Are Technological Innovations Driving Sustainability in Emerging Economies? The Role of R&D Investments and Patent Sources in Energy Efficiency

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Abstract

Research, particularly from advanced economies, suggests that technological innovations are crucial for improving energy efficiency and promoting sustainability. However, a key question remains: To what extent can this assumption be extended to countries with different institutional arrangements and development trajectories? To address this question, this study examines the interconnected impacts of R&D efforts and patent sources on energy efficiency in emerging economies. For the empirical analysis, we use annual data from Brazil, Russia, India, China, and South Africa covering the period between 1994 and 2019. The two-step System Generalised Method of Moments (System-GMM) technique is employed to address endogeneity concerns. The results indicate that R&D efforts and patents filed by non-residents contribute positively to energy efficiency in emerging economies. In contrast, patents filed by residents increase the intensity of GHG emissions per capita. Finally, we propose policy recommendations to strengthen innovation systems and human development efforts in developing and emerging economies.

Keywords Energy efficiency · R&D investments · Patents · Emerging economies

JEL Classification D8 · D81 · G30 · G31 · G32

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1. Introduction

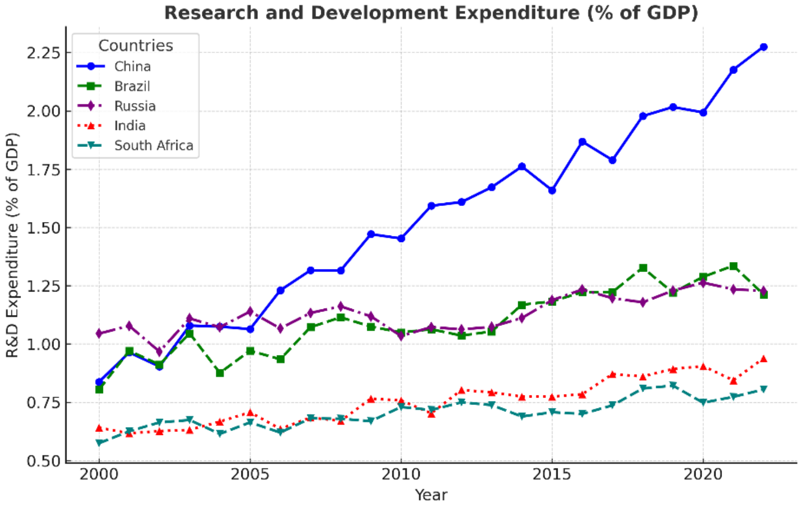
Energy efficiency is crucial for the sustainable economic development of emerging economies (Liu & Dong, 2021; Miao et al., 2017). However, energy demand is increasing as these nations undergo rapid industrialisation and urbanisation (Edeh et al., 2024). This trend has raised concerns about resource depletion, environmental sustainability, and energy security. For example, over-extraction of groundwater is causing a severe water crisis in India, leading to more than 600 million people being exposed to high water stress (Gulati et al., 2019). Brazil's Amazon rainforest is rapidly being cleared for agricultural and industrial purposes, posing serious biodiversity problems (Ortega & Ossandon Busch, 2024). In China, rapid industrialisation, fossil fuel dependence, and urbanisation result in high temperatures and severe air pollution (Zhou, Zhang & Lin, 2025). These examples highlight the urgent need for innovative solutions that address energy demands while safeguarding environmental sustainability. In other words, strategies and policies enhancing energy efficiency in emerging economies are critical for sustainable economic growth (Irfan, 2021).

Prior studies have identified technological innovations, particularly research and development (R&D) efforts, as effective strategies for enhancing energy efficiency (Amin et al., 2025). R&D efforts play a crucial role in fostering innovation and facilitating the transition to low-carbon, sustainable energy systems (Yin & Chang, 2021). For instance, by investing in R&D activities, countries in emerging economies can make progress in renewable energy, smart grids, energy storage, and industrial efficiency. This can, in turn, reduce their reliance on fossil fuels and mitigate negative environmental impacts. However, despite existing research, particularly in advanced economies, indicating positive effects of R&D efforts on energy efficiency, emerging economies often face significant human and financial challenges in supporting the transition towards a renewable energy-based future (Khan et al., 2023). Additionally, inadequate infrastructure and weak institutional frameworks hinder the advancement of energy-efficient innovations (Dube & Horvey, 2023). Thus, a key question remains: can the positive relationship between technological innovations and energy efficiency hold for emerging economies, given their different institutional arrangements and development trajectories? Therefore, this study examines whether technological innovation efforts drive energy efficiency in the context of weak innovation systems that characterise many emerging economies.

