



# The influence of technological innovation and human capital on environmental efficiency among different regions in Asia-Pacific

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## Abstract

This study employs super-efficiency DEA model with desirable inputs and an undesirable output in calculating environmental efficiency values in different regions in Asia-Pacific from 1990 to 2018. The study compares environmental efficiency index in South East Asia, South Asia and East Asia. The study also evaluates the determinants of environmental efficiency using truncated regression. The mean environmental efficiency score demonstrates that East Asia region is highly efficient whereas South East Asia is the least efficient. Results from the truncated regression established an inverted U-shape relationship between environmental efficiency and Technological Innovation (TI) in the main panel, and the three regions. Also, economic growth shows an inverted “U” shape link with environmental efficiency in the panels except in South East Asia. Human capital promotes environmental efficiency in the main panel and the rest of the regions. Moreover, while FDI promotes environmental efficiency in the main panel and East Asia, it reduces environmental efficiency in both South East and South Asia regions within the Asia-Pacific. In addition, an interaction effect between technological innovation and renewable energy use, advances environmental efficiency within the entire study countries. Based on the findings the study proposes several policy recommendations.

**Keywords** Environmental efficiency · Technological innovation · Human capital · Asia-Pacific

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## Introduction

The rate at which the earth’s system is experiencing acute environmental changes is alarming. Humans’ very own actions such as the use of fossil fuel, the burning of coal, high energy consumption and emission of all sorts of pollutants, coupled with the rapid economic growth and total negligence for environmental health have resulted in the gradual depletion of the ozone layer, posing potential danger to human survival, hence, the increasing awareness of global environmental health. Developed and developing countries have realized the need to combine economic development and environmental protection to ensure sustainable growth (Wang et al. 2018). The goal of sustainable development is to improving standard of living, promoting environmental efficiency and conserving energy (L. Li et al. 2011). Many countries under the Paris Agreement have designed robust national climate actions in attempt to achieving sustainable environment whiles emphasizing on the essentialities in shifting from non-renewable to renewable energy use, green and technological innovation in order to achieve environmental quality. The consumption of clean energy advances the reduction of carbon emission (Paramati et al. 2017).

Environmental sustainability growth requires that technological innovation is efficiently exploited for the benefit of humans to enhance generational needs today and in posterity. In recent times, a lot of researchers have emphasized on the importance of technological innovation and its role in achieving environmental sustainability. According to Apergis and Payne (2009), energy consumption plays a vital role in economic growth and in their investigation of the relationship between energy use and economic growth, their findings indicated a positive relationship. The kind of energy used, therefore, is important for achieving high environmental performance. Apergis and Payne (2010) again examined the relationship between renewable energy and economic growth and found that, the use of renewable energy has a long run effect on economic growth, while it supports environmental sustainability.

Asia-Pacific, being part of the largest continent with a population of over 4.3 billion, is recorded to be the highest emitter of carbon dioxide and other pollutants due to their global economic dominance and excessive use of fossil energy. A good number of emerging economies in the region have become the centerpiece of the world due to both economic and geo-political reasons. China for instance is presently into urbanization and industrialization, implying that, increase in energy consumption as well as CO<sub>2</sub> emissions is inevitable (Yang et al. 2017). The region has made conscientious efforts to improve environmental performance through their various conferences such as the Asia Pacific Roundtable on Sustainable Innovation and Production (APRSCP), the International Conference on Green and Sustainable Innovation (ICGSI), with the aim to improve and assess environmental performance through technological innovation.

However, Asian economies are largely global giants when it comes to production for consumption and export and therefore their activities have equally influenced pollution emission and environmental efficiency (Buckley 2011; Stiglitz 1996). The region in November, 2020, has signed in Vietnam the biggest free trade agreement, the Regional Comprehensive Economic Partnership (RCEP), with the goal to helping their economies recover from the shocks from the COVID-19 pandemic. While their focus has been on improving economic growth, it is not without a cost because attention will be directed towards more production and more consumption activities.

Environmental efficiency as an index of an ecological performance, serving as a model (Wu et al. 2019), is affected by numerous factors including pollution, energy use and human activities as well as environmental rules. From the perspective of Asia, a lot of studies have been made on eco-efficiency (Chin and Low 2010; Zeng et al. 2020). However, there is little or no consideration for the determinants of environmental efficiency from the standpoint of various regions within Asia. Indeed, domestic governments' activities relating to technological innovation one way or the other influence environmental efficiency (Bian et al. 2020; Hua et al. 2018), which

eventually affect global environment. The motivation for this research is to determine the factors influencing environmental efficiency from the outlook of 15 Asia-Pacific countries under different regions to fill the academic gap.

Asia-Pacific comprises of a diverse group of countries, with different levels of economic achievement and resource endowment. Different from previous studies, this study contributes to the extant studies by employing a two-stage DEA model to examine environmental efficiency in distinct regions in Asia-Pacific. This is an attempt to investigate the effect of technological innovation and human capital on environmental efficiency and its influencing mechanism with other control variables such as FDI, per capita GDP, and renewable energy consumption. However, this analysis assumes that the countries of the survey have identical characteristics. Therefore, this study bears some important research questions. (1) Does technology innovation have non-linear impact on environmental efficiency across the sample regions? (2) Does environmental Kuznets Curve hold in the selected countries? (3) What are the key driving forces of environmental efficiency across these countries?

