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# The role of technological innovation and cleaner energy towards the environment in ASEAN countries: proposing a policy for sustainable development goals

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## ABSTRACT

The association between economic growth (EG) and environmental degradation (ED) has been highlighted extensively in prior studies. However, investigation regarding ‘technological innovation and clean energy role’ in dealing with environmental concerns has comprised limited context while considering the ASEAN economies under sustainable development goals. Therefore, the study attempts to investigate the phenomenon by using CS-ARDL analysis under short as well as long run. The findings through CS-ARDL in long- and short-run indicate that REN have impact carbon emission and ecological footprints negatively. Additionally, the EG in targeted economies is causing a higher level of CE and ecological footprints. Whereas, GDP2ofund to be significant in lowering the ED in the form of CE and ecological footprints. It is suggested that policies related to CE through EG should be developed in order to control the environmental issues in the future.

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## 1. Introduction

In the contemporary environment, one of the growing concerns which has attained prominent attention among policymakers and researchers is ED in the form of CO<sub>2</sub> emission and ecological footprints (Adebayo & Kirikkaleli, 2021; Destek, 2021; Nasir et al., 2021; Nathaniel et al., 2021) Nevertheless, past studies have proposed various measures to address the issues. For example, Buchanan and Honey (1994) and López-Peña et al. (2012) suggested that the improvement in the efficiency of energy can effectively reduce CE in the natural environment. Additionally, Buchanan and Honey (1994) and Huang et al. (2021) found that energy conservation and improvement in

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its efficiency are the optimal solutions towards emission reduction but under the short run. It is also believed that energy efficiency is observed as cheaper than renewable energy sources (Xiang et al., 2021; Zhang et al., 2017). In addition, the adjustment in the form of energy demand also plays a significant role when dealt with CE and ED (Chien et al., 2021a; Fan et al., 2017; Huang et al., 2020).

Developing economies primarily depend on industrial activities in order to achieve their economic targets while improving the standard of living for their citizens (Wu et al., 2021). Meanwhile, the adoption of technological production methods in advance economies in making the industrial production more attractive has resulted in a growing trend of utilizing non-renewable sources (Shair et al., 2021). Such effort has provided significant outputs in the form of GDP per capita along with the quality of life. However, the efforts of increasing good/services' production for higher economic growth are compromising the quality of natural environment's quality (Mohsin et al., 2021). Various authors have claimed that higher environmental quality is essential to stimulate the living standard of the community members. Therefore, the idea of economic development specifically for the developing economies is suspected to intensify the ED through carbon emission and haze pollution (Sadiq et al., 2021b).

Considering the dynamic association between ecological innovation, REN, EG, and ED in terms of carbon emission and ecological footprints, the present study attempts to examine the influence of these factors on the carbon emission and ecological footprints within the ASEAN region through a sample of six economies. The study also attempts to establish a relationship between the said constructs and provide empirical evidence towards the existing environmental studies, which reflects the easternized attitudes and beliefs and hence eliminates the gap in the literature.

As the preceding argument highlights the study problem and issues, the further section provides a detailed discussion of constructs by synthesizing different articles. The third section of study explains the research methodology and data collection following with the results and discussion, whereas the last section concludes the whole study along with some policy implications.

## 2. Literature review

The nexus between ecological innovation and carbon emission has extensively been discussed in current body literature (Chien et al., 2021d; Sadiq et al., 2021a). For instance, Wang et al. (2020) have observed the diversification of eco-innovation and export in order to control the CE among G-7 member states. They believe that it is hard to achieve significant results in the form of CE without considering factors like ecological innovation and export. The study gathered data between 1990 and 2017 to analyze the trend in CE through export diversification and ecological innovation and reported advocating evidence that ecological innovation reduced the CE in the targeted economies. Meanwhile, Nguyen et al. (2020) probed information technologies & innovations' role in determining the CE and growth dynamics among G-20 member states. Their study confirms that spending on innovation has a significant impact in lowering the CE. Similarly, the study by Zhang et al. (2021) also investigated the

cruciality of innovation agglomeration especially in dealing with CE for China. It was observed that CE has its classical inverted U-shaped association with the innovation agglomeration. Wang et al. (2020) also investigated the role of REN, TI, and human capital development in dealing with the CE for the N-11 economies. Their findings support the results by Pesaran (2007) who reported that technological innovation is considered to be a significant tool in lowering the CE. In addition, a research conducted by Mahmood Ahmad et al. (2020) looked into the dynamic effect of technological innovation on ecological footprints through advance panel estimation and it was observed that innovation in technology reduces environmental degradation.