While R&D efforts are pivotal to energy efficiency technologies, research suggests that patents are essential intellectual property instruments for protecting inventions and securing economic growth (Klein & Yang, 2024; Nguyen & Doytch, 2022). Patents can incentivise private sector investments and facilitate cross-border technology transfer, enabling emerging economies to leverage global advancements (Danish & Sharma, 2023). Moreover, success in commercialising patented innovations and inventions in the form of energy-efficient products and processes contributes to cost reductions, lower carbon footprints, and long-term sustainability (Esmaeilpour Moghadam & Karami, 2024).

To achieve its objectives, this study draws on the Innovation System Theory to examine the interconnected roles of R&D efforts and patent sources in facilitating energy efficiency in emerging economies. It focuses on Brazil, Russia, India, China and South Africa (BRICS), using annual panel data covering the period between 1994 and 2019. First, focusing on the BRICS countries is particularly interesting due to their varying

R&D investment efforts. As Figure 1 shows, China invests substantially in R&D activities. Between 2000 and 2021, its R&D spending exceeded 172%, reinforcing China's position as a global leader in technological innovations. Brazil's R&D expenditures have grown modestly, increasing up 9.3% between 2000 and 2020. In contrast, South Africa, Russia and India show relatively volatile R&D investment levels. Thus, it is unclear whether and how these R&D efforts affect energy efficiency in these economies. This study contributes to the literature by enhancing our understanding of how emerging economies leverage R&D in improving energy efficiency.



Source: World Bank

Second, while prior studies employ patents to capture the private sector's technological innovations, they fail to explain the role of patent sources in sustainability efforts. This study overcomes these limitations, thus contributing to the literature by examining the impacts of the patent-filing capacity of both residents and non-residents on energy efficiency. In so doing, it emphasises the importance of considering patent sources when analysing knowledge diffusion and energy efficiency.

Third, from an empirical perspective, this study provides new insights into how the interplay of R&D efforts and patent sources contributes to energy efficiency. The findings reveal that technological innovation efforts have varied impacts on energy efficiency in emerging economies. Thus, the study offers policy implications, suggesting that governments in developing and emerging economies should strengthen their innovation systems and invest in human development, as both are pivotal to achieving long-term energy efficiency and sustainable economic development.

The remainder of the paper is structured as follows. Section 2 presents the theoretical framework and research hypotheses. Section 3 presents the data and methodology, while Section 4 discusses the results of this study. Finally, Section 5 provides policy recommendations.

2. Theoretical Framework

2.1. Innovation System Theory

Technological innovation is widely recognised as a critical determinant of economic growth and sustainability. In today's global economy, characterised by fierce competition and increasing environmental concerns, scholars argue that governments and organisations engaging in openness are likely to succeed in their technological innovation objectives (Lee, Lee, & Lee, 2020; Chesbrough & Bogers, 2014). In other words, the innovation process is characterised by dynamic interactions and collaborative actions embedded within ecosystems (Nelson 1993; Freeman, 1987). The idea of openness in the innovation process challenges the traditional perspective, which suggests that knowledge is internally generated and produced within organisations or closed systems.

In this context, Innovation System Theory (IST) offers a robust analytical framework for explaining how innovation and technological development emerge from a complex web of interactions. Originally, the IST was proposed by Lundvall (1985) and later refined (Edquist, 1997; Lundvall, 1992; Freeman, 1987). It argues that the innovation process is shaped by factors such as policies, institutions and knowledge flows among actors within a defined system. For Lundvall (1992, p. 2), an innovation system is "constituted by the elements and relationships which interact in the production, diffusion and use of new, and economically useful, knowledge … and are either located within or rooted inside the borders of a nation state" (Lundvall, 1992, p. 2). This definition highlights the collaborative and systemic nature of the innovation process, where interactions among actors such as enterprises, universities, research institutions, and government's policy initiatives drive the direction and performance of innovation activities (Lee, Lee, & Lee, 2020; Hsu & Chen, 2002; Nelson, 1993).