To answer the above important research questions, this study adds specifically the following novelties to the previous literature as follows: firstly, the study applies directional distance function of super-efficiency two-stage DEA technique to obtain environmental efficiency index in each region. This will enable us compare environmental efficiency score in each region to know which region is doing better in terms of environmental efficiency performance for others to emulate and for effective policy proposal. Most importantly, the study further examines and discusses the non-linear relationship between technological innovation and environmental efficiency within the Pacific regions which previously has been ignored in the sample countries. The study assumes that relationship between environmental efficiency and innovation could not always be linear. Therefore, to capture the full characteristics of innovation and environmental efficiency, the study introduces the quadratic term of technological innovation and economic growth. Third, the study focuses on the existence of Environmental Kuznets Curve by incorporating the quadratic term of per capita income in the model. Last, this study examines the impact of important macroeconomic indicators such as, foreign direct investment, renewable energy use and the interaction term between renewable energy and endogenous innovation on the environmental efficiency. Therefore, this study sets out important guidelines for policy makers to enhance the environmental quality in the Asia-Pacific.

## Literature review

### Environmental efficiency using DEA methods

Exploring extant studies on the method of estimating environmental efficiency indicate that different DEA methods have

been used in the estimation of efficiency scores. The widely used method in evaluating environmental efficiency is the Data Envelopment Analysis (DEA) as a nonparametric programming approach developed by Charnes et al. (1978) and improved by Färe et al. (1989). DEA has been applied in relative evaluation of efficiency in industrial, energy and environment and due to its considerable convenience in usage and economic background, particularly in assessing environmental performance (Halkos and Tzeremes 2013a; Q. Wang and Yuan 2018). Within a traditional DEA model, it is more desirable to input few resources to produce more outputs: nonetheless, in practicality, the process of production results in a sort of another unintended output called undesirable (bad) output for which is not preferred. For instance, pollution and hazardous waste in the process of production in the industries represent undesirable output of which less is needed but inescapably produced (Han et al. 2018; Toloo and Hančlová 2019).

Bian et al. (2020) use per capita GDP and SO<sub>2</sub>, waste water and dust as variables and applied super-efficiency DEA approach to measure eco-efficiency in 278 Chinese cities. Song et al. (2017) divided the process of generation of electricity into the phase of production and the phase of emission reduction. The research uses the SBM model to study the production efficiency and environmental performance of the coal-fired power generation sector from 2006 to 2010 under two different policies. The results indicate that compulsory measures were effective than self-motivating measures in China's environmental quality. In addition, He et al. (2018) offered a comprehensive environmental efficiency index based on assessing the environmental efficiency of major socioeconomic sectors such as power, transportation and industry. The findings show that there exist regional disparities in environmental efficiency scores. Ouyang and Yang (2020) use 27 OECD countries to carry out a case study and the findings demonstrate that the multiplicative model is more effective in calculating energy and environmental quality than the conventional DEA model.

Also, Xie et al. (2014) assessed the environmental efficiency of electric power industries in organization of Economic Cooperation for Development (OECD) and Brazil, Russia, India, and China (BRIC) by using the Malmquist index method based on DEA. Similarly, the following studies (Bian et al. 2020; Halkos and Tzeremes 2013a; Khan et al. 2020; Qin and Du 2017) examined foreign direct investment, per capita GDP, human capital and renewable energy consumption on environmental efficiency. In other words, human capital and renewable energy consumption will help reduce emissions and consequently improve environmental quality (Bano et al. 2018; Sarkodie et al. 2020). All these studies from diverse perspective have contributed to the literature on environmental efficiency by applying data envelopment analysis in different settings. One main advantage of DEA is that there

is no need for one to assume any relationship between the input and the output (Seiford and Thrall 1990). Besides, Wu et al. (2014) assert that it is crucial to measure regional environmental efficiency as it acts as a resource for policy makers to make policies in favor of every region.

## Technology innovation and environmental efficiency

Porter and Class (1995) claimed that strong environmental regulations can motivate firms to increase their innovative capabilities especially green innovation, which will ultimately improve environmental efficiency. This phenomenon is termed as “Porter hypothesis.” On opposing note, Goulder and Schneider (1999) stated that investment in innovation might lower production or emissions reduction costs thus, leading to the low productivity which can eventually reduce environmental efficiency. This hypothesis is termed as “crowding out effect” Technological innovation and environmental guidelines are an effective means for governments to regulate environmental pollutions. These measures help improve the economy and environmental efficiency (Mazzanti and Zoboli 2009; Yuan and Xiang 2018). Numerous studies have analyzed technology innovation-environmental efficiency nexus. According to Lina et al. (2013), technology is the internal driving force behind the improvement of environmental efficiency. Using the super-efficiency DEA technique, they analyzed urban collection of eco-efficiency and their findings indicated that technological progress improves the growth rate of eco-efficiency. Wan et al. (2015) examined the impact of technological innovation on eco-efficiency in the industrial sectors in China and their findings were that, overall, technological innovation improves environmental efficiency. Yasmeen et al. (2020) also investigated the roles of technological innovation in eco-efficiency in China. They employed the super-efficiency DEA to estimate efficiency and Generalized Method of Moment to explore the impact of technological innovation on eco-efficiency, and found technological innovation to improve environmental efficiency. Meanwhile, Sun et al. (2020) also had studied the relationship between digital finance, technological innovation and marine eco-efficiency, and one more time, their findings were also consistent with the other studies when they found technological innovation to promote marine eco-efficiency. In fact, the role of green technology innovation and clean production in the achievement of environmental sustainability can never be downplayed (Yasmeen et al. 2020).

In the conventional economic theory, the relationship between technological innovation and environmental regulation is negative and the reason is that environmental regulation surges costs of firms and thereby absorbs resources for innovation (Pan et al. 2019). Based on the above literature, this study proposes the following research hypothesis.

Hypothesis 1: Technology innovation has significant positive effect on environmental efficiency across the underlined regions.

