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CO_2 emissions, electricity consumption and output in ASEAN

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ABSTRACT

This study examines the causal relationship between carbon dioxide emissions, electricity consumption and economic growth within a panel vector error correction model for five ASEAN countries over the period 1980–2006. The long-run estimates indicate that there is a statistically significant positive association between electricity consumption and emissions and a non-linear relationship between emissions and real output, consistent with the environmental Kuznets curve. The long-run estimates, however, do not indicate the direction of causality between the variables. The results from the Granger causality tests suggest that in the long-run there is unidirectional Granger causality running from electricity consumption and emissions to economic growth. The results also point to unidirectional Granger causality running from emissions to electricity consumption in the short-run.

1. Introduction

The increasing threat of global warming and climate change has focused attention on the relationship between economic growth and environmental pollutants. In 2007, the intergovernmental panel on climate change reported that the average global temperature was estimated to rise between 1.1 and 6.4 °C in the next 100 years [29]. It is predicted that a mere 2 °C increase in temperature would generate substantial change to many natural ecosystems and an increase in the sea-level that would have a major impact on the lives of half of the world's population that live in coastal zones [34].

Until relatively recently there have been two parallel literatures on the relationship between economic growth and environmental pollution. The first set of studies has focused on the economic growth-environmental pollutants nexus and has been closely allied to testing the Environmental Kuznets Curve (EKC) hypothesis [16,61]. One of the limitations of this literature is that it is conceivable that causation could run from emissions to income whereby emissions occur in the production process and, as a consequence, income increases. Some studies have started to address this point through considering the direction of Granger causality (see [73]) between economic growth and environmental pollution (see [1,15,17,37]). These studies have the advantage over the standard EKC literature that they model the time series dynamics. However, as they have only two variables, they still potentially suffer from the problem of omitted variables bias.

A second set of studies on the relationship between economic growth and environmental pollution has focused on the economic growth-energy consumption nexus, since pollution emissions are primarily generated by burning fossil fuels. Since the seminal study by Kraft and Kraft [33], a voluminous Granger causality literature has emerged examining the link between economic growth and energy consumption (see [48,49] for recent reviews). One of the limitations of this literature, similar to those Granger causality studies that have considered the link between economic growth and environmental pollutants, is that many consider the relationship between economic growth and energy consumption in a bivariate framework and thus suffer from omitted variables bias [59,60].

A marriage of these two literatures whereby the relationship between economic growth, energy consumption and pollution emissions are considered within a Granger causality multivariate framework is a relatively new area of research. Most extant studies are for single countries. There are studies for developed countries, such as France [3] and the United States [57], developing countries, such as China [68]; Malaysia [4] and Turkey [26,56], as well as the oil-rich OPEC countries [52]. The results from these studies, however, are mixed. For example, Soytas et al. [57] and Soytas and Sari [56] found unidirectional Granger causality running from energy consumption to pollution emissions in the long run, while Halicioglu [26] found bidirectional Granger causality in the long run and short run between economic growth and pollution emissions. Zhang and Cheng [68] found unidirectional Granger causality running from economic growth to energy consumption and energy consumption to pollution emissions in the long run, while Ang [3] found unidirectional Granger causality running from economic

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growth to energy consumption and pollution emissions in the long-run. Sari and Soytas [52] reached conflicting results for five OPEC countries – Algeria, Indonesia, Nigeria, Saudi Arabia and Venezuela.

This paper extends this literature to consider the relationship between economic growth, energy consumption and pollution emissions for a panel of countries in the Association of South East Asian Nations (ASEAN) over the period 1980–2006. Our analysis focuses on the ASEAN-five (Indonesia, Malaysia, Philippines, Singapore and Thailand). These five countries were the original founding members of ASEAN in 1967 and remain the most influential members of ASEAN in the 21 century. There are panel-based Granger causality studies of the economic growth-environmental pollution nexus [17,37] and the economic growth-energy consumption nexus (see e.g. [2,6,7,14,31,35,41,42,36,43,45,46]). However, the only panel-based studies to use a multivariate framework to examine the relationship between economic growth, energy consumption and pollution emissions are Apergis and Payne [5], who do so for a panel of Central American countries, and Apergis and Payne [8] who do so for a panel of the Commonwealth of Independent States.