2.2. Technological Innovations and Energy Efficiency: The Role of R&D Actors

In this study, we extend the IST to explain how R&D efforts shape the energy efficiency trajectories of emerging economies. Specifically, we argue that the transition to energy efficiency in emerging economies is closely linked to the ability of their innovation systems to produce, implement and diffuse new knowledge. Within these innovation systems, we focus on four actors that are pivotal to fostering energy efficiency through their R&D efforts.

First, research shows that the private sector firms are the main drivers of technological innovations through their R&D investments, technology adoption, and strategic collaborations (Ishibashi & Matsumura, 2006). These firms can leverage knowledge outputs to improve the efficiency of their production methods and develop clean energy sources (Fleta-Asín & Muñoz, 2024; Laguir et al., 2019). Segarra-Blasco & Jove-Llopis (2019) find that energy efficiency and renewable energy actions are highly persistent among European small and medium-sized enterprises. Edeh, Chowdhury and Edeh (2024) find a bi-directional causality between FDI inflows and renewable energy, suggesting reinforcing effects of R&D spillover from multinationals into the clean energy technologies in emerging economies. In other words, by interacting with the multinational corporations, local firms can leverage knowledge spillover and advanced technologies to enhance their production efficiency and implement sustainable energy practices (Lööf, 2009).

Second, governments, through their policies and programmes, play a vital role in supporting R&D efforts and innovation systems, which can lead to energy efficiency (Duan et al., 2024). Zhu, Liao and Liu (2021) find that government energy R&D investments are crucial for reducing energy intensity and decarbonising the energy mix. Similarly, Khan, Chatti and Zhu (2024) reveal that public energy R&D budgets foster clean energy in the G7 countries. Government in emerging economies can promote energy-efficient products and processes through their policy instruments, loans, subsidies, and regulatory frameworks that support innovation ecosystems. Additionally, they can invest in research projects, fund clean energy initiatives, and implement initiatives that incentivise sustainable production (Caglar & Ulug, 2022). In other words, government-level strategy and institutional supports can affect how other actors within the innovation systems interact and coordinate their generation and diffusion of new knowledge relevant to achieving energy efficiency at the national level.

Third, universities and research institutes are centres of knowledge generation and key actors in the innovation systems. Achieving energy efficiency requires radical innovations and advanced technical competencies, which these institutions can readily provide (Edeh & Vinces, 2024). They are well-equipped to conduct theoretical and applied research, which can lead to technological success in energy efficiency. Through their collaborations with other actors in the systems, they can co-create energy-efficient solutions (Dall-Orsoletta, Romero & Ferreira, 2022; Trencher, Yarime & Kharrazi, 2013). Additionally, through external R&D support, universities and research institutes produce energy-efficient technologies and facilitate the creation of spin-off companies in the clean energy sector.

Lastly, as important actors in the innovation systems (Lindgren, 2019), non-governmental and philanthropic organisations support actors such as private sector firms and research institutes through research funds or grants (Brunner & Marxt, 2013). Besides, they are knowledge disseminators and serve as transition intermediaries in sustainability transformations (Wolf et al., 2021). For example, Zhang et al. (2023) find that environmental non-government organisations promote green and low-carbon industrial transformations in Chinese eastern and western regions. Moreover, non-governmental and philanthropic organisations can facilitate information sharing among the system actors and advocate for energy-efficient policies to support Sustainable Development Goals (SDGs), particularly goal 7 (Li et al., 2018). Based on the R&D efforts of these four actors in the innovation systems, we hypothesise that in emerging economies:

Hypothesis 1: R&D investments by firms, governments, research institutions, and non-profit organisations contribute to energy efficiency by reducing greenhouse gas emissions intensity relative to per capita income.