### Human capital and environmental efficiency

Extant literatures have established that many of the global environmental challenges are human induced, which means that human activities, either intentional or unintentional have been the main cause of poor environmental performance. However, there are other studies which also have concluded that human activities can increase environmental quality and that through education, human capital improves environmental performance because education causes a turn in the actions of humans. Iorember et al. (2020) investigated the environmental implications of renewable energy, trade and human capital in South Africa and their findings revealed that human capital improves environmental performance. Also in the investigation of the effect of renewable energy, economic growth, and human capital on carbon emission, Mahmood et al. (2019) found human capital to control and reduce carbon emission. Moreover, Nathaniel et al. (2020) studied the effect of natural resources, urbanization, globalization and human capital on environmental degradation and found that while urbanization, natural resource and globalization all increase environmental degradation, human capital rather reduces and controls environmental degradation. Enhancing human capital via education will have a long-term positive effect on the environment because human capital reduces carbon emission. In the achievement of sustainability, human capital needs to be considered an ally (FarC~nik and IsteniC~ 2020). Human capital development decreases ecological footprint in the study conducted by Ahmed et al. (2019).

Hypothesis 2: Human capital has significant positive effect on environmental efficiency across the underlined regions in the Asia-Pacific.

### Per capita income and environmental efficiency

This strand of research explains the relationship between per capita income and environmental efficiency, known as Environmental Kuznets Curve (Grossman and Krueger 1991). This hypothesis postulates that environmental efficiency reduces as income per capita increases during the early stages of economic development. However, after income per capita reaches a threshold income level, the environmental efficiency improves with further increase in income per capita thus, this relationship exhibits a U-shaped curve. Subsequently, many studies explored this relationship using different datasets and countries (Halkos and Tzeremes 2009;

Halkos and Tzeremes 2013a; Salman et al. 2019b). In addition, Cheng et al. (2018) argued that economic growth affects the environmental efficiency. Halkos and Polemis (2018) measure the productivity of the US power generation system by using the Window Data Envelopment Analysis (W-DEA). The findings indicate that there is an N-shape correlation between environmental performance and global economic development, but an inverted N-shape for local pollutants. Moutinho et al. (2020) measured the impact of per capita income on eco-efficiency based on super-SBM and found that per capita GDP has negative impact on the performance of environmental efficiency.

Hypothesis 3: Per capita income might have a U-shaped relationship with environmental efficiency across the underlined regions in the Asia-Pacific.

### Foreign direct investment and environmental efficiency

Foreign direct investment may influence the environmental efficiency of a country through mechanisms such as “Pollution heaven” and “Pollution halo.” The former hypothesis generally explains the negative consequences of foreign investment on the condition of environmental efficiency. It says that multinational corporations mainly shift their production units to country where environmental regulations are not strong thus, turning the host country into pollution paradise. On the other hand, “Pollution halo” hypothesis claims that the host country can augment the environmental efficiency by enforcing strict environmental guidelines, thus forcing the foreign companies to adopt cleaner production technologies. Previously, many scholars have validated both the hypothesis from different perspectives (Salman et al. 2019a). For instance, Feng et al. (2018) highlighted that over the years, policies in China have eased the negative effect of FDI on green innovation efficiency in the regions. Again, the study realized that the mechanisms of environmental regulation strategies largely promote FDI by promoting indicators that have positive impact on innovation efficiency in the regions. However, the research asserts that positive effect of regulation is not realized in some regions in China. FDI inflows positively affect clean energy use and the environment (Paramati et al. 2016) Moreover, other studies provide contradicting results regarding FDI-environmental efficiency nexus (Zhang and Zhang 2018; Li et al. 2018). Following the mechanisms of FDI and the results of previous studies, this study puts forward the following hypothesis.

Hypothesis 4: FDI might have significant negative effect on environmental quality across the underlined regions.



## Methodology and data source

### Model construction and variable selection

There is no one index to represent technological innovation but patent is a generally used index because patent is the product of the R&D operations and the technical basis of industrialization. In this paper, patent applications represent technological innovation. This is because information on patent grants is converted into patent application (Acs et al. 2002; Song et al. 2015) hence making more feasible for technological innovation.

### Super-efficiency DEA model

DEA is a process that involves estimating the relative efficiencies of a set of comparable DMUs by particular mathematical programming models (Halkos and Tzeremes 2013a; Q. Wang and Yuan 2018). It has been known to be an important approach in the estimation of relative performance of a homogenous DMUs that have multiple input and output. Per the efficiency scores estimated, the DEA is able to categorize the DMUs into different groups; efficient and inefficient. However, while the inefficient DMUs are easy to rank, the efficient DMUs remain rather challenging to be ranked based on their efficiency scores due to the fact that they have same efficiency score unity. On a more reasonable term, it would be a huge mistake to just assume that all the efficient DMUs have same performance in reality. The bone of contention here lies with how efficient DMUs can be ranked.

The super-efficiency DEA as introduced by Banker and Gifford (1988) and Banker et al. (1989) focuses on the ability of the DMUs to possibly increase its input and output without compromising its efficiency. The super-efficiency method is uniquely known for multiple functions such as being able to (1) identify outliers, (2) identify overly efficient DMUS, (3) rank the overly efficient DMUs, (4) measure changes in technology and productivity, (5) address two-persons ration efficiency games, and (6) calculate stability regions.

Therefore, following Shuai and Fan (2020), this research applied the super-efficiency DEA technique to construct a model to evaluate environmental efficiency. The DMU<sub>j</sub> (j = 1, 2, 3, ..., n) has h inputs

Following these steps

Step 1: Let  $X_j = (x_{1j}, x_{2j}, \dots, x_{hj})$  and s term output  $Y_j = (y_{1j}, y_{2j}, \dots, y_{sj})^T$ , where  $x_{mj}$  represents the mth type of input of the jth UDM<sub>j</sub>, the quantity,  $y_{lj}$  represents the input quantity of the jth UDM<sub>j</sub>,  $x_{mj} > 0$ ,  $y_{sj} > 0$ ,  $m = 1, 2, 3, \dots, h$ ,  $l = 1, 2, \dots, s$ .