The link between REN sources and environmental concerns like CE and ecological footprint has been investigated from both theoretical and empirical perspectives. For instance, the study by Saidi and Omri (2020) had looked on the impact of REN towards the CE of the 15 major REN consuming economies. Their findings confirm that REN plays a crucial role in increasing the EG and lowering the CE. Meanwhile, Vo, Vo, Ho, and Nguyen et al. (2020) scrutinized REN and other energy sources' role in mitigating CO<sub>2</sub> emission. It was found that energy consumption especially from REN sources can reduce CO<sub>2</sub> emission, whereas the study by F. Liu et al. (2020) and Hsu et al. (2021) further contribute to the discussion by integrating water assets with REN in order to analyze the annual CE. They reported that water assets with REN sources can reasonably reduce the annual CO<sub>2</sub>. Whereas, Akram et al. (2020) and Ehsanullah et al. (2021) observed the heterogeneous effect of REN on CE involving the sample of developing economies. The results proved that energy efficiency and REN impact CO<sub>2</sub> emission negatively. Furthermore, Padhan et al. (2020) reported on the significant positive effect of carbon emission per capita on the REN consumption. Finally, the study by Amin et al. (2020) analyzed the carbon emission factors from different European economies while taking the role of REN and urbanization as well. Their study also tested the 'Environmental Kuznets Curve (EKC)'. It was found that in transportation sector, 12% reduction in CO<sub>2</sub> could be witnessed by increasing REN consumption and that there is a validation of EKC.

The nexus between EG and ED has also been investigated by a number of researchers such as (Chien et al., 2021c). In addition, Wawrzyniak and Doryń (2020) examined the institution's quality in modifying the growth-CO<sub>2</sub> emissions nexus for developing and emerging economies during the period of 1995–2014. The findings clearly encompass that for the low values of institutional indicator, there is a diminishing increment of carbon dioxide emission with the growth of GDP. Q. Wang and Zhang (2021) investigated the differences in the decoupling status of CE and EG under various income levels. Their study observed the fact that REN and high oil prices contribute towards decoupling EG along with CE. Meanwhile, Galli et al. (2012) scrutinized the dynamic linkage between 'EG and ecological footprints' involving the sample of China and India. It was found that China showed a typical trend over the past 45 years with the growing change in the per capita ecological footprints as well. Furthermore, Danish et al. (2019) applied the autoregressive distributive lagged econometric approach along with the structural break between 1971 and 2014 and found that EG has increased the ecological footprints, subsequently contributing towards a higher level of ED. This is further supported by Hassan et al. (2019) who

investigated the nexus between EG, natural resources, and ecological footprints from the context of Pakistan with the help of ARDL for long-run trends. Their empirical findings revealed a positive effect of natural resources on ecological footprints, which is further supported by EKC. Besides, several other studies have explored the association between ecological footprints and EG both in developed and developing economies (Ahmed et al., 2021; Othman et al., 2020)

Although there is a plethora of research covering the dynamic relationship between REN, ecological footprints, innovation, economic growth, and carbon emission. Solarin et al. (2021), the study reported in this paper is unique as it considers the main ASEAN economies which have been understudied. Therefore, this study has filled the gap in the literature gap by being among the pioneers that explore the trends in carbon emission and ecological footprints for ASEAN countries, which are determined by ecological and related innovations as well as economic growth and REN. Furthermore, this study has covered the methodological literature gap by applying the CS-ARDL approach, which has not been well implemented specifically in the literature of environmental degradation, energy economics, and sustainability. Additionally, the implication of CS-ARDL is also linked with the pre-testing of cross-sectional dependence, unit root or stationarity properties, homogeneity in the slope coefficients, and cointegration analysis. Furthermore, the empirical findings reported in this study also serve as a significant justification to the application of the CS-ARDL method.