2.3. Patent Sources and Energy Efficiency

Innovation outputs, especially patents, are indicators of technological efforts. In the context of IST, patents represent the codified knowledge produced through the R&D efforts of various actors (Dolfsma & Leydesdorff, 2011). Additionally, patents are effective instruments for preventing infringements within the systems and promoting competitive advantages (Griliches, 1990). To understand the impacts of patent sources on energy efficiency in emerging markets, we group them into resident and non-resident patents. The former is the patent applications filed by domestic individuals or organisations. Resident patents allow us to explain the impact of a country's technological innovation efforts and its ability to achieve energy efficiency. We assume that a higher number of resident patents is related to a strong national innovation ecosystem and improved energy efficiency. The latter is the patent applications filed by foreign individuals or organisations in a host country. These patents enable us to examine the effect of international knowledge spillovers and technology transfer into emerging economies, and whether they foster energy efficiency. Based on the role of patents in promoting energy-efficient technologies, we hypothesise that in emerging economies:

Hypothesis 2a: Patents filed by residents contribute to energy efficiency by reducing greenhouse gas emissions intensity relative to per capita income.

Hypothesis 2b: Patents filed by non-residents contribute to energy efficiency by reducing greenhouse gas emissions intensity relative to per capita income.

Figure 1. Conceptual Model

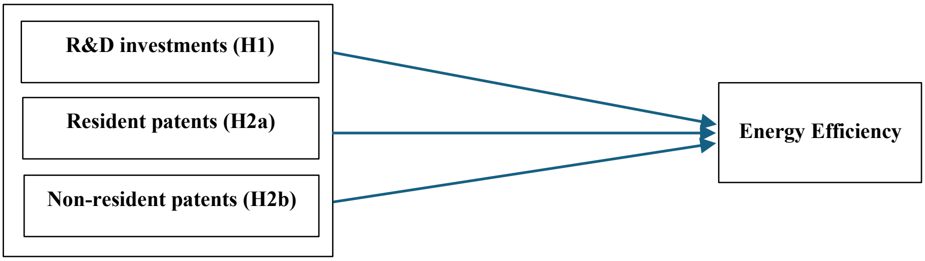


Figure 1 presents the conceptual model of the hypotheses developed in this study. It illustrates the impacts of technological innovations on energy efficiency in emerging economies.

3. Data

We use a panel sample of Brazil, Russia, India, China, and South Africa covering the period from 1994 to 2019. The data are from the World Development Indicators (WDI) published by the World Bank and Penn World Table 10.0 (Feenstra et al., 2015). The timeframe of 25 years is sufficient for a longitudinal study of the impacts of R&D efforts and patents on energy efficiency in emerging economies. The WDI provides comprehensive information on resident and non-resident patents as well as R&D expenditures of business enterprises, government, research institutions and private non-profit organisations. Additionally, we included a set of control variables that may influence energy efficiency in emerging economies. The WDI and Penn World Table are widely used in prior technological innovations, development and energy studies (e.g., Chen & Ma, 2024; Chien, Chau, & Sadiq, 2023; Chang & Fang, 2022; Chen, DeJuan, & Tian, 2018). Table 1 contains the variables and their respective measurements.

Table 1. Data, measurement and sources

Variable	Definition and measure	Source
Energy efficiency	CO_2e from Energy + Process Emissions + Methane + Flaring / GDP per capita	WDI
R&D investments	Research and development expenditure (% of GDP), capturing both capital and current expenditures of business, government, higher education and private non-profit organisations	WDI
Resident patents	The sum of patent applications filed in a country by residents of that country	WDI
Non-resident patents	The sum of patent applications filed in a country by non-residents of that country	WDI
Foreign Direct Investment (FDI)	The net inflows (% of GDP) of investment to acquire a lasting management interest (10% or more of voting stock) in an enterprise operating in an economy other than that of the investor.	WDI
Population	Total population between the ages of 15 to 64 as a percentage of the total population.	WDI
Trade openness	Trade is the sum of exports and imports of goods and services measured as a share of gross domestic product.	WDI
Human capital	Human capital index based on years of schooling and returns to education	PWT
Welfare-relevant TFP	Welfare-relevant TFP levels at current PPPs (USA=1)	PWT

