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RESEARCH ARTICLE

Research and development intensity and its influence on renewable energy consumption: evidence from selected Asian economies

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Abstract

The main objective of this study is to investigate the impact of research and development (R&D) intensity on renewable energy consumption in selected Asian economies. We have relied on the autoregressive distributive lag (ARDL) method to get empirical estimates. The short- and long-run results show that a rise in R&D intensity increases renewable energy consumption in China and Japan. In the long run, energy intensity and financial development increase renewable energy consumption in China and India only. Among other control variables, a rise in CO_2 emissions causes renewable energy consumption to rise in all three economies in the long run. The trade increases renewable energy consumption in India and Japan in the long run. This study shows the important policy implications of promoting R&D and renewable energy consumption in the selected Asian economies.

Keywords R&D intensity · Renewable energy consumption · Energy intensity · Asian economies · ARDL

Introduction

Over the last few decades, the world has observed massive greenhouse gases emissions due to anthropogenic activities. The infusion of greenhouse gases emissions into the atmosphere is one of the most significant causes of global warming and climate change which have become the focus of discussion at international forums. As a result, the focus of empirical researchers in environmental and energy economics has shifted to analyze the factors that can significantly control greenhouse gases emissions, particularly carbon emissions. In this regard, a plethora of studies is available that have examined various determinants of environmental quality, such as renewable energy, GDP, trade, globalization, urbanization, ICT, and tourism, among others (see Dinda, 2004; Ullah et al. 2021; Usman et al. 2021). Most of the studies have included various determinants in the framework of the environmental Kuznets curve (EKC), which says that there exists an inverted U-shaped association between economic growth and CO_2 emissions. In other words, EKC suggests that environmental quality deteriorates during the early phases of development and improves once the growth process is consolidated. Nevertheless, a consensus has emerged among the researchers that have tested the EKC hypothesis that technological improvement is one of the significant determinants of better environmental quality. Such an improvement in the environment via technological advancement is given the name of "technological effects."

According to endogenous growth theory, investment in research and development can lead to the promotion of technological advancement that will eventually increase the level of production efficiency and encourage the efficient use of natural resources and energy. As the level of economic prosperity increases, the country can make more expenditure on research and development activities, resulting in the development of more sophisticated and advanced technology. Such sophisticated and advanced technologies can lead to the more efficient use of natural resources and produce less waste and emissions (Dinda, 2004), resulting in a better, pure, and green environment (Komen et al., 1997). For example, spending more on research and development

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projects improves environmental quality by effectively managing the waste management system to guarantee fewer waste discharges (Arora and Cason, 1996).

However, the relationship between carbon emissions and technology is not clear. On one side, research and development can positively impact growth and trade via scale effect (Castellani and Pieri, 2013; Minniti and Venturini, 2017). On the other hand, increased production and trade activities can negatively impact environmental quality. Although newer and modern technology can bring more efficiency in the production process, however, increasing output still needs to utilize more natural resources and input that deteriorate environmental quality by releasing more CO_2 emissions (Jian et al., 2021). The law of diminishing returns is also applicable to the process of research and development. Over time as the accumulation of knowledge increases, the development of newer technology requires much more time, effort, and budget, resulting in a reduced level of research and development activities (Newell et al., 2009). Nonetheless, the process of economic growth demands more inputs and natural resources.

Although we can draw some inferences from the EKC model's technological effect, in-depth knowledge on the association between research and development and CO_2 emissions across countries is still missing. One school of thought has used models like integrated assessment models (Bosetti and Tavoni, 2009; Grimaud et al., 2011; Marangoni and Tavoni, 2014) to analyze the relationship between research and development intensity and environmental quality. Overall, the findings of these studies confirmed the positive link between research and development and CO_2 emissions; however, research and development expenditures alone are not enough, and a lot will depend on the improved performance of contemporary technologies.