### 3. Research method and data

The present study has considered the cross-sectional dependence among the units. In this regard, the testing of cross-sectional dependence is often meaningful with the help of the first, second, and third generation test. Different environmental and economic variables like CE, ecological footprints, innovation, REN, and gross domestic products are linked with cross-sectional dependence (Chien et al., 2021b). For this reason, cross-sectional dependence issue needs to be addressed seriously as it may lead to specious findings, hence leading towards poor generalization of the results and inappropriate policy implications as well (Juodis & Poldermans, 2021). Once the cross-sectional dependence has been checked, the next step is to deal with the 'stationarity process' for the panel data estimation. Various studies have observed the unit root process in different data sets (Soylu et al., 2018; Yilanci & Pata, 2020).

In the existing body of literature, non-stationarity panel data are categorized into the first, second, and third generation, which are further divided based on the issues tackled by each approach (Uddin et al., 2017). For example, it is suggested that the non-stationarity issue with the homogenous panel is handled by Maddala and Wu (1999). However, the heterogenous panel is handled by Im et al. (2003) On the other hand, Maddala and Wu (1999) and Levin (2002) have discussed the second generation panel unit root test proposed by Pesaran (2007) and Liu et al. (2021), which addresses the problems of CSD. The present study thus adhered to Carrion-i-Silvestre and German-Soto (2009), Pesaran (2007) and López-Peña et al. (2012) in order to deal with CSD while using the test of 1st generation panel unit root.

In contrast with first- and second-generation test, Westerlund and Edgerton (2008) not only dealt with CSD but also managed to resolve the issue of serially correlated errors successfully. Besides, the CS-ARDL approach is highly helpful when there is an issue of slope heterogeneity and CSD among the study variables. Additionally, the CS-ARDL approach is dynamic in nature which uses common correlated effects estimator in order to subdue other numerous issues. Therefore, the starting point for applying the CS-ARDL approach is given with the help of Equation 1:

$$W_{i,t} = \sum_{I=0}^{Pw} \gamma_{I,i} W_{i,t-1} + \sum_{I=0}^{Pz} \beta_{I,i,t-1} + \varepsilon_{i,t}. \tag{1}$$

The above equation (Equation 1) is observed as an autoregressive distributed lag model. Furthermore, Equation 2 is an extended form of Equation 1 while using the cross-section averages for each of the study regressors.

$$W_{i,t} = \sum_{I=0}^{Pw} \gamma_{I,i} W_{i,t-1} + \sum_{I=0}^{Pz} \beta_{I,i,t-1} + \varepsilon_{i,t} + \sum_{I=0}^{Px} \partial_i IX_{t-1}, \tag{2}$$

In the above equations,  $X_{t-1} = (W_{i,t-1} Z_{i,t-1})$  are the averages for both of the dependent variables named as CE and ecological footprints. Meanwhile,  $Z_{i,t}$  indicates all of the independent variables under investigation, which are named as ecological innovation, REN, GDP, and the square of GDP. Whereas,  $X$  indicates the cross-sectional average in order to avoid from cross-sectional dependence as observed by the spillover effects. For the long-run estimation of the CS-ARDL, the following mean group estimation is observed with the help of Equation (3).

$$\Pi_{Cs-ARDL,i} = \sum_{i=0}^{Pz} B_{i,iPW} / 1 - \sum 1 = 0 \gamma_{I,i} \tag{3}$$

The mean group is described using Equation (4).