* World Development Indicators (WDI) **Penn World Table (PWT), Version 10.0

3.1. Model Specification

First, we analyse the relationship between R&D investments and energy efficiency in emerging economies. The model is specified as follows:

$$EE_{it} = \alpha_0 + \alpha_1 EE_{it-1} + \alpha_2 R\&D_{it} + \emptyset X_{it} + \varepsilon_{it} \quad (1)$$

Second, we estimate the impacts of resident patents and non-resident patents on energy efficiency in emerging economies. Accordingly, the model is specified as follows:

$$EE_{it} = \alpha_0 + \alpha_1 EE_{it-1} + \alpha_2 PAT_{res,it} + \alpha_3 PAT_{nonres,it} \emptyset X_{it} + \varepsilon_{it} \quad (2)$$

Where: EE_{it} is the Energy efficiency of country i in time t; EE_{it-1} represents lagged energy efficiency, which captures persistence; $R\&D_{it}$ is the R&D investments of business enterprises, government, research institutions and private non-profit organisations;

$PAT_{res,it}$ represent the resident patents; $PAT_{nonres,it}$ is the non-resident patents; X_{it} denotes the control variables, and ε_{it} is the idiosyncratic error term. We transformed the variables into a natural logarithm to stabilise the variance of the series and prevent heteroscedasticity issues.

3.2. Estimation Strategy

We use the two-step System Generalised Method of Moments (System-GMM) approach to analyse the relationship between energy efficiency, R&D investments, and patents in emerging economies (Blundell & Bond, 1998). This estimation technique effectively addresses the problem of weak instruments that occurs when variables show high temporal persistence (Abid, 2017). More so, unlike traditional panel data estimation approaches (e.g., pooled ordinary least squares, fixed-effects, and random-effects models), the System-GMM is more appropriate for estimating our panel models that have a dependent variable (energy efficiency) whose current values may depend on its past values. Besides, the System-GMM allow us to capture the potential long-term impacts of technological innovations in emerging economies on energy efficiency. Moreover, System-GMM effectively handles serial autocorrelation, omitted variable issues, simultaneity bias, and endogeneity concerns arising from reverse causality, which are common in technological innovation research (Blundell & Bond, 1998). In other words, the System-GMM approach ensures consistent and efficient estimates that are fitting for understanding the dynamic relationships between R&D investments and patent sources and energy efficiency in emerging economies.

4. Empirical Analysis and Results

4.1. Descriptive Statistics

Table 2 presents the descriptive statistics for the variables used in our study. Energy efficiency in emerging economies has an average value of 0.97 (standard deviation, 1.23).

Table 2. Descriptive statistics

	Obs.	Mean	SD	Min	Max
Energy efficiency	130	0.9702	1.2353	0.3202	6.1699
R&D investments	130	0.8814	0.5101	0.0001	2.2446
Resident patents	130	9.0325	1.9716	4.9272	14.1474
Non-resident patents	130	9.6454	0.9757	7.7832	11.9641
FDI	130	0.2306	0.3488	-0.7581	0.7772
Population	130	1.7286	0.1924	1.2804	1.8649
Trade openness	130	1.5982	0.1560	1.1941	1.8413
Human capital	130	0.3814	0.0871	0.1980	0.53585
Welfare-relevant TFP	130	-0.3430	0.1293	-0.6065	-0.05524

Next, R&D investments have a mean value of 0.88 and a standard deviation of 0.51. Resident patents have a mean value of 9.03 (standard deviation, 1.97), and non-resident patents have a slightly higher mean of 9.64 (standard deviation, 0.97).

4.2. Correlation Analysis

Figure 2 presents the correlation among the primary variables used in this study. The strength and direction of correlations are visually represented through the size and colour of the circles: larger, darker blue circles denote stronger positive correlations, while red indicates negative associations.