Model construction

Min  $\theta_j$ :

$$\begin{aligned} \sum_{j=1}^n \rho_j X_j + s^- &= \theta_i X_i \quad i = 1, 2, \dots, n. \\ \sum_{j=1}^n \rho_j X_j - s^+ &= Y_i \quad i = 1, 2, \dots, n. \end{aligned} \tag{1}$$

$$\begin{aligned} \rho_j &\geq 0, j = 1, 2, \dots, n. \\ s^+ &\geq 0, s^- \geq 0 \end{aligned}$$

where Eq. (1),  $\theta_i$  is the actual value of  $U_{DM_j}$ , which is closer to 1, the more effective the input of this DMU is. The validity judgment method is: if  $\theta_i = 1$ ,  $U_{DM_j}$  is called valid or weak effective for DEA. When  $s^+ = s^- = 0$ ,  $U_{DM_j}$  it is said DEA is valid; if  $\theta_i < 1$ , then  $UDM_j$  is invalid for weak DEA. The inputs data slacks variable is  $s^-$ , and  $s^-$  denotes an input surplus, that is, an unused resource. If  $s^- \neq 0$  it suggests that the output is permanent, the input can also reduce  $s^-$ ; the output slack variable for  $s^+$ ,  $s^+$  indicates that output is inadequate, and  $s^- \neq 0$  indicates a possible increase in output if the input remains constant  $s^+$ . Therefore, if the DMU is not valid, the DEA can be easily modified by not adding the input variable to the DMU.  $\bar{X}_i = \theta_i X_i - s^-$ . Assuming a static input level, the output variable is modified as  $\bar{Y}_i = Y_i + s^+$ .

In the standard DEA model, multiple DEAs can be useful when evaluating green economic performance. Here, the complete technical efficiency index is  $\theta = 1$ , making evaluation of effective DEA unfeasible. Thus, the use of a super-efficiency model provides a more in-depth production efficiency ranking of all DEA effective decision-making units. The super-efficient DEA (SE-DEA) model is written below:

$$\begin{aligned} \min & \left[ \theta - \epsilon \left( \sum_{i=1}^m s_i^- + \sum_h^s s_h^+ \right) \right] \\ & \sum_{j=1}^n \rho_j X_{ij} + s^- \leq \theta X_0 \\ & \sum_{j=1}^n \rho_j Y_j - s^+ = Y_0 \\ & \rho_j \geq 0, j = 1, 2, 3, \dots, n \quad s^+ \geq 0; s^- \geq 0 \end{aligned} \tag{2}$$

$\rho$  is the weight variable of the DMU,  $\theta$  is the estimated parameter, slack variables  $s_h^+$ ,  $s_h^-$ ,  $X$  denotes input, and  $Y$  denotes output. The solution model is represented by  $\theta^*$ . If  $\theta^* < 1$ , it postulates that the decision unit output is not lower than  $j_0$  decision unit, and the input ratio is  $j_0$  decision units. If  $\theta^* = 1$  and the slack variables are all 0, the  $j_0$  decision unit is DEA valid; and  $\theta^* < 1$ , then the  $j_0$  decision unit is valid for weak DEA.

### Data source

Table 1 outlines the source of data as well as the variable definition. The variables for the research are per capita GDP

(constant 2010 US\$), renewable energy consumption (per capita kg), innovation (total patent application), CO<sub>2</sub> emissions, and are all obtained from World Bank World Development Indicators (WDI 2018) whereas human capital (HC) is obtained from Pen World Table version 9.0 DATA. In this paper, 15 sampled Asia-Pacific countries are divided into three (3) regions, South East Asia, South Asia, and East Asia. The selection of the countries was done based on availability of data, especially for the key variable; total patent application proxied for innovation. Table 2 shows the descriptive statistics of the selected variables.

Obs denotes observations, Std.Dev is standard deviation, environmental efficiency index (EE), economic growth (PGDP), foreign direct investment (FDI), human capital (HC) and technological innovation (TI), and renewable energy consumption (REC)

### Econometric model construction

This paper examines the influencing factors of technological innovation, human capital and economic growth on environmental efficiency in 15 countries in Asia grouped under different regions. Employing truncated regression this study further explores the nonlinear relationship between technological innovation and environmental efficiency. The study assumes that relationship between environmental efficiency and innovation could not always be linear. Therefore, to capture the full characteristics of innovation and environmental efficiency, the study introduces the quadratic term of technological innovation and economic growth. Based on (Halkos and Tzeremes 2013b; Li et al. 2018), the study proposes the following model.

$$EE_{it} = \beta_{0+} \beta_1 \ln PGDP_{it} + \beta_2 (\ln PGDP_{it})^2 + \beta_3 \ln TI_{it} + \beta_4 (\ln TI_{it})^2 + \beta_5 \ln FDI_{it} + \beta_6 HC_{it} + \beta_7 \ln REC^* \ln TI_{it} + \beta_8 \ln REC_{it} + \mu_{it} \quad (3)$$

### Variable selection

The dependent variable in this research is environmental efficiency (EE). Environmental efficiency is influenced by technological innovation (TI), therefore, the study chooses technological innovation (TI) and its quadratic term. The cost of pollution control enhances innovation capabilities of countries and firms to be competitive in the market (Dangelico and Pujari 2010). When environmental regulations are stringent it promotes clean production through innovation which consequently improves environmental efficiency.