$$\tag{4}$$

The estimation of short-run coefficients is conducted using Equation (5):

$$\begin{aligned} \Delta W_{i,t} = & \vartheta_i [W_{i,t-1} - \pi_i Z_{i,t}] \sum_{I=1}^{Pw-1} \gamma_{I,i} \Delta W_{i,t-1} + \sum_{I=0}^{Pz} B_{I,i} \Delta Z_{i,t} \\ & + \sum_{I=0}^{Px} \partial_i IX + \varepsilon_{i,t} \end{aligned} \tag{5}$$

where in the above equation the titles like

$$\tau_i = -\left(1 - \sum_{I=1}^{pw} \gamma I, i\right) \quad (6)$$

$$\Pi_i = \sum_{I=0}^{pz} B_{I,i} \quad (7)$$

$$\Pi_{MG} = I/N \sum_{i=1}^N \Pi_i \quad (8)$$

For the CS-ARDL findings, the term ‘error correction mechanism’ shows the adjustment speed to the wards equilibrium for any economy to reach the ultimate point of equilibrium.

Besides, the measurement of the study variables like innovation was observed through the total number of patents registered during a particular year, whereas, clean energy refers to the REN consumption, GDP shows the measure of EG in terms of GDP, and EFP indicates the measurement of ecological footprints network for all the states under observation. Meanwhile, the data for all the study variables were collected between the period of 1995–2018 from various sources like the World Bank, world development indicators (WDI), OECD website, and the website for the Global Footprint network.

#### 4. Results and discussion

Table 1 provides the CSD outcomes for all the variables under investigation. The findings for carbon emission, ecological footprints, innovation, REN, and gross domestic product confirm that the null hypotheses for all the variables are rejected at 1% due to significant test statistics. The reason to provide cross-sectional dependence analysis first is that it reduces the biasness under cointegration and ‘unit root analysis’. Therefore, the values in Table 1 significantly confirm the existence of CSD in the study variables.

Table 2 contains the outcomes for the ‘unit root test’, structural breaks (with & without), so that the stationary properties of study constructs could be justified especially in the presence of CSD. The finding indicates that the null hypothesis for the unit root at level cant be rejected Pesaran (2007) and Carrion-i-Silvestre and German-Soto (2009). This shows that structural break issues is existed along with the

**Table 1.** CSD analysis.

Variables	T Statistics (Sig.)
CE	18.123*** (0.000)
EFP	21.218*** (0.000)
INV	17.342*** (0.000)
REN	20.210*** (0.000)
GDP	22.121*** (0.000)

Note. Whereas CE = carbon emission; EFP = ecological footprints; INV = innovation; REN means REN; GDP = gross domestic product.

Source: authors estimation.

**Table 2.** URT.

Constructs	Level I(0)		First Difference I(1)		
	CIPS	M-CIPS		CIPS	M-CIPS
CE	-5.050***	-9.010**		-	-
EFP	-4.020***	-8.011**		-	-
INV	-5.002***	-8.101**		-	-
REN	-4.010***	-6.021**		-	-
GDP	-5.012***	-7.102**		-	-

Carrion-i-Silvestre and German-Soto (2009)						
	Z	$P_m$	P	Z	$P_m$	P
CE	0.425	0.825	21.149	-3.035***	6.215***	68.154***
EFP	0.304	0.943	17.148	-4.005***	5.556***	72.058***
INV	0.421	0.741	24.365	-3.658***	7.059***	70.187***
REN	0.384	0.662	16.176	-3.066***	6.389***	69.089***
GDP	0.327	0.846	19.765	-4.505***	7.005***	79.058***

Note. CE means carbon emission, EFP means ecological footprints, INV means innovation, REN means REN, GDP means gross domestic product, respectively.

Source: authors estimation.

presence of CSD and heterogeneity. Similarly, after observing the ‘structural breaks’, the findings of the study unable to reject the null hypothesis for the nonstationarity as well. In terms of Pesaran (2007) all of the study variables were observed as stationarity at level and for this reason, our study applied the Carrion-i-Silvestre and German-Soto (2009) the first-order difference. Additionally, the outcomes of our study reject the null hypothesis for the unit root of the study variables (i.e. carbon emission, ecological footprints, innovation, REN, GDP) with the presence of CSD, structural breaks, and heterogeneity. This indicates that all of the study variables are stationary at first difference.