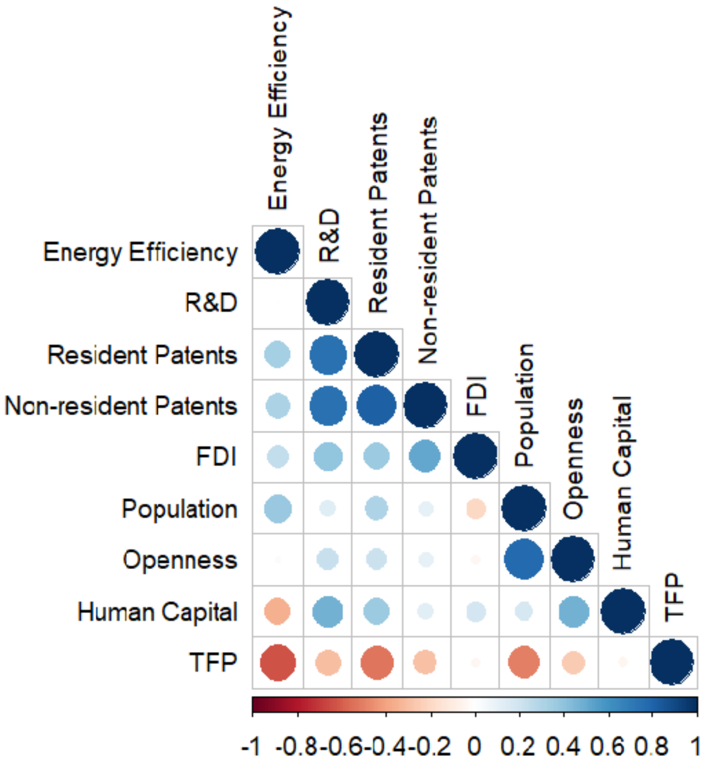


Figure 2: Correlation of main variables

In addition, we conducted the Variance Inflation Factors (VIF) test. The values range from 1.63 to 7.08 with a mean value of 4.18, below the threshold of 10 (Hair et al., 1998). Therefore, based on these results, we conclude that there is no serious risk of multicollinearity.

4.3. Regression Results and Discussions

First, we conducted two diagnostic tests to ensure the robustness of our dynamic panel estimation using the System-GMM approach. We ran the Arellano–Bond AR (2) test, where the null hypothesis shows that there is no second-order serial correlation in the differenced error terms. The results of the four models are statistically insignificant

AR (2) p-values (0.123 to 0.187), thus showing the absence of second-order autocorrelation, as shown in Table 3. Additionally, we conducted the Sargan test to assess the validity of the instruments. The p-values range from 0.120 to 0.230, all exceeded the conventional threshold of 0.05. Therefore, these results confirm that the instruments are valid, and our model is appropriately specified.

Furthermore, Table 3 presents the results of the System-GMM estimations of the determinants of energy efficiency in emerging economies. The lagged variable of energy efficiency is positive and statistically significant across the models. These results suggest a strong persistence in energy intensity trends, which validates prior research suggesting the path-dependent nature of energy use (Jaffe et al., 2005). Thus, these findings reveal the cumulative increase in energy consumption in emerging economies. The energy intensity level attained in these economies is likely to persist over time unless there are considerable changes in technological advances and policies to facilitate efficient energy use (Edeh et al., 2024).

Besides, our control variables, human capital (-0.5204, $p<0.000$) and welfare-relevant TFP (-0.4361, $p<0.000$), have negative and significant coefficients as shown in Model 1. These findings indicate that a 1% increase in human capital development and welfare-relevant TFP leads to reductions in per capita GHG emissions intensity by -52.04% and -43.61%, respectively. This, in turn, contributes to improving energy efficiency in emerging economies. The findings are interesting as they confirm the linkage between human capital level and sustainable energy (Shidong et al., 2022). In other words, these results are consistent with prior studies arguing that human capital is critical to the sustainable energy transition (Dehghan Shabani, 2024). For example, Pegkas (2024) finds that human capital stimulates renewable energy as well as decreases non-renewable energy consumption. Likewise, improvement in welfare-relevant TFP can foster cleaner technologies and transition to low-carbon socio-economic structures in emerging economies (Yin et al., 2022). Therefore, our study shows that human capital and welfare-relevant TFP are drivers of energy efficiency.