One possible reason for conflicting results with single country studies is that for many countries, we have annual data with a maximum span of only 40–45 years and often less. The problem is that the power of traditional unit root tests, such as the Augmented Dickey–Fuller (ADF) test and traditional cointegration tests, such as the Johansen [30] test, can be distorted when the span of data is short (see e.g. [12]). One reason for employing a panel-based cointegration and Granger causality approach is that it has the advantage over focusing on a single country that it provides more informative data, more variability, more degrees of freedom and thus greater efficiency in estimation.

A second reason for considering a panel of ASEAN countries is that an objective of the ASEAN Vision 2020, adopted in 1997, is to pursue a consistent approach to regional cooperation in pooling and maximizing efficient utilization of resources. At a practical level, coordinated policies exist at the ASEAN regional level under the ASEAN Plan of Action for Energy Cooperation (APAEC) 2004–2009 [9]. Foremost among joint initiatives is the ASEAN Power Grid and the Trans-ASEAN Gas Pipeline Infrastructure Project (TAGP), which have been established to ensure complete regional access to gas reserves and greater stability and security of energy supply within ASEAN. Similarly, many of the environmental problems faced by ASEAN members have a trans-boundary character and, as such, demand a collective response. In Indonesia and Malaysia, the burning of tropical rainforests to create space for palm trees to produce biodiesel and oil has been emitting a huge pulse of carbon that spreads to neighbouring countries causing adverse effects to health [62]. The ASEAN Secretariat ([10], p. 33) acknowledges "the importance, if not urgency, of conserving the region's resources and protecting its environment", noting that "any drastic and irreversible reduction in the region's resources or degradation of its environment will .... have far-reaching implications for the region's ecosystem and quality of life". Thus, it makes sense to examine the relationship between economic growth, energy consumption and pollution emissions for ASEAN as a whole.

2. The ASEAN context

The choice of the ASEAN-five is motivated by the fact that these countries have been among the highest growth economies in the world over the last three decades. ASEAN's rapid economic growth has been associated with a sharp rise in energy consumption. The main sources of environmental emissions are power generation plants, cement factories, oil refineries, agri-based industries, such as palm oil and rubber processing, chemical plants and wood-based industries. About 90% of ASEAN's primary commercial energy requirement is fulfilled by fossil fuels (coal, oil and gas) [32]. The rapid increase in use of information and communication technologies (ICTs), such as personal computers, digital video recorders and digital music players that require substantial electricity input, has placed increased pressure on the use of fossil fuels for electricity generation. ASEAN's rapid industrialization over the last three decades has also resulted in the development of infrastructure and managerial processes that consume a lot of electricity. The worldwide shift towards a digital society is expected to increase electricity consumption in the future. One estimate is that between 2000 and 2010, the use of coal for electricity generation will increase 235% [32]. According to the ASEAN Centre for Energy, energy consumption in ASEAN is expected to increase from 200 million tons of oil equivalent (MTOE) in 2000 to approximately 580 MTOE in 2020 [67].

With the exception of Singapore, carbon dioxide emissions per capita in ASEAN are not high, certainly relative to China, India and the United States. Nevertheless, pollution emissions are increasing steadily in the ASEAN-five due to fast economic growth and fossil fuel combustion. Moreover, the effects of climate change are beginning to be strongly felt in the ASEAN countries. Air quality in Bangkok, Jakarta, Kuala Lumpur and Manila is amongst the poorest in the world [32]. One of the manifestations of climate change is a rise in the sea level, an increase in the frequency of tropical storms and a higher incidence of cardiovascular and respiratory disease [13]. Several parts of South-east Asia are experiencing a higher incidence of diseases such as dengue fever and malaria associated with warmer temperatures. Indonesia and the Philippines, which are both archipelagic states, are particularly vulnerable to climate change. Indonesia consists of about 17,000 islands. One forecast is that 2000 of them will be submerged by 2030 due to rising sea levels, if the current trend of global warming continues unabated. The Philippines, which consists of approximately 7,100 islands, has experienced an increase in the prevalence of tropical cyclones and flooding that are damaging the country's agriculture [13].

ASEAN has taken a lead in arguing for a reduction in carbon dioxide emissions worldwide through negotiations on the Kyoto protocol and in the post-Kyoto negotiations in Bali in 2008. Thavasi and Ramakrishna [62] suggest that, in response to global warming, countries should adopt several strategies to realize a low-carbon society. These strategies suggest a causal link running from CO_2 emissions to electricity consumption. The strategies are promoting competition in electricity markets, policies to improve energy efficiency, policies to diversify energy supplies, promoting nuclear energy and policies to promote renewable energy.