Furthermore, the results in Table 3 report on the slope of heterogeneity analysis while observing carbon emission with ecological footprints as the main dependent variable of the study. Findings under the Delta tilde (DT) and Delta tilde Adjusted (DTA) have reported significant outcomes for both of the dependent variables, namely CE and EFP. This means that the null hypothesis is rejected at 1%.

Table 4 depicts that the null hypothesis shows no presence of cointegration among the variables. The empirical findings in Table 4 thus reject the null hypothesis related to the no integration along with the mean shift and regime shift.

In Table 5, the results confirm the presence of cointegrating association between the variables for the full sample as well as for Malaysia, Indonesia, Thailand, Vietnam, Singapore, and Philippines at 1% significance. Similarly, the findings are significant for the full sample as well as for the individual states when the dependent variable is ecological footprints. As the cointegrated nexus among the study variables is confirmed, we can move towards both short run as well as long estimation for the findings.

Table 6 shows that INV impacts CE negatively. This justifies the statement that INV plays a role in lowering the CE among the selected economies. During recent years, numerous studies have provided empirical contributions while observing the association between CE and ecological innovation. For example, Zhang et al. (2017) and Li et al. (2021) confirmed the prominent role of environmental innovation factors in reducing the CE in China. Meanwhile, the empirical findings by Nguyen et al. (2020) advocate that spending on innovation impedes the CE, while Ganda (2019)



**Table 3.** Slope heterogeneity analysis.

Statistics	Test value (Sig-value)
CE (DV1)	
DT	28.289*** (0.000)
DTA	33.357*** (0.000)
EFP (DV2)	
DT	27.278*** (0.000)
DTA	32.167*** (0.000)

Note. Whereas CE means carbon emission, EFP means ecological footprints, INV means innovation, REN means REN, GDP means gross domestic product, respectively.

Source: authors estimation.

**Table 4.** PCA.

Test	No break	Mean shift	Regime shift
CE (DV1)			
$Z_{\phi}(N)$	-4.201***	-3.221***	-5.010***
$P_{value}$	0.000	0.000	0.000
$Z_{\tau}(N)$	-3.452***	-2.700***	-4.110***
$P_{value}$	0.000	0.000	0.000
EFP (DV2)			
$Z_{\phi}(N)$	-8.234***	-7.276***	-11.001***
$P_{value}$	0.000	0.000	0.000
$Z_{\tau}(N)$	-7.470***	-6.236***	-9.100***
$P_{value}$	0.000	0.000	0.000

Note. Whereas CE means carbon emission, EFP means ecological footprints, INV means innovation, REN means REN, GDP means gross domestic product, respectively.

Source: authors estimation.

**Table 5.** CA.

States	No deterministic specification	With constant	With trend
CE emission (DV1)			
Full Sample	-5.872***	-5.761***	-6.983***
Malaysia	-4.285***	-4.174***	-5.396***
Indonesia	-6.145***	-6.034***	-7.256***
Thailand	-7.247***	-6.136***	-7.358***
Vietnam	-5.276***	-5.165***	-6.387***
Singapore	-4.176***	-4.065***	-4.287***
Philippines	-6.278***	-6.167***	-7.389***
EFP emission (DV2)			
Full Sample	-4.418***	-4.357***	-4.123***
Malaysia	-6.105***	-5.465***	-6.321***
Indonesia	-5.656***	-5.388***	-5.155***
Thailand	-7.334***	-7.555***	-8.204***
Vietnam	-4.270***	-4.907***	-4.301***
Singapore	-6.008***	-5.088***	-7.105***
Philippines	-7.134***	-6.303***	-8.010***

Source: authors estimation.

justifies that spending on research and development-related activities impacts CE negatively. In addition, findings under the CS-ARDL long run estimation showed that REN impacts CE negatively among the selected economies ( $\beta = -0.295$ ,  $t$ -statistics =  $-3.017$ ,  $p$ -value =  $0.000$ ). This explains that higher consumption of energy from renewable sources like solar and wind may lead towards lower emission in the natural environment. Such finding is similar to Acheampong et al. (2019) who provided empirical justification for lower carbon emission due to REN consumption.