The second group of studies includes those studies that have examined the said relationship in the context of firms, countries, and regions by using panel data over the period of 10–20 years. For instance, in the context of Japanese firms for 2001–2010, Lee and Min (2015) analyzed the relationship between green research and development and CO_2 emissions. Zhou et al. (2017) analyzed the relationship between research and development and CO_2 emissions for Chinese provinces. For 13 advanced economies, Garrone and Grilli (2010) observed the relationship between research and development in energy and CO_2 emissions over the period 1980–2004. For 13 advanced economies, Garrone and Grilli (2010) analyzed the link between energy research and development and CO_2 productions for the period 1980–2004. Fernandez et al. (2018) analyzed the impact of research and development activities on environmental quality.

R&D is connected with renewable energy consumption through various channels (Sohail et al. 2021b). For instance, R&D can moderate renewable energy consumption by triggering technological innovation in the energy sector (Yao et al., 2019; Sohail et al. 2021a). Endogenous growth theory reveals that technological innovation and progress from investing in the R&D sector could enhance the effectiveness of energy production and consumption. Hence, R&D intensity results in reducing over-dependence on natural resources by empowering more effective technologies that alleviate production-based CO_2 emissions (Churchill et al., 2021; Dinda, 2004). Moreover, through an increase in economic development and provision of more opportunities for trade openness, R&D intensity results in high use of energy due to increased production associated with economic development and trade openness. It happens when nations experience diminishing margining returns to R&D and innovation over time. It states that due to an increase in knowledge accumulation, the innovations become more challenging, hence resulting in reducing R&D-specific returns (Newell, 2009, and Jebli et al. 2016). The impact of R&D intensity on energy consumption becomes more aggravated when the consumption of energy is separated into dirty and clean energy components (Ozturk et al., 2010, and Rehman et al. 2021).

On 4 November 2016, an important agreement regarding climate change, the Paris Agreement, came into effect. This agreement demands the member states reduce carbon emissions significantly. Tugcu et al. (2012) and Murshed et al. (2022) agreed that increasing the role of renewable energy is the most viable solution to achieve the said target. It is widely recognized that increasing the installed capacity of renewable energy is an efficient technique in the long-term transformation of the global energy system. Moreover, international organizations also pointed out that without increasing the share of renewable energy in the total energy mix, the goal of a sustainable environment cannot be realized (Murshed et al. 2021). To that end, most economies are replacing their energy structure loaded with fossil fuels energy with the energy structure based on renewable energy sources that will eventually lead to the complete transformation of the energy system. The increased investment in research and development expenditures can help replace non-renewable energies with renewable energies in the nations' energy structure, resulting in a cleaner environment.

The emerging economies' investment in clean energy has enlarged from 18 to 42 percent of worldwide investment (Ozcan and Ozturk, 2019). China, India, and Japan are the largest consumers of renewable energy consumption in Asia that have been selected for analysis. Very few studies in the literature are available that have analyzed the impact of research and development intensity on renewable energy consumption in Asian economies. This research contributes significantly to the literature of the energy and environmental sector by providing new evidence regarding how R&D activities influence renewable energy consumption. Another contribution is that the study has explored the long-run and short-run nexus between R&D and renewable energy consumption. Moreover, the findings obtained from this study will help in the formulation of green policies related to the R&D sector and renewable energy consumption. The findings of this study will deliver considerable policy implications, as it emphasizes the importance of policymakers and governments to revive the adoption of major sources of renewable energy consumption in selected Asian economies.

Methodology and data

Following earlier empirical and theoretical literature of Wang et al. (2020) and Churchill et al. (2021), we assume that the main determinants of the renewable energy consumption model are R&D intensity, energy intensity, environmental pressures, trade, and financial development. Therefore, we begin with the following econometric model:

$$\mathrm{REC_t} = \varphi_0 + \varphi_1 \mathrm{RD_t} + \varphi_2 \mathrm{EI_t} + \varphi_3 \mathrm{CO_{2,t}} + \varphi_4 \mathrm{Trade_t} + \varphi_5 \mathrm{FD_t} + \varepsilon_t \tag{1}$$