To differing degrees ASEAN has implemented these strategies over time. For example, Singapore has liberalized its gas and electricity markets to enable full competition in the electricity market [62]. The average efficiency of Singapore's oil-fired plants has also increased through measures such as the adoption of a combined cycle using gas and steam turbines. Singapore's energy intensity, as an indicator of energy efficiency, improved by 15% between 1990 and 2005 [62]. ASEAN has indicated it will diversify energy supplies by developing bio-fuels and civilian nuclear power. Malaysia has adopted a four-pronged approach to diversifying its energy supplies, i.e. utilization of a combination of oil, hydropower, coal and natural gas in the national energy supply. Indonesia, the Philippines and Thailand have signalled an intention to build nuclear power plants [74]. With the exception of Myanmar and Singapore, the ASEAN countries already have nuclear research reactors for the production of radio-isotopes [62]. While nuclear energy has not been feasible in Singapore, Singapore has successfully pursued solar energy. The ASEAN countries agreed to cooperate in the development of renewable energy since an agreement signed in 1986 [32]; however, there is still a gap between actual use and potential use of renewable energy in ASEAN [38]. Singapore has engaged Norway's Renewable Energy Corporation to build a $6.3 billion solar complex for silicon water and thin-film production [62]. Hydropower resources are plentiful in most ASEAN countries and are being used to a significant degree in Indonesia, Malaysia, Philippines, Thailand and Vietnam [38].

3. Data and model

The study adopts the same approach as that taken by Ang [3] for France, Apergis and Payne [15] for a panel of Central American countries and Apergis and Payne [8] for a panel of the Commonwealth of Independent States. The long-run relationship between carbon dioxide emissions, electricity consumption and real GDP is specified as follows:

$$CO_{2it} = \alpha_{it} + \beta_{1i}GDP_{it} + \beta_{2i}GDP^2_{it} + \beta_{3i}EC_{it} + \varepsilon_{it} \tag{1}$$

where $i = 1, \ldots, N$ for each country in the panel, $t = 1, \ldots, T$ refers to the time period. CO_2 is carbon dioxide emissions (metric tons per capita), EC is electricity consumption (million kWh per capita), GDP is real GDP per capita (measured in 2000 US dollars) and GDP^2 is the square of GDP.[1] β_1, β_2 and β_3 represent the long-run elasticity estimates of carbon dioxide emissions with respect to real GDP, the square of real GDP and electricity consumption respectively. The EKC hypothesis suggests that we should expect $\beta_1 > 0$ and $\beta_2 < 0$. $\beta_1 > 0$ captures the initial increase in carbon emissions as income increases while $\beta_2 < 0$ reflects the inverted U-shape pattern, once income passes the threshold. It is hypothesised that $\beta_3 > 0$ because higher electricity consumption will result in more carbon dioxide emissions.

The empirical study is based on a panel of five ASEAN countries (Indonesia, Malaysia, Philippines, Singapore and Thailand) over the period 1980–2006. The sample is restricted to those ASEAN countries for which data on electricity consumption per capita, real GDP per capita and carbon dioxide emissions per capita is available over this period. Annual data on electricity consumption (million kWh per capita) was obtained from the Asian Development Bank. Annual data on real GDP per capita, measured in US dollars at 2000 prices, was sourced from the Statistics Department of each of the five countries. Data on carbon dioxide emissions (metric tons per capita) was collected from the Energy Information Administration. All the data were converted into natural logarithms prior to conducting the analysis.

4. Econometric methodology and results

The empirical study has two objectives. The first is to examine the long-run relationship between carbon dioxide emissions, electricity consumption and real output. The second is to examine the dynamic causal relationship between the variables. The testing procedure entails four steps. The first step is to test whether the variables contain a unit root. If the variables contain a unit root, the second step is to test whether there is a long-run cointegrating relationship between the variables. If a long-run relationship between the variables is found, the third step is to estimate Eq. (1) using an appropriate long-run estimator. If a long-run relationship between the variables is found, the final step is to estimate a panel vector error correction model in order to infer the Granger causal relations between the variables.

[1] We also used GDP, measured in purchasing power parity (in 2005 international dollars) and the results are quantitatively similar to those which are reported below.