Control variables affecting environmental efficiency of Asia-Pacific countries are also included in the model. These control variables included per capita GDP of each country and its square term is added to the model. Halkos and

Polemis (2018) identify a nexus of economic growth and environmental efficiency. Foreign direct investment (FDI) generally reflects the performance of foreign firms with respect to environmental performance. FDI has a direct relationship with environmental efficiency as well as sustainable growth (Sarkodie and Strezov 2019; Yang and Li 2019). Hence, FDI is included in the model, functioning as a control variable. FDI is calculated by the percentage of foreign direct investment to GDP, renewable energy consumption (REC), and human capital (HC). Human capital encourages the clean production technology application and provides the needed support for reducing emission as well as energy conservation (Zhao et al. 2016). Energy is inevitable in any economy and therefore to capture renewable energy innovation in these countries, the study added an interaction term between technological innovation and renewable energy consumption (TI\*REC).

## Results and discussion

### Environmental efficiency scores

In Fig. 1, the mean environmental efficiency for the main panel shows that East Asia has the highest. It rises and falls within a range of 0.92 and 0.82 between 1990 and 2014. There was a dramatic fall from 2014 to 2016. Since then it rises drastically to about 0.93 where it flattens in 2018. The efficiency score for South East Asia and South Asia started off with 0.68 and 0.75 in the year 1990, respectively. However, from 1998 these regions' environmental efficiency rises at a decreasing proportion till 2016 where South Asia rises and reaches its plateau in 2018 of about 0.75.

In Fig. 2, the environmental efficiency score for East Asia region indicates that between 1990 and 2014, the score for Japan ranges between 1.4 and 1.6. Since 2014, it drastically falls and rises from 2016 to 2018. Japan's environmental efficiency is probably due to its stringent environmental policies. Moreover, it is one of the developed countries with advanced technological capabilities in the world. China and Korea Republic on the other hand, recorded 0.5 and 0.7 respectively within the same period from 2016. There was a dramatic turn where China increases its environmental efficiency to about 1.6 in 2018. China over the years has also instituted environmental regulation policies which were focused on improving environmental efficiency.

In Fig. 3, the environmental efficiency score in South Asia region, indicates that while Sri Lanka has the highest efficiency score ranging between 1.2 and to about 0.78 in 2016, from 2016 to 2018, Pakistan was highly inefficient. Moreover, the environmental efficiency for Bangladesh, Pakistan and India were almost stable hovering 0.62 especially India where it flattens around same value from 1990 to 2018. In this region, the poor performance of the individual countries in

**Table 1** Data source and definition of variables

Variables	Definition	Source
Per capita GDP	Gross domestic product per capita in constant 2010 US\$ dollar	World Development Indicators
Total patent application	Resident patent and non-resident patent	World Development Indicators
Renewable energy consumption	Total renewable energy consumption % total energy consumption	World Development Indicators
Human capital	Human capital index, centered on years of schooling, returns to education	Pen World Table version 9.0 DATA
CO <sub>2</sub> emissions	Kilotons	World Development Indicators
Foreign direct investment	Gross domestic product per capita in constant 2010 US\$ dollar	World Development Indicators
GDP	Constant 2011 US\$	Pen World Table version 9.0
Capital stock		Pen World Table version 9.0 DATA
Energy consumption	Energy use (kg per capita oil equivalent)	World Development Indicators

Captial stock is constant 2011 US\$

Energy consumption is kilotons

environmental efficiency may be as result of the recent increase in manufacturing activities and its accompanying emissions in the region.

The results of the environmental efficiency (EE) for South East Asia (SEA) region in Fig. 4 for individual countries show that all the countries in SEA are largely stable. The EE score ranges from 0.5 to about 0.7 from 1990 to 2018 except Singapore which has some spiral movement between 1996 and 2011 and the highest point is in 2001. In this region Singapore is considered to one of the developed countries and therefore has potential for clean production resulting in quality environment.

### Truncated regression results

The results for influencing factors of environmental efficiency are presented in Table 3. From the perspective of technological innovation (TI), the coefficient for TI is negative and significant for the main panel, South East Asia and East Asia. This means TI reduces environmental efficiency in the main panel, South East Asia and East Asia. At the same time the square of TI increases environmental efficiency in the main panel and the three regions of South East Asia, South Asia and East Asia. This is similar to Sun et al. (2020) who found out that technological innovation has positive effect on environmental efficiency of electric power industry. This

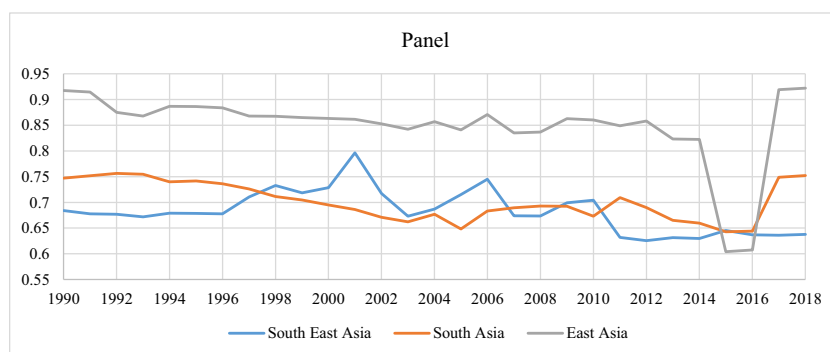
shows that there is an inverted U-shape relationship between environmental efficiency and technological innovation. When innovation is constant within a certain “level” its effect on environmental efficiency decreases, but if this concentration exceeds after that “level,” it presupposes that the effect is advanced and environmental efficiency is promoted. In conclusion, it can be specified that the link between technological innovation and environmental efficiency is not entirely positive or negative but technological innovation continues to promote environmental efficiency as the development of the economy progresses. In early phase of development, TI may not be enough in the production process to offset the negative effect of production but as the countries develop, the technology sector also improves, causing a spillover to other areas including the environment, hence, the positive effect of technology spillover on the environment can then increase environmental efficiency in these regions. Therefore, the quest for improving environmental efficiency through technological innovation should be a continued process because it takes a while before its benefits are realized. As was pointed by Pan et al. (2019), technological innovation has a major role in advancing eco-efficiency.