4.4. The Role of Technological Innovations in Energy Efficiency in Emerging Economies

In hypothesis 1, we posit that R&D investments by firms, governments, research institutions, and non-profit organisations contribute to energy efficiency by reducing per capita GHG emissions intensity. This hypothesis is supported as the coefficient is positive and statistically significant (-0.0672, $p<0.007$) as shown in Model 2. These findings indicate that a 1% increase in R&D investments leads to reductions in per capita GHG emissions intensity by -6.72%. These results are in line with the endogenous growth theory, which argues that innovations are the main determinants of productivity and sustainability (Romer, 1990). Similarly, Solarin, Bello and Tiwari (2022) find that technological innovations contribute to renewable energy production in BRICS countries. In a study of G10 countries, Khan and Su (2023) find that technology innovation has a significant impact on renewable energy in Germany, the Netherlands, Sweden, the UK, and the USA due to their strong knowledge base and R&D investments.

Table 3. System-GMM Results

Variables	Model 1	Model 2	Model 3	Model 4
Lagged Energy Efficiency	0.872***	0.878***	0.912***	0.874***
	(0.0113)	(0.0115)	(0.0168)	(0.0130)
FDI (log)	0.0240	0.00254	0.0377*	-0.0127
	(0.0303)	(0.0313)	(0.0225)	(0.0506)
Population(log)	0.1041	0.104	0.149	-0.249
	(0.0891)	(0.0891)	(0.105)	(0.157)
Trade openness (log)	-0.0778	-0.103	-0.158**	-0.0743
	(0.0965)	(0.0970)	(0.0720)	(0.116)
Human capital (log)	-0.5204***	-0.550***	-0.137	-0.336**
	(0.124)	(0.124)	(0.171)	(0.162)
TFP (log)	-0.4361***	-0.339***	-0.489**	-0.696***
	(0.0899)	(0.0968)	(0.210)	(0.155)
R&D (log)		-0.0672**		
		(0.00248)		
Resident patents (log)			0.0142**	
			(0.00595)	
Non-resident patents (log)				-0.0299***
				(0.0122)
Constant	0.0623	0.155*	0.0350	0.224
	(0.0819)	(0.0888)	(0.155)	(0.181)
AR (1)	0.262	0.180	0.178	0.133
AR (2)	0.144	0.123	0.187	0.126
Sargan test p-value	0.162	0.230	0.120	0.222
Number of Countries	5	5	5	5

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

In other words, our study shows that the combined R&D efforts of business enterprises, government, research institutions and private non-profit organisations in the innovation systems are critical to the production, diffusion and applications of energy-efficient technologies such as smart grids, and cleaner production processes. For instance, knowledge generated through the interactions between research institutions and private sector businesses can foster technological advancements in the areas of clean energy solutions and energy management systems.

More so, in hypothesis 2a, we posit that patents filed by residents contribute to energy efficiency by reducing per capita GHG emissions intensity. The results reveal a positive and significant coefficient (0.0142, p< 0.017) as shown in Model 3. These findings indicate that a 1% increase in resident patents leads to an increase in per capita GHG emissions intensity by 1.42%. In other words, patents filed by residents do not contribute to energy efficiency in emerging economies. Unlike in advanced economies, many of the patents filed by residents of emerging economies tend to lack real-world implementation due to commercialisation challenges and inefficient technology transfer mechanisms. Another possible explanation for these findings may be a result of misalignment between patenting activities and efficient energy implementations in emerging economies. In contrast, non-resident patents are negatively related to per capita GHG emissions intensity (-0.0299, $p < 0.000$) as shown in Model 4. These findings indicate that a 1% increase in non-resident patents leads to a decrease in per capita GHG emissions intensity by -2.99%. These findings highlight the role of international knowledge spillover and technology transfer in enhancing energy efficiency in emerging economies. These findings are consistent with prior studies emphasising the relevance of technology diffusions and implementations in emerging economies (Friebe et al., 2014).

4.5. Robustness Check

To check the robustness of the results contained in Table 3, we re-estimated the models using a different dependent variable, namely, Energy use (kg of oil equivalent per capita). The results are presented in Table 4. Model 2 shows that R&D investments of business enterprises, government, research institutions and private non-profit organisations have a negative and significant impact on energy use. These findings suggest that a 1% increase in R&D investments reduces primary energy use, thereby increasing energy efficiency in emerging economies. In other words, a 1% increase in R&D investments decreases energy use in emerging economies by -7.14%. The results of Model 3 show that a 1% increase in resident patents increases energy use in emerging economies by 12.91%. On the contrary, the results of Model 4 show that a 1% increase in non-resident patents decreases energy use in emerging economies by -10.8%. In summary, the results in Table 4 are consistent with the main results in Table 3, therefore confirming the robustness of our findings.