4.1. Panel unit root tests

We use the panel unit root tests proposed by Im et al. [28], Maddala and Wu [40] and Breitung [11]. The t-bar test, which was proposed by Im et al. [28], assumes that all countries converge towards the equilibrium value at different speeds under the alternative hypothesis. There are two stages in constructing the t-bar test statistic. The first step is to calculate the average of the individual ADF t-statistics for each of the countries in the sample. The second step is to calculate the standardized t-bar statistic as follows:

$$t\text{-bar} = \sqrt{N}(t_\alpha - \kappa_t)/\sqrt{v_t} \tag{2}$$

where N is the size of the panel, t_α is the average of the individual ADF t-statistics for each of the countries, with and without a trend, and κ_t and v_t are, respectively, estimates of the mean and variance of each $t_{\alpha i}$. Im et al. [28] provided Monte Carlo simulations of κ_t and v_t and tabulated exact critical values for various combinations of N and T. A potential problem with the t-bar test is that in the presence of cross-sectional dependence in the disturbances, the test is no longer applicable. However Im et al. [28] suggested that in the presence of cross-sectional dependence, the data can be adjusted by demeaning and that the standardized demeaned t-bar statistic converges to the standard normal in the limit.

Maddala and Wu [40] criticized the Im et al. [28] test on the basis that in many real world applications, cross correlations are unlikely to take the simple form proposed by Im et al. [28] that can be effectively eliminated by demeaning the data. Maddala and Wu [40] proposed a panel ADF unit root test based on Fisher [20]. The Fisher ADF test essentially combines the p-values of the test statistic for a unit root in each residual cross-sectional unit. The test is non-parametric and has a chi-square distribution with 2 N degrees of freedom, where N is the number of cross-sectional units or countries. Using the additive property of the chi-squared variable, the following test statistic can be derived:

$$\lambda = -2\sum_{i=1}^{N} \log_e \pi_i \tag{3}$$

Here, π_i is the p-value of the test statistic for unit i. The Maddala and Wu [40] test has the advantage over the Im et al. [28] test that it does not depend on different lag lengths in the individual ADF regressions. Maddala and Wu [40] performed Monte Carlo simulations showing that their test is superior to that proposed by Im et al. [28].

The Breitung [11] panel unit root test has the following form:

$$y_{it} = \alpha_{it} + \sum_{k=1}^{p+1} \beta_{ik} x_{i,t-k} + \varepsilon_t \tag{4}$$

In Eq. (4) the Breitung [11] test statistic tests the following null hypothesis that the process is difference stationary: $H_0 : \sum_{k=1}^{p+1}\beta_{ik} - 1 = 0$. The alternative hypothesis assumes that the panel series is stationary; that is, $\sum_{k=1}^{p+1}\beta_{ik} - 1 < 0$ for all i. Breitung [11] uses the following transformed vectors to construct the test statistic:

$$Y_i^* = AY_i = \left[y_{i1}^*, y_{i2}^*, \ldots, y_{iT}^*\right]'$$
$$X_i^* = AX_i = \left[x_{i1}^*, x_{i2}^*, \ldots, x_{iT}^*\right]'$$

leading to the following test statistic:

$$\lambda_B = \frac{\sum_{i=1}^{N}\sigma_1^{-2} Y_i^{*\prime} X_i^{*\prime}}{\sqrt{\sum_{i=1}^{N}\sigma_1^{-2} X_i^{*\prime} A' A X_i^*}} \tag{5}$$

which is shown to have a standard normal distribution.

The results of the panel unit root tests are reported in Table 1. The test statistics for the log levels of CO_2, EC, GDP and GDP^2 are

Table 1
Panel unit root tests.

Unit root test	GDP	GDP^2	CO^2	EC
Level				
IPS test	0.3811	0.3344	1.9091	2.0409
MW-Fisher ADF	6.0097	6.1465	6.4063	5.6907
Breitung test	−1.3683*	−1.4684*	1.6863	2.0474
First difference				
IPS test	−3.8662***	−3.8466***	−3.7313***	−7.4936***
MW-Fisher ADF	36.5664***	36.1461***	33.6809***	61.6394***
Breitung test	−5.1070***	−4.9728***	−1.7973**	−3.0009***

Notes: All unit root tests were performed with individual trends and intercept for each series. The optimal lag length was selected automatically using the Schwarz information criteria. The null hypothesis is a unit root for all the tests.
* Statistical significance at 10% level.
** Statistical significance at 5% level.
*** Statistical significance at 1% level.

statistically insignificant with the exception of the Breitung [11] test applied to GDP and GDP^2, which are significant only at the 10% level. Taken as a whole, the log levels results suggest that all three variables are panel non-stationary. When we apply the panel unit root tests to the first difference of the four variables, all three tests reject the joint null hypothesis for each variable at the 1% level. Thus, from all of the tests, we can conclude that each of the variables contain a panel unit root.