Moreover, the results show that economic growth is significantly negative and decreases environmental efficiency within the main panel, South Asia and East Asian regions. This shows that economic growth requiring consumption of energy

**Table 2** Summary statistics of the selected variables

Variable	Units	Obs	Mean	Std.Dev.	Min	Max
EE	Index	435	0.79	0.25	0.52	1.09
FDI	Constant 2010 US\$	435	18,300,000,000.00	37,100,000,000.00	1,971,713.00	247,000,000,000.00
PGDP	Constant 2010 US\$	435	13,650.05	17,262.74	411.16	58,247.87
TI	Patent Application	435	78,200.00	187,000.00	62.00	1,540,000.00
REC	Per capita oil equivalent	435	279.68	282.79	7.37	1380.00
HC	Years of schooling and returns on education	435	2.51	0.66	1.31	3.72

**Fig. 1** Environmental efficiency for the main panel over the period 1990–2018



such as fossil energies have adverse effect on the environment. The over-dependence on excessive use of energy producing by-products which exceeds the capacity of the environment to absorb, leads to reduction in environmental efficiency. Then also, per capita GDP square increases environmental efficiency in the main panel, South Asia and East Asian regions. This portrays that there is an inverted U-shape relationship between environmental efficiency and economic growth in the main panel, East Asia and South Asia. This is similar to Halkos and Paizanos (2013). The impact of economic growth on environmental efficiency is negative at the early stages of development to a certain “critical point” exceeding this point; its effects promote environmental efficiency. Therefore, the correlation between environmental efficiency and economic growth is dynamic hence can be positive or negative depending on the stage of development. At higher income level people tend to be more conscious about their health and therefore generally demand clean environment with stringent environmental regulations which consequently promote environmental efficiency in some of these countries.

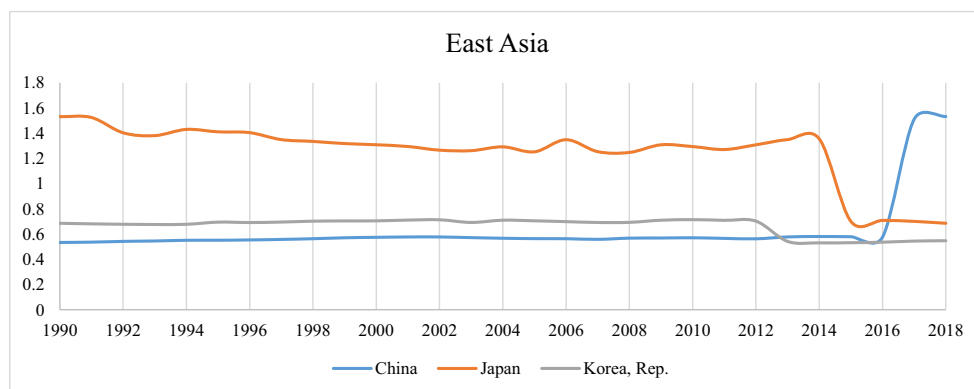
Foreign direct investment FDI is positively significant and reduces environmental efficiency at the main panel and East Asia. FDI in overall panel and East Asia has a significant positive relationship with environmental efficiency. FDI in East Asia region improves environmental efficiency could be that countries in this region can ensure the quality of FDI inflow to this region. Besides, in Asia some of the developed countries including Japan are found in this region. Therefore, their

environmental regulations could largely attract quality FDI with a high knowledge spillover to reduce pollutions and consequently promote environmental efficiency. However, at regional level, South Asia and South East Asia have negative relationship with environmental efficiency but South Asia region failed to pass the significant test. This indicates that FDI deteriorates environmental efficiency since it could largely be pollution intensive FDI. Yang and Li (2019) found similar results for China. Again, heterogeneity in development levels plays a role because developed countries have more stringent environmental regulation that deter pollution intensive industries than their counterparts in the developing level.

Human capital increases environmental efficiency in the main panel, and in the three regions. Human capital has a significant role in climate change mitigation because educated people tend to be more responsive to environmental regulations. Therefore, in countries where people have attained certain level of education, it is likely their actions will directly or indirectly influence environmental efficiency. As Ouyang et al. (2020) argued that advanced human capital has positive impact on environmental regulation which ultimately improve the environmental efficiency across the underlined countries. This in effect can also increase environmental efficiency in those countries. Hence, there is a positive interaction between human capital and environmental efficiency.