5. Policy Implications

The findings of this study have two main policy implications for governments and decision-makers in emerging economies. Energy efficiency is critical to economic development and sustainability. As a result, governments and policymakers in emerging economies should put considerable efforts into fostering technological innovation activities and human development. To achieve these objectives, they should prioritise the following policy recommendations.

First, our study shows that domestic patenting activities are not beneficial for improving energy efficiency in emerging economies. These findings, among other things, suggest that the innovation systems in emerging economies are not efficiently enabling the development, diffusion and implementation of knowledge. To address this challenge, governments and policymakers in these economies should significantly strengthen their intellectual property protection frameworks. This will incentivise local firms and creative industries to engage in more energy-efficient technological innovation efforts.

Table 4. System-GMM Results with Energy Use (Dependent variable)

Variables	Model 1	Model 2	Model 3	Model 4
Lagged energy use	0.540***	0.311**	1.010***	0.437*
	(0.0869)	(0.157)	(0.0189)	(0.239)
FDI (log)	-0.0461	-0.0286	-0.0297**	-0.0425
	(0.0360)	(0.0336)	(0.0129)	(0.0289)
Population(log)	1.642	4.103**	-0.217***	3.430*
	(1.040)	(1.826)	(0.0567)	(1.988)
Trade openness (log)	0.192*	0.0682	0.311***	0.260
	(0.106)	(0.106)	(0.0703)	(0.217)
Human capital (log)	1.638**	2.531**	-0.421***	1.551*
	(0.679)	(1.278)	(0.151)	(0.902)
TFP (log)	0.683***	0.830***	-0.00411	1.173**
	(0.154)	(0.239)	(0.116)	(0.457)
R&D(log)		-0.0714***		
		(0.0176)		
Resident patents (log)			0.1291***	
			(0.00428)	
Non-resident patents (log)				-0.108**
				(0.0805)
Constant	-2.186	-5.824**	-0.0953*	-3.156
	(1.638)	(2.899)	(0.0541)	(2.969)
AR (1)	0.167	0.941	0.000	0.702
AR (2)	0.700	0.152	0.916	0.951
Sargan test p-value	0.140	0.359	0.064	0.770
Number of Countries	5	5	5	5

Standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Furthermore, there are substantial gaps between research institutions and industry in many developing and emerging economies. Governments and policymakers in these countries must foster collaborations between these entities to stimulate the co-creation of knowledge and patented innovations that solve real-world energy and sustainability crises. Likewise, they should promote joint energy-efficient R&D initiatives between domestic firms and international organisations to facilitate technology transfer and knowledge spillovers in the host countries. It is expected that these public efforts will significantly improve national innovation systems and, consequently, contribute to energy efficiency in emerging economies.

Second, our study shows that human capital and welfare-relevant TFP contribute to energy efficiency in emerging economies. Governments in these economies should strengthen policies that support productivity. Additionally, they should invest more in human capital development, especially in their growing young population. These efforts are not only critical to reducing the poverty and unemployment rate in these economies, but also to facilitating a transition to economic growth driven by sustainable energy.

5.1. Conclusion

The relationship between technological innovations and sustainability is attracting sustained attention from scholars and policymakers. Emerging economies are experiencing rapid industrialisation and urbanisation, which are placing increasing constraints on energy and natural resources (Edeh et al., 2024). Given its relevance, we examined the role of R&D investments and patent sources in improving energy efficiency using a panel sample of BRICS countries. Overall, our study establishes that technological innovations are crucial to driving energy efficiency in these countries. Lastly, our study has some limitations, which should be addressed in future research. While focusing on BRICS countries is interesting, they differ from other developing and emerging economies. More empirical studies should focus on other developing nations to validate the findings of this study. Besides, we focused on direct impacts, we call on scholars to explore the mechanisms and boundary conditions underlying the linkage between technological innovation and energy efficiency.

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