**Table 6.** Autoregressive distributed lag analysis for long run.

Constructs	B-Coeff	t-stats	Sig
CE (DV1)			
INV	−0.311***	−4.011	0.000
REN	−0.295***	−3.017	0.000
GDP	0.171***	3.171	0.000
GDP <sup>2</sup>	−0.153*	−1.712	0.082
CSD-statistics	–	0.044	0.910
EFP (DV2)			
INV	−0.517***	−3.845	0.000
REN	−0.470***	−5.006	0.000
GDP	0.354***	5.607	0.000
GDP <sup>2</sup>	−0.267**	2.122	0.041
CSD-statistics	–	0.013	0.956

Note. CE means carbon emission, EFP means ecological footprints, INV means innovation, REN means REN, GDP means gross domestic product, respectively.

Source: authors estimation.

In addition, the long-run estimation of the CS-ARDL approach also found that there is a positive correlation between GDP and CE in selected economies. This is due to the fact that more economic activities tend to utilize more resources like transportation and energy for the production of goods and services. Such production, in return, will generate a higher level of CE in the natural surrounding. This is further justified by our empirical results where a one-unit increase in GDP causes a carbon emission of 0.171 in the natural environment. Numerous empirical studies have propounded on the direct role of GDP in creating more CE. This includes Ahmad et al. (2018) who reported that there is a significant and positive impact of GDP on the CE for the economy of China. Whereas, Lin and Benjamin (2017) have also justified the direct impact of GDP in determining the CE. Similarly, Dehghan Shabani and Shahnazi (2019) investigated the level of carbon dioxide emissions within the Iranian economic sectors. It was observed that there is a long-run causality from GDP to CE in all of the economic sectors. Besides, Wang and Ye (2017) have also confirmed the non-linear effect of EG (GDP) on the CE. Furthermore, the CS-ARDL findings in Table 7 indicate that GDP2 influences carbon emission negatively as the beta value is negative and *t*-value is  $-4.482$ . This means that GDP has its positive impact while GDP2 has its negative impact in determining the CE among the selected economies under the present study. Anser et al. (2020) claimed that in Latin American & Caribbean economies, GDP2 is found to effect CE in negative manner. Cetin and Ecevit (2017) have also justified similar arguments under the long-run estimation and claimed similar evidence.

Table 6 presents results for the second-dependent variable of ecological footprints. It is revealed that Inv impacts EFP negatively. This shows that for every single unit increase in ecological innovation value, there is a decline of 0.517 in the value of EFP and vice versa. Various studies have also examined the linkage between INV and EFA. For suppose, Mahmood Ahmad et al. (2021) have observed the dynamic link between ecological innovation, EG, and EFP with the presence of financial globalization among the G7 economies. Their findings confirmed that ecological innovation in the G7 plays a significant role in decreasing ecological footprints. Whereas, Zeraibi et al. (2021) have provided similar evidence where higher technological innovation reduces ecological footprints. This is further supported by Ahmad et al. (2020) who

justified that technological innovation helps to abate environmental degradation. However, Ke et al. (2020) claimed that innovation efficiency promotes and then suppresses the ecological innovation within the economy of China where innovation improvements and related efficiency still contribute towards the rise in ecological footprints, particularly in western and northeastern China. Additionally, the findings reported in Table 6 predict that REN impacts EFP in negative, which means that a higher level of REN sources leads towards the lower level of EFP and vice versa. This is in line with Danish and Khan (2020) who provided the evidence that REN plays a role in reducing the EFP in BRICS countries. Similarly, Usman et al. (2020) claimed that REN exerts negative pressure on ecological footprints in the USA while Sharma et al. (2021) found that REN sources significantly reduced the ecological footprints in the region. Meanwhile, the impact of GDP on EFP is also significant and positive, thus proving that higher economic activities are causing more ED in the form of ecological footprints, whereas GDP2 is playing its role in reducing the EFP.