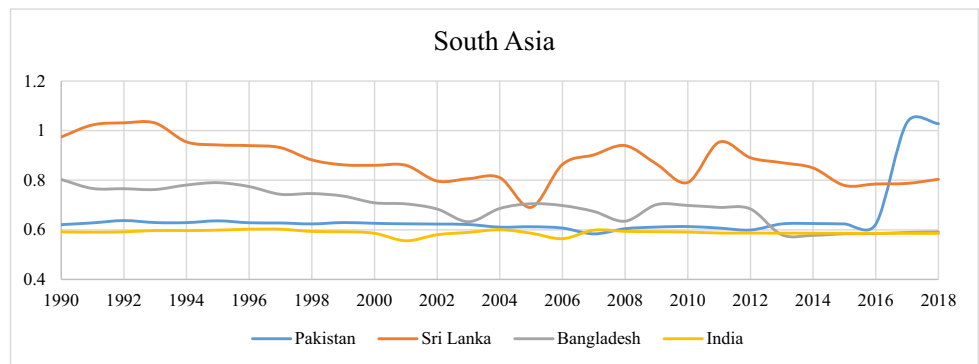
Renewable energy consumption is positive and improves environmental efficiency in the main panel, South Asia and East Asia. Renewable energies are noted for their positive

**Fig. 2** Environmental efficiency for East Asia over the period 1990–2018





**Fig. 3** Environmental efficiency for South Asia over the period 1990–2018



effects on environment due to less carbonated by-product from its consumption. As a result, its consumption decreases emissions and hence promotes environmental efficiency in these countries. Energy consumption has a tremendous effect on economic development and the environment. However, in South East Asia, it decreases environmental efficiency but failed the significance test.

From the perspective of the interaction term between renewable energy consumption and technological innovation, the interaction term is positively significant in the main panel and in the three regions. This shows that the impact of the term on environmental efficiency is conducive hence it increases environmental efficiency.

**Endogeneity analysis**

The truncated regression comes with numerous benefits. However, to do away with biasedness in the results, this study adopted a Two-Stage Least Square, 2SLS to test for endogeneity. Endogeneity, to a large extent refers to how the endogenous variable, otherwise known as the dependent variable, relates with the error term in the model due to reasons such as variable omission. To address a possible case of endogeneity, the study used 2SLS procedure for consistent estimation of simultaneous equation with endogenous predictors.

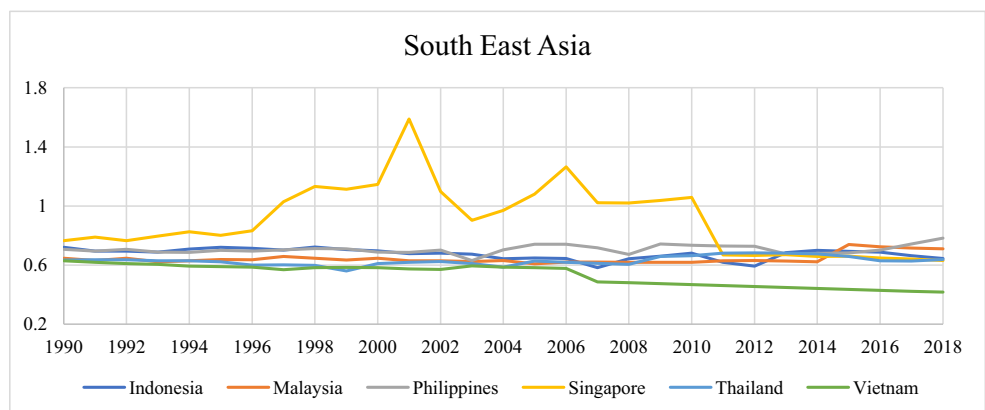
The results of the two-stage least square (2LS) in Table 4, was in lieu with findings of the truncated regression. The 2SLS established the inverted U-shape relationship between environmental efficiency and technological innovation in the main panel, South East Asia, South Asia and East Asian. Besides, human capital enhances environmental efficiency in all the regions collaborating the results for the truncated regression. Furthermore, the relationship between environmental efficiency and economic growth is an inverted U-shape. This means Environmental Kuznets Curve is confirmed in South East Asia, and East Asian. This is similar to the truncated regression results. Also, the interaction effect between renewable energy consumption and technological innovation  $\ln REC * TI$  promotes environmental efficiency at the main panel level and in most of the regional panel level. The instrumental variables show that human capital increases economic growth at panel levels.

**Conclusion and policy implications**

**Conclusion**

The study employs super-efficiency DEA model with desirable inputs and an undesirable output to calculate

**Fig. 4** Environmental efficiency for South East Asia over the period 1990–2018



**Table 3** Results of truncated regression

Variable	Panel	South East Asia	South Asia	East Asia
lnTI	0.0224 (0.017)	− 0.115** (0.0518)	− 0.257*** (0.0416)	− 0.00094** (0.0943)
lnTI <sup>2</sup>	0.0015** (0.0081)	0.0104*** (0.00374)	0.0112*** (0.00187)	0.00978*** (0.00402)
lnPGDP	− 0.0739** (0.052)	0.103** (0.0709)	− 1.224** (0.273)	− 0.344*** (0.219)
lnPGDP <sup>2</sup>	0.0537** (0.0081)	− 0.0046 (0.00374)	0.0741*** (0.00187)	0.0258** (0.00402)
lnFDI	0.0158*** (0.0031)	− 0.0296 (0.0068)	− 0.0194*** (0.0041)	0.0190*** (0.0078)
HC	0.0291*** (0.0090)	0.131*** (0.0168)	0.111*** (0.0126)	0.0500*** (0.016)
lnREC	0.0441*** (0.0069)	− 0.00686 (0.013)	0.0592*** (0.0137)	0.0896*** (0.0134)
lnREC*lnTI	0.0385*** (0.0062)	0.0173* (0.0096)	0.0110*** (0.00235)	0.0523*** (0.0087)
Constant	0.336*** (0.0681)	0.247 (0.262)	1.682*** (0.119)	0.187 (0.521)
Obs	334	162	111	60
Log likelihood	390.9976	201.8988	179.0502	115.2132
Wald chi <sup>2</sup>	149.31	66.25	491.18	176.61
Prob > chi <sup>2</sup>	0.000	0.000	0.000	0.000

Note: <sup>a</sup> Standard errors in parentheses. <sup>b</sup> \*\*\*, \*\*, \* signify 1%, 5%, 10% significance

environmental efficiency values in different regions in Asia from 1990 to 2018. The study compares environmental efficiency index in South East Asia, South Asia and East Asia. The mean environmental efficiency score demonstrate that East Asia region has the highest from 0.78 to 0.94 whereas South East Asia has the lowest with a range from 0.62 to 0.71.