where REC is the renewable energy consumption that depends on R&D intensity (RD), energy intensity (EI), CO_2 emissions (CO_2), trade openness (Trade), and financial development (FD). Since an increase in R&D intensity is expected to increase renewable energy consumption, we expect an estimate of φ_1 to be positive. Energy intensity can improve renewable energy consumption by reducing the harms of dirty energy consumption; thus, we expect an estimate of φ_1 to be positive. Also, since an increase in environmental pressures is expected to boost consumption of renewable energy, we expect an estimate of φ_3 to be positive. Finally, trade and financial development boost and open new sources of clean energy; thus, estimates of φ_4 and φ_5 are expected to be positive. The coefficient estimates reported above in Eq. (1) are long-run estimates. Since specification (1) is a long-run model, it cannot be used to scrutinize short-run effects. In order to assess short-run effects, specification (1) must be expressed in an error-correction format as follows:

$$\begin{aligned}\Delta REC_t = \varphi_0 &+ \sum_{k=1}^{n} \beta_{1k} \Delta REC_{t-k} + \sum_{k=0}^{n} \beta_{2k} \Delta RD_{t-k} + \sum_{k=1}^{n} \beta_{3k} \Delta EI_{t-k} \\ &+ \sum_{k=0}^{n} \beta_{4k} \Delta CO_{2,t-k} + \sum_{k=1}^{n} \beta_{5k} \Delta Trade_{t-k} + \sum_{k=0}^{n} \beta_{6k} \Delta FD_{t-k} \\ &+ \varphi_1 REC_{t-1} + \varphi_2 RD_{t-1} + \varphi_3 EI_{t-1} + \varphi_4 CO_{2,t-1} + \varphi_5 Trade_{t-1} \\ &+ \varphi_6 FD_{t-1} + \lambda .ECM_{t-1} + \varepsilon_t\end{aligned} \tag{2}$$

The above specification (2) now looks like the Autoregressive Distributive Lag Order (ARDL) model of Pesaran et al. (2001). The biggest advantage of this method is that it can estimate short- and long-run results simultaneously. From Eq. (2), we can confer that coefficients attached to difference variables provide short-run results and the coefficients $\varphi_2 - \varphi_6$ normalized on φ_1 provide the long-run results. However, the long-run results are considered genuine only if co-integration among them is proven with the application of bounds *F*-test to co-integration. The bounds *F*-test was proposed by Pesaran et al. (2001) which confirms if the lagged variables are jointly significant or not. Pesaran et al. (2001) developed critical values for the bounds *F*-test, and if the calculated value of the *F*-test is greater than the critical value, this is a sign of a valid long-run relationship. Furthermore, unlike other time series models such as Johansen (1988) and Johansen and Juselius (1990), which require that all variables must be $I(1)$ to be co-integrated, we do not need to worry about the order of integration because the ARDL method can even analyze the variables of a different order of integration. Other time series techniques work efficiently only if the span of data is long enough; whereas, the ARDL model can provide efficient estimates even the number of observations is small (Li et al. 2022). Lastly, the bounds testing approach can control the issues of multicollinearity and endogeneity due to the inclusion of a short-run dynamic process (Bahmani-Oskooee et al. 2020).

R&D intensity impact on renewable energy consumption is examined for Asian economies for the time period 1990 to 2019. Table 1 provides details regarding symbols,

Table 1 Variables and sources

Variables	Symbol	Definitions	Sources
Renewable energy consumption	REC	Nuclear, renewables, and other (quad Btu)	https://www.eia.gov/international/data/world/total-energy/total-energy-consumption
R&D intensity	RD	Research and development expenditure (% of GDP)	https://databank.worldbank.org/source/world-development-indicators#
Energy intensity	EI	Energy intensity level of primary energy (MJ/$2011 PPP GDP)	
CO_2 emissions	CO_2	CO_2 emissions (kt)	
Trade	Trade	Trade openness(% of GDP)	
Financial development	FD	Domestic credit to private sector (% of GDP)	