4.2. Panel cointegration

Given that each of the variables contains a panel unit root, we proceed to examine whether there is a long-run relationship between the variables using the Johansen Fisher panel cointegration test proposed by Maddala and Wu [40]. The Johansen Fisher panel cointegration test is a panel version of the individual Johansen [30] cointegration test (see [69]). The Johansen Fisher panel cointegration test has the advantages that it is flexible, simple to implement and is intuitively appealing [69]. Moreover, Hanck [69] conducts a simulation study which finds that the Johansen Fisher panel cointegration test performs well relative to popular alternatives proposed by Pedroni [70], Kao [71] and Larsson et al. [72]. Based on the same principles underpinning the Fisher ADF panel unit root test described above, the Johansen Fisher panel cointegration test aggregates the p-values of individual Johansen maximum eigenvalue and trace statistics. If π_i is the p-value from an individual cointegration test for cross-section i, under the null hypothesis for the panel,

$$-2\sum_{i=1}^{N}\log(\pi_i) \rightarrow \chi^2_{2N} \tag{6}$$

The value of the chi-square statistic is based on the MacKinnon et al. [39] p-values for Johansen's [30] cointegration trace test and maximum eigenvalue test. However, in the Johansen-type panel cointegration test, results are known to depend heavily on the VAR system lag order. The results, which are reported in Table 2, use one lag and indicate that a single cointegrating vector exists. The results are the same if two lags are employed.

Table 2
Johansen Fisher panel cointegration test – unrestricted cointegration rank test (trace and maximum eigenvalue).

Hypothesized No. of CE(s)	Fisher statistic* (from trace test)	Prob.	Fisher statistic* (from max-eigen test)	Prob.
None	53.10	0.0000	37.25	0.0001
At most 1	25.27	0.0049	22.62	0.0123
At most 2	10.88	0.3669	10.01	0.4398
At most 3	8.208	0.6085	8.208	0.6085

* Probabilities are computed using the asymptotic Chi-square distribution.

4.3. Panel long-run estimates

Given the existence of a long-run cointegrating relationship between the variables we estimated Eq. (1) using a panel version of dynamic ordinary least squares (DOLS) proposed by Pedroni [50]. Consider the regression $y_{it} = \alpha_i + \beta_i X_{it} + \mu_{it}$ such that y_{it} is CO_2 and X represents the vector of EC, GDP and GDP^2. This regression is augmented with lead and lagged differences of the regressor to control for endogenous feedback:

$$y_{it} = \alpha_i + \beta_i X_{it} + \sum_{p=-p_i}^{p_i} \gamma_{ip}\Delta X_{it-p} + \mu^*_{it} \tag{7}$$

From this regression, the group-mean panel DOLS estimator can be constructed as

$$\hat{\beta}^*_{GD} = \left[N^{-1}\sum_{i=1}^{N}\left(\sum_{t=1}^{T} Z_{it}Z'_{it}\right)^{-1}\left(\sum_{t=1}^{T} Z_{it}\tilde{s}_{it}\right)\right] \tag{8}$$

where Z_{it} is the $2(K+1)\times 1$ vector of regressor $Z_{it} = (X_{it} - \overline{X}_i, \Delta X_{it-K}, \ldots, \Delta X_{it+K}), \tilde{s}_{it} = s_{it} - \bar{s}_i$. As the expression following summation over i is identical to the conventional DOLS estimator, the panel DOLS estimator can be constructed as $\hat{\beta}^*_{GD} = N^{-1}\sum_{i=1}^{N}\hat{\beta}^*_{D,i}$, where $\hat{\beta}^*_{D,i}$ is the conventional DOLS estimator, applied to the ith member of the panel. As a consequence, the t-statistics for the panel DOLS estimator can be constructed as:

$$t_{\hat{\beta}^*_{GD}} = N^{-1/2}\sum_{i=1}^{N} t_{\hat{\beta}^*_{D,i}} \quad \text{where}$$

$$t_{\hat{\beta}^*_{D,i}} = \left(\hat{\beta}^*_{D,i} - \beta_o\right)\left(\hat{\sigma}_i^{-2}\sum_{t=1}^{T}(X_{it} - \overline{X}_i)^2\right)^{1/2} \tag{9}$$