Finally, our analysis has provided meaningful outcomes for the CS-ARDL short-run estimation. The findings in Table 7 posit that innovation has a significant and negative impact on carbon emission. In this regard, both the long run and short run CS-ARDL results are consistent with previous studies like Erdoğan et al. (2020) who reported that an increase in innovation for the industrial sector leads to a reduction of CE. Meanwhile, Wang et al. (2020) claimed that technological innovation is adversely related to the CE. Similarly, the role of REN was observed to be negative and significant in dealing with the ecological footprints among the targeted economies, whereas GDP has been confirmed to have a direct impact on EFP, thus providing the evidence that more EG will lead towards higher environmental degradation. This is in line with Toth and Szigeti (2016) who observed a positive correlation between GDP and ecological footprints. Similarly, Wang et al. (2020) indicate that EG is putting an adverse impact on the climate change. However, GDP2 has been observed to be negatively linked with the EFP under the long-run estimation.

Finally, Table 7 contains the CS-ARDL analysis results for the short-run covering of CE and EFP as the main dependent variables. The results confirm that innovation and REN both negatively and significantly determine carbon emission, whereas GDP was observed as a positive indication of higher ED like CE. However, like long-run

**Table 7.** Autoregressive distributed lag model for short run.

Constructs	Beta-coeff	t-statistics	Sig.
CE (DV1)			
INV	-0.176***	-3.067	0.000
REN	-0.117**	-2.351	0.037
GDP	0.216***	5.013	0.000
GDP2	-0.074***	-4.482	0.000
ECT(-1)	-0.322***	-4.003	0.000
EFP (DV2)			
INV	-0.097***	-3.556	0.000
REN	-0.038***	-6.101	0.000
GDP	0.112***	8.133	0.000
GDP2	-0.075*	-1.901	0.055
ECT(-1)	-0.103***	-3.801	0.000

Note. CE means carbon emission, EFP means ecological footprints, INV means innovation, REN means REN, GDP means gross domestic product, respectively.

Source: authors estimation.

estimation, GDP2 was observed to be negatively linked with the CE, which means that it contributes towards lowering the CE in the natural environment. The negative impacts of INV and REN on CE are consistent with a number of past studies (Ganda, 2019; Long et al., 2015; Nguyen et al., 2020; Yuaningsih et al., 2021; Zhang et al., 2017). In addition, findings for EFP as the main dependent variable also posit a significant and negative impact from innovation and renewable. These findings are consistent with those reported by previous studies where innovation and REN have been propounded as among the good signs in lowering ecological footprints and environmental degradation. Besides, GDP has also been found as a direct source for higher EFP, with the exception of GDP2.

## 5. Conclusion

The current paper has examined the effect of innovation, renewable energy, EG & square of EG in terms of GDP in determining the CE and ecological footprints for the six ASEAN economies. The Pesaran (2007) test along with various unit root tests were applied to check the CSD while the CS-ARDL approach was conducted to examine the long run and short-run association between the dependent and independent variables. It was found that innovation, REN, GDP, and square of the gross domestic product have a significant impact towards CE and ecological footprints. However, innovation, REN, and GDP2 play a negative role in lowering the CE and ecological footprints while GDP has a direct role towards higher carbon emission and EFP. This thus justifies the argument that higher ecological and related innovations can be observed as constructive in reducing the ED in ASEAN economies. Meanwhile, the negative and adverse impact of GDP needs to be controlled through environmental reforms that do not restrict the trades but only target the reduction of CE in the selected regions. It was also observed that the economic activities in these economies are significantly dependent upon transportation and various other means where there is more utilization of traditional energy sources for the production and movement of goods and services. Therefore, these economies should focus on importing environmental-friendly machinery and equipment for a longer period of time. Besides, policies and practices related to carbon emission and ecological footprints need to be aligned with the global environmental concerns in order to achieve significant generalized outcomes. Future studies are suggested to expand their sample size in terms of regional context for the entire developing economies in the Asian region.

## Disclosure statement

We declare that there is no competing interest.

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