definitions, and sources of data. Data for renewable energy consumption is obtained from EIA which is measured in terms of nuclear, renewables, and others in quad BTU. R&D is a productive factor in the endogenous growth model, which in turn increases renewable energy consumption. Following the study of Churchill et al. (2019), we used research and development expenditure as an indicator of R&D intensity. Data for focused variable, i.e., R&D intensity, is taken from the World Bank, and it is calculated as R&D expenditures in percent of GDP. Data for control variables, such as energy intensity, CO_2 emissions, trade, and financial development, is sourced from the World Bank. Energy intensity is measured as the energy intensity level of primary energy, while CO_2 emission is taken into kilotons of carbon dioxide emission. Trade is measured in percent of GDP, and financial development is measured in terms of domestic credit to the private sector in percent of GDP. In Table 2, the highest means of R&D intensity (3.130) is found in Japan. On the other hand, China has the highest mean of renewable energy consumption (7.836). The detailed descriptive statistics of the variables are given in Table 2.

Results and discussion

Before performing regression analysis, unit root characteristics of variables are tested by applying PP tests and DF-GLS test. Table 3 displays the empirical outcomes of PP test and DF-GLS test. We find that some variables are stationary at level, i.e., $I(0)$, while others confirm non-stationarity at the level. The non-stationary variables become stationary after taking their first difference. In short, there is a mixture of the order of integration, i.e., $I(0)$ and $I(1)$ series of variables in the model. Findings of unit root tests encouraged us to use the ARDL approach for empirical investigation. In Table 4, panel (a) displays short-run coefficient estimates of all three models, panel (b) represents long-run findings, and panel (c) provides findings of some necessary diagnostic tests.

We find that the R&D intensity effect on renewable energy consumption is positively significant at the 10% level in China and the 1% level in Japan in the long run. We find that a 1 percent upsurge in R&D intensity increases renewable energy consumption by 2.023 percent in China and 1.826 percent in Japan in the long run. Our findings demonstrate that promoting R&D could be an effective policy tool to increase renewable energy consumption in China and Japan. However, R&D intensity has an insignificant impact on renewable energy consumption in India in the long run.

This finding is also consistent with Churchill et al. (2021), who noted that increased investment in R&D is promoting the consumption of renewable energy in OECD. It is considered that R&D causes a substitution away from non-renewable energy consumption toward renewable energy consumption. This finding is also supported by Yao et al. (2019), who infer that R&D reduces conventional energy consumption by improving clean energy consumption. This also means that R&D investment promotes efficiency in the energy market by improving renewable energy consumption. Findings infer that R&D intensity is switching the polluting economies to renewable energy sources. This economic meaning supports the study of Alvarez-Herranz et al. (2017). The R&D intensity induces a slow expansion of renewable energy consumption sources. We also observed that R&D intensity can also increase structural changes and promote diversity in the energy market. China has a relatively large share of R&D, which in turn consumes more renewable energy consumption. Environmental economist has more emphasized R&D as one of the possible options to boost renewable energy consumption and consequently reduce carbon emissions. R&D investments tend to decrease the dependence on natural resources by

Table 2 Descriptive statistics

		REC	RD	EI	CO_2	Trade	FD
China	Mean	7.836	1.465	9.082	15.64	45.27	124.0
	Std. dev	6.111	0.554	1.885	0.474	10.12	21.02
	Min	1.801	0.563	6.123	14.93	32.42	89.45
	Max	21.01	2.334	13.30	16.22	64.47	165.3
Japan	Mean	3.359	3.130	4.630	13.98	27.51	174.8
	Std. dev	1.092	0.197	0.599	0.034	6.733	19.03
	Min	1.496	2.692	3.608	13.91	18.12	157.6
	Max	4.461	3.400	5.325	14.04	37.43	217.7
India	Mean	1.745	0.735	5.749	14.14	39.40	41.18
	Std. dev	0.716	0.059	1.067	0.389	11.12	11.01
	Min	0.844	0.639	4.034	13.56	21.92	23.40
	Max	3.358	0.859	7.530	14.71	55.79	52.38

