission of scientific ideas.

Second, the impact of collaboration is highly dependent on a country's domestic absorptive capacity. We identify a critical threshold effect of domestic R&D expenditure, demonstrating that the returns to international collaboration increase substantially once a country possesses a robust local research infrastructure. This highlights the strong complementarity between national R&D investments and global collaboration. Third, our sub-sector analysis reveals that emerging, highly interdisciplinary fields like energy storage benefit more from international networks than mature technologies like wind energy.

6.2 Limitations and Future Research

While this study provides valuable insights, several limitations point to fruitful avenues for future research. First, our empirical analysis relies primarily on patent citations as a proxy for knowledge diffusion. Although widely accepted, patent citations do not capture all forms of knowledge transfer, particularly tacit knowledge or innovations that are protected by trade secrets rather than patents. Future research could incorporate alternative metrics of technology diffusion, such as international trade flows of clean energy goods or foreign direct investment in clean energy projects [14].

Second, our country-level focus may mask important micro-level heterogeneities. Future studies could utilize firm-level or university-level datasets to examine how organizational structures, corporate strategies, and cultural differences influence the success of international research collaborations. Third, our study does not fully account for the quality and depth of individual collaborative relationships. Utilizing social network analysis tools to map the topology of global clean energy networks, including the centrality and clustering of specific research institutions, could provide a more granular understanding of how knowledge flows through global scientific communities.

In conclusion, accelerating the global transition to clean energy requires not only technological breakthroughs but also the rapid, worldwide diffusion of these innovations. By showing that international collaboration and domestic absorptive capacity work hand-in-hand, this paper provides a clear roadmap for policymakers aiming to build effective, inclusive, and highly productive global energy innovation networks.

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