Table 3 provides the panel DOLS results for Eq. (1). For the panel of ASEAN countries as a whole, all the coefficients have the expected sign and are significant at the 5% level or better. For the panel, the results indicate that a 1% increase in electricity consumption per capita is associated with an increase in carbon dioxide emissions per capita of 0.511%. This result is consistent with the results of Ang [3] and Apergis and Payne [5] who find that an increase in energy consumption per capita is associated with an increase in carbon dioxide emissions per capita. The elasticity of carbon dioxide emissions per capita with respect to real GDP per capita in the long-run is 3.106–0.404 GDP with the threshold income of 7.688 (in logarithms). This result seems to be supportive of the EKC hypothesis in that for the ASEAN-five as a whole the level of carbon dioxide emissions first increases with an increase in income, then stabilizes and declines following the threshold income level. This

Table 3
Panel DOLS long-run estimates.

Country	CO^2 is the dependent variable		
	EC	GDP	GDP^2
Malaysia	0.7240*** (4.3987)	−0.5616 (−0.1061)	0.0329 (0.1011)
Singapore	0.4235*** (3.3426)	0.7526 (0.6920)	−0.0215 (−0.3688)
Indonesia	0.3868*** (8.1212)	5.1220* (1.8767)	−0.3473 (−1.7234)
Philippines	0.3083*** (4.7362)	8.0619** (3.0502)	−0.5522** (−2.7852)
Thailand	0.7117*** (9.2804)	2.1535 (1.3387)	−0.1211 (−1.1023)
Panel	0.5109*** (13.3623)	3.1057** (3.0641)	−0.2018** (−2.6290)

Notes: The t-statistics are given in parenthesis.
* Significance at 10% level.
** Significance at 5% level.
*** Significance at 1% level.

result is consistent with the findings of Ang [3] and Apergis and Payne [5] and generally consistent with the results of Shafik and Bandyopadhyay [55], Seldon and Song [53] and Grossman and Krueger [25] who also reported an inverted U-shaped relationship between carbon dioxide emissions per capita and real GDP per capita.

Turning to the results for individual countries, in each case an increase in electricity consumption per capita is associated with an increase in carbon dioxide emissions per capita. The results indicate that a 1% increase in electricity consumption per capita is associated with an increase in carbon dioxide emissions per capita of 0.308% in the Philippines at the lower end through to 0.724% in Malaysia at the upper end. The results for the relationship between income and pollution emissions, however, are mixed. The EKC hypothesis is supported in the Philippines, while in Indonesia pollutant emissions are monotonically increasing with income levels. The results for Indonesia are consistent with extant findings reported in Holtz-Eakin and Seldon [27] and Shafik [54]. There is no relationship between income and pollutant emissions in Malaysia, Singapore and Thailand.

4.4. Panel Granger causality

The existence of a long-run cointegrating vector implies the existence of Granger causality, at least in one direction; however, it does not indicate the direction of causality [23,24]. To infer Granger causality among the variables we specify a model with a dynamic error correction representation [23,24]. The Granger causality test is based on the following regressions:

$$\Delta CO2_{it} = \pi_{1i} + \sum_p \pi_{11ip}\Delta CO2_{it-p} + \sum_p \pi_{12ip}\Delta EC_{it-p} + \sum_p \pi_{13ip}\Delta GDP_{it-p} + \sum_p \pi_{14ip}\Delta GDP^2_{it-p} + \psi_{1i}ECT_{it-1} + \varepsilon_{1it} \tag{10a}$$

$$\Delta EC_{it} = \pi_{2i} + \sum_p \pi_{21ip}\Delta CO2_{it-p} + \sum_p \pi_{22ip}\Delta EC_{it-p} + \sum_p \pi_{23ip}\Delta GDP_{it-p} + \sum_p \pi_{24ip}\Delta GDP^2_{it-p} + \psi_{2i}ECT_{it-1} + \varepsilon_{2it} \tag{10b}$$