Table 3 Unit root testing

		PP			DF-GLS		
		I(0)	*I*(1)	Decision	*I*(0)	*I*(1)	Decision
China	REC	−2.734*		*I*(0)	−1.986**		*I*(0)
	RD	−0.453	−4.243***	*I*(1)	0.562	−4.325***	*I*(1)
	EI	−1.882	−3.101**	*I*(1)	0.875	−2.325**	*I*(1)
	CO_2	−0.915	−2.631**	*I*(1)	−0.623	−1.968**	*I*(1)
	TRADE	−3.012**		*I*(0)	−1.752*		*I*(0)
	FD	−0.356	−4.052***	*I*(1)	−0.289	−3.259***	*I*(1)
India	REC	0.184	−3.828***	*I*(1)	0.653	−3.875***	*I*(1)
	RD	−1.912	−3.521**	*I*(1)	−1.564	−3.065***	*I*(1)
	EI	−0.475	−5.258***	*I*(1)	−0.145	−4.152***	*I*(1)
	CO_2	−0.378	−4.094***	*I*(1)	−0.785	−4.123***	*I*(1)
	TRADE	−1.634	−3.954***	*I*(1)	−1.896*		*I*(0)
	FD	−2.634*		I(0)	−1.752*		I(0)
Japan	REC	−1.111	−3.435**	I(1)	−1.023	−3.895***	I(1)
	RD	−2.854**		I(0)	−2.185**		I(0)
	EI	0.886	−4.455***	I(1)	0.621	−4.125***	I(1)
	CO_2	−3.824***		I(0)	−3.545***		I(0)
	TRADE	−1.181	−4.993***	*I*(1)	−1.256	−4.356***	*I*(1)
	FD	−1.326	−3.661**	*I*(1)	−1.356	−3.456***	*I*(1)

***$p<0.01$.
**$p<0.05$.
*$p<0.1$

permitting more efficient renewable energy consumption (Dinda, 2004). Normally, R&D may also lead to higher renewable energy consumption as a result of increased renewable energy production. Studies done by Meleddu and Pulina (2018) claim that R&D intensity contributes significantly to reducing the risk of new technologies and their associated benefits to sustainability, security, and environmental protection.

Control variables report a positive and statistically significant positive impact on renewable energy consumption in most cases but with different magnitude. It is shown that energy intensity reports a positive and statistically significant impact on renewable energy consumption in the case of China and India. We find that a 1 percent upsurge in energy intensity increases renewable energy consumption by 0.183 percent in China and 0.330 percent in India. The association between CO_2 emissions and the renewable energy consumption is positive in three selected economies. We find that a 1 percent intensification of CO_2 increases renewable energy consumption by 2.212 percent in China, 0.954 percent in India, and 1.334 percent in Japan in the long run. Trade reports significant and positive impact on renewable energy consumption in India and Japan. It is found that a 1 percent expansion in trade increases renewable energy consumption by 0.048 percent in India and 0.251 percent in Japan. Financial development reports a significant and positive impact on renewable energy consumption in China and India in the long run. It is shown that a 1 percent increase in financial development increases renewable energy consumption by 2.857 percent in China and 2.002 percent in India.

In the short run, we find that the effect of research and development intensity on renewable energy consumption is positive and significant in China and Japan. The association between energy intensity and the renewable energy consumption is negative and significant in India, while positive and significant in Japan. CO_2 emissions report a significant effect on renewable energy consumption in China and Japan. The linkage between trade and renewable energy consumption is also positive and significant in the case of India only. However, the influence of financial sector development on renewable energy consumption is negative and statistically significant in the case of India only in the short run. Table 4 confirmed long-run co-integration in all three models, as shown by *F*-statistics and ECM. The negative sign attached with ECM confirms that short-run deviation converges toward equilibrium in the long run. Findings of LM and BP tests denote that all their models are free from autocorrelation and heteroskedasticity issues. Error terms are also normally distributed, and models are stable, as shown by Ramsey RESET test and CUSUM and CUSUM-sq tests.