In the second phase, the study evaluates the determinants of environmental efficiency using truncated regression and the

main variable is technological innovation (TI). The results confirmed an inverted U-shape relationship between environmental efficiency and TI in the main panel, South East Asia, East Asia and South Asia regions. Also, economic growth has an inverted “U” form relationship with environmental efficiency within the main panel, East Asia and South Asia. Human capital improves environmental efficiency in the main panel and the rest of the regions. Moreover, while FDI

**Table 4** Two-stage least square results for endogeneity test

Variable	Panel	South East Asia	South Asia	East Asia
1 <sup>st</sup> stage: Dependent variable = Economic growth				
HC	2.072*** (0.048)	1.351*** (0.0833)	0.813*** (0.0439)	2.236*** (0.0752)
lnREC	− 0.147*** (0.0344)	− 0.723*** (0.0466)	0.352*** (0.0459)	0.162*** (0.0493)
Constant	4.037*** (0.212)	8.819*** (0.364)	3.496*** (0.214)	1.983*** (0.385)
Obs	435	174	116	87
R <sup>2</sup>	0.811	0.832	0.854	0.917
Variable	Panel	South E Asia	South Asia	East Asia
2 <sup>nd</sup> stage: Dependent variable = Environmental efficiency				
lnT	− 0.232*** (0.0762)	− 0.2141*** (0.137)	− 0.311*** (0.0826)	− 0.0384*** (292.5)
lnT <sup>2</sup>	0.00606*** (0.00356)	0.013 (0.0103)	0.0124*** (0.00295)	2.237 (9.373)
lnPGDP	0.715** (0.551)	− 0.682* (0.382)	0.651 (0.934)	− 184.7 (761.2)
lnPGDP <sup>2</sup>	− 0.0339*** (0.0291)	0.0429* (0.0232)	− 0.0483 (0.0616)	2.264*** (38.08)
lnFDI	0.00845*** (0.00987)	− 0.0342** (0.0157)	− 0.0164*** (0.0185)	− 0.558 (2.206)
HC	0.00138** (0.0942)	0.0617 (0.0381)	0.135*** (0.0458)	1.774** (71.67)
lnREC*lnT	0.00693*** (0.00147)	− 0.00069 (0.00541)	0.0160** (0.0063)	− 0.261 (1.085)
Constant	− 1.72 (1.865)	3.144** (1.315)	− 0.464 (3.245)	359.6 (1455)
Obs	435	174	116	87
R <sup>2</sup>	0.56	0.39	0.76	0.44

Note: <sup>a</sup> Standard errors are in parentheses. <sup>b</sup> \*\*\*, \*\*, \* signify 1%, 5%, 10% significance, respectively.

increases environmental efficiency in the main panel and East Asia, it reduces environmental efficiency in South East Asia and South Asia regions. In addition, the interaction effect between technological innovation and renewable energy consumption, improves environmental efficiency in all the study countries.

### Policy implications

Based on the findings the following policies are proposed. First, strengthening regional integration in the fight against climate change and environmental pollution in the region will ultimately result in advancing environmental efficiency. Since there are disparities in economic development and resource endowment, those countries lacking will be encouraged to emulate from those that are technological advanced. Second, human capital development should be given a priority since it was clear in this study that human development and public awareness have significant positive influence on environmental efficiency. Educated people are more likely to observe environmental regulations than those who are not. It is therefore, recommended that policy makers in selected countries invest more in their human capital, thus education and skills, for long-term positive effect on the environment. Third, technological innovation is very crucial in any economic development and Asia is not an exception. Therefore, governments should encourage innovations and remove all red tapes to make it easy for inventors to apply for patent applications. Technological innovation is double edged sword which improves production process and at the same time reduces environmental pollution. It is also recommended that the regions strengthen, cooperate and adopt open innovation so that they can share green technologies to improve environmental performance in the long term. They should seek to invest more into R&D to promote the use of technologies that can help them save energy and the environment. Four, foreign firms should be screened to reduce the tendency of pollution intensive industries into the host countries. Considering the recent free trade agreement, the regions can use that as an opportunity to invite more investment of green industries. Furthermore, research and development expenditure should be increased to support academic research into strategic climate change mitigations.

**Authors' contribution** Florence Appiah Twum—conceptualization, data curation, methodology, literature review, first draft and editing, analysis, final draft and editing. Xingle Long—conceptualization, methodology, analysis, funding, administration, software. Muhammad Salman—methodology, literature review, first draft and editing, analysis, software. Claudia Nyarko Mensah—conceptualization, data curation, methodology, literature review, first draft and editing, analysis, final draft and editing. William Adomako Kankam—methodology, literature review, first draft and editing, methodology analysis, software. Andrew Kwamina Tachie—data curation, methodology, literature review, first draft and editing, analysis, software.

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### Compliance with ethical standards

**Ethical approval** The study is conducted using human experimentation or animal experimentation. Therefore, no animal or human parts were used in this study.

**Consent to participate** We, the authors (author and co-authors), agreed to participate in this study on the effect of technological innovation on environmental efficiency in Asia-Pacific without compulsion. This is a voluntary consent to participate in this research and we do agree on and with everything in the manuscript.

**Consent to publish** We have read the author's guide, rules and ethics for publication in Environmental Science and Pollution Research. All authors agree for the manuscript to be published in Environmental Science and Pollution Research.

**Competing interest** The authors declare that they have no conflict of interest.

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