$$\Delta GDP_{it} = \pi_{3i} + \sum_p \pi_{31ip}\Delta CO2_{it-p} + \sum_p \pi_{32ip}\Delta EC_{it-p} + \sum_p \pi_{33ip}\Delta GDP_{it-p} + \sum_p \pi_{34ip}\Delta GDP^2_{it-p} + \psi_{3i}ECT_{9m-1} + \varepsilon_{3it} \tag{10c}$$

$$\Delta GDP^2_{it} = \pi_{4i} + \sum_p \pi_{41ip}\Delta CO2_{it-p} + \sum_p \pi_{42ip}\Delta EC_{it-p} + \sum_p \pi_{43ip}\Delta GDP_{it-p} + \sum_p \pi_{44ip}\Delta GDP^2_{it-p} + \psi_{4i}ECT_{it-1} + \varepsilon_{4it} \tag{10d}$$

The explicit definition of the error-correction term is as follows:

$$E\widehat{C}T_{it} = CO2_{it} - \hat{\alpha}_i - \hat{\beta}_{1i}GDP_{it} - \hat{\beta}_{2i}GDP^2_{it} - \hat{\beta}_{3i}EC_{it} \tag{11}$$

Here *GDP*, GDP^2, *CO2* and *EC* are as previously defined, Δ denotes the first difference of the variable, *ECT* is the error-correction term, and *p* denotes the lag length. The optimal lag length was selected automatically using the Schwarz information criteria.

Causality runs from ΔGDP and ΔGDP^2 to $\Delta CO2$ (ΔEC) if the joint null hypothesis $\pi_{13ip} = \pi_{14ip} = 0\forall_{ip}$ ($\pi_{23ip} = \pi_{24ip} = 0\forall_{ip}$) is rejected via a Wald test. The presence of two variables measuring real output growth (i.e. ΔGDP and ΔGDP^2) in the system requires cross-equation restrictions to determine the causality from either $\Delta CO2$ or ΔEC to real output growth using a likelihood ratio test. Causality from $\Delta CO2$ (ΔEC) to ΔGDP and ΔGDP^2 is supported if the null hypothesis $\pi_{31ip} = 0\forall_{ip}$ and $\pi_{41ip} = 0\forall_{ip}$ ($\pi_{32ip} = 0\forall_{ip}$ and $\pi_{42ip} = 0\forall_{ip}$) is rejected. For long run causality, if the null hypothesis $\psi_{3i} = \psi_{4i} = 0\forall_i$ is rejected, then ΔGDP and ΔGDP^2 jointly respond to deviations from long run equilibrium.

Table 4
Panel granger causality results.

	ΔGDP, ΔGDP^2	ΔEC	ΔCO2	ECT
ΔGDP, ΔGDP^2	–	2.2667 (0.1319)	1.7553 (0.1846)	10.6401*** (0.0011)
ΔEC	1.2805 (0.2817)	–	5.9539** (0.0162)	2.1241 (0.1476)
ΔCO2	0.7565 (0.4715)	0.7850 (0.3774)	–	0.0811 (0.7764)

Notes: The *p*-values are given in parenthesis. χ^2 statistic and *F* statistic are used for likelihood ratio test and Wald test respectively.
** Rejection of the null hypothesis at 5% level.
*** Rejection of the null hypothesis at 1% level.

The panel short-run and long-run Granger causality results are reported in Table 4. The findings in Table 4 indicate that there is short-run panel Granger causality running from CO_2 emissions to electricity consumption. This result reflects the short-run effects of the adoption of policies to promote energy efficiency and the use of renewable energy in the face of concern about the effects of global warming. There is long-run unidirectional panel Granger causality running from electricity consumption and CO_2 emissions to GDP.

5. Discussion and policy implications

The results of the DOLS estimates indicate that for the ASEAN-five there is a statistically significant non-linear relationship between CO_2 emissions and income and a positive relationship between electricity consumption and CO_2 emissions. The long-run estimates, however, do not indicate the direction of causality between the variables. The results from the Granger causality tests suggest that in the long-run there is unidirectional Granger causality running from electricity consumption and CO_2 emissions to economic growth.

Unidirectional Granger causality running from electricity consumption to economic growth in the long-run implies that the ASEAN-five are energy dependent economies. An increase in electricity consumption results in higher GDP because, in addition to the direct effect of energy consumed for commercial use which generates higher rates of economic growth, higher electricity consumption results in an increase in energy production, which has the indirect effect of generating employment and infrastructure in energy services.

The conclusion that the ASEAN-five are energy dependent economies makes sense given that a significant amount of economic growth in ASEAN has been fuelled by industrial growth, which requires intensive use of electricity. In 2007, industry value added as a percentage of GDP was 48% in Malaysia, 47% in Indonesia and 44% in Thailand [66]. Interestingly, the results suggest that higher electricity consumption and economic growth do not Granger cause CO_2 emissions. This result might reflect the fact that while CO_2 emissions have been steadily increasing with economic growth in ASEAN, with the exception of Singapore, they are still relatively low. While ASEAN is blessed with renewable energy sources, progress towards utilizing them under APAEC has been slow and renewable energy sources in the region remain underutilized [38].

To some extent, the results in this study reduce the urgency for ASEAN policy-makers to find and utilize renewable energy sources because of the perceived impact of energy consumption and economic growth on greenhouse gas emissions. This said, economic growth is the outcome of growth in inputs or more efficient use of inputs. Thus, the policy implication for ASEAN is that continued rapid economic growth requires higher and/or more efficient consumption of electricity. The findings suggest that these countries should adopt the multi-pronged strategy of increasing investment in energy infrastructure to expand energy inputs, and regulatory reform of energy infrastructure and putting in place energy conservation policies to improve delivery efficiency. In addition to regional initiatives to ensure energy security, such as the ASEAN Power Grid and TAGP, several of the ASEAN countries have already taken steps to bolster energy inputs and improve energy efficiency. For example, Singapore has liberalized its electricity and gas markets to enable full competition in the retail electricity market and taken steps to improve energy efficiency. The average efficiency of oil-fired plants in Singapore is comparable to OECD countries. Between 2000 and 2006, overall generation efficiency in Singapore increased from 38% to 44% through the adoption of combined cycle using gas and steam turbines, accounting for approximately 16% reduction in CO_2 emissions [62].

The results also indicate that environmental degradation Granger causes economic growth in the long run. This finding is consistent with emissions occurring in the production process and reflects the experience of many industrializing countries. This, of course, is not to say that environmental degradation is an appropriate course to promote economic growth. At one level, policy-makers need to be mindful of the literature on sustainability which suggests that social welfare rather than per capita income should be the focus of government policy [21,22]. There are a growing number of studies that suggest environmental degradation, including air and noise pollution, lowers life satisfaction [19,18,51,58,63–65]. At another level, a persistent decline in environmental quality may generate negative externalities for the economy through reducing health human capital and, hence, productivity in the long-run [4].

In 2007, 100% of the population in Singapore lived in urban areas. The corresponding figure in Malaysia was 69%, in the Philippines 64% and in Indonesia 50% [66]. The environmental situation of Asian countries with 50% or more of the population in urban areas has had an adverse effect on people's health [62]. It is warned that indoor pollution from cooking, lighting and heating/cooling in many Asian countries is a cause of blindness, heart disease, lung cancer, and tuberculosis. A biomass cooking stove is reported to release 6–20% of the carbon as pollutant and thus cause chronic ill-effects on health on ingestion [47]. Outdoor pollution generated by motor vehicle emissions is a major factor contributing to respiratory disease in many Asian cities. Reductions in the volume of traffic would improve outdoor pollution. For example, Singapore has taken positive steps in this respect which include introduction of the Mass Rapid Transport system in order to curb CO_2 emissions.

6. Conclusions: limitations and directions for future research

One of the limitations of this study is that the analysis is at an aggregated level. Different industries have different intensities of electricity. To this point, there are few studies that examine the relationship between electricity consumption, or energy consumption more generally, and GDP at a disaggregated level and no such panel-based studies. It would be difficult to obtain disaggregated data on energy consumption for a panel of ASEAN countries; however, even if such data could be obtained for a single country, such as Malaysia, such a project would be a useful topic for future research. Second, this study uses electricity consumption as a proxy for energy consumption and CO_2 emissions as a proxy for environmental degradation. Future studies which use other proxies for energy consumption and environmental degradation may provide further insight regarding the link between environmental degradation, energy consumption and economic growth.

A third direction for future research would be to examine the causal relationship between economic growth, pollution emissions and other potentially relevant variables such as automobile use, health expenditure