Table 4 Short- and long-run estimates of ARDL

	China		India		Japan	
Variable	Coefficient	*t*-Stat	Coefficient	*t*-Stat	Coefficient	*t*-Stat
Short run						
D(RD)	2.963**	2.254	0.243	0.263	1.311***	2.969
D(EI)	0.025	0.089	− 0.542***	4.073	3.079***	4.835
D(EI(− 1))		0.325	0.545		0.366	0.871
D(CO_2)	2.927**	2.145	0.389	0.705	2.363***	3.921
D(CO_2(− 1))	2.722	1.388				
D(TRADE)	0.015	0.610	0.020**	2.545	− 0.011	0.331
D(TRADE(− 1))					0.038	1.207
D(FD)	− 2.325	0.992	− 2.039***	2.850	− 0.210	0.134
D(FD(− 1))	2.648	1.476				
Long run						
RD	2.023*	1.670	0.596	0.276	1.826***	2.632
EI	0.183**	2.091	0.330**	2.285	0.574	0.781
CO_2	2.212*	1.908	0.954*	1.922	1.334***	3.225
TRADE	0.112	0.745	0.048*	1.665	0.251*	1.946
FD	2.857**	2.077	2.002**	2.272	2.837	1.331
C	8.306**	2.032	12.10	0.579	8.670***	2.685
Diagnostics						
F − test	4.593*		11.23***		4.123*	
ECM(− 1)	− 0.334*	1.692	− 0.408**	2.011	− 0.527	4.756
R2						
LM	1.245		2.032		1.356	
BP	1.287		1.742		1.195	
RESET	0.387		0.856		1.325	
CUSUM	S		S		S	
CUSUM-sq	S		S		S	

***$p < 0.01$.

**$p < 0.05$.

*$p < 0.1$

Conclusion and implications

Global warming and climate change have become the central theme of all international forums and conferences. As a result, researchers and policymakers tried to find the factors that can mitigate carbon emissions, a major cause of rising temperature. Literature has concluded that renewable energy sources could prove a panacea for environment-related problems. Therefore, recently, policymakers have shifted their focus to finding the determinants of renewable energy consumption. In this regard, investment in research and development proved to be an important factor in transforming the energy structure of the economy and helping the nation to raise the share of renewable energy in the total energy mix. The main objective of this study is to investigate the effect of research and development intensity on renewable energy consumption in Asian economies. We have relied on the autoregressive distributive lag (ARDL) model to get empirical estimates.

The results show that the short- and long-run estimates attached to research and development intensity are significantly positive in China and Japan, signifying that a rise in research and development intensity increases the renewable energy consumption in Asian economies. Conversely, the short-run estimated coefficients of energy intensity are significantly negative in India and positive in Japan. In the long run, the estimates of energy intensity are positive and significant in India and Japan only. The short-run estimates of CO_2 appeared to be significant in India and Japan; whereas, the long-run estimates are positive and significant in all three countries. However, the short-run estimate of trade is significant only in China, and the long-run estimates are also positive in China and Japan. Lastly, an increase in financial development increases renewable energy consumption in India and China in the long term but, in the short term, reduces renewable energy consumption in China only.

Based on the findings, we provide some important policy guidelines. Our findings imply that increased research and development intensity causes renewable energy consumption to rise. Therefore, policymakers should focus on investing more in research and development activities that will improve the process of technological innovations in the economy. The overall technological improvement in the economy has a positive external impact on the energy sector, which increases the renewable energy share in the total energy mix. Given the significance of research and development activities in controlling carbon emissions, the need of the hour is that countries should share their research and development experiences with each other. In this regard, Asian economies should follow the footprint of advanced economies that have attained sustainable development by investing heavily in research and development activities.

This study contains several limitations. The study mainly focuses on research and development intensity on renewable energy consumption in empirical analysis. Furthermore, this research examined the asymmetric impact of research and development intensity on renewable energy consumption. This study has not incorporated the role of environmental innovation in the model. Thus, future studies should investigate the role of environmental innovation on renewable energy consumption. Similar research can also be replicated for other highly polluted economies. This study has taken renewable energy consumption at the aggregate level. In future studies, major sources of renewable energy consumption should be considered, such as wind, solar, hydroelectric, geothermal, and biomass. Future research should also explore the impact of R&D intensity on green growth.

Author contribution This idea was given by Wei Li. Wei Li and Sana Ullah analyzed the data and wrote the complete paper. While Sana Ullah read and approved the final version.

Data availability The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate I am free to contact any of the people involved in the research to seek further clarification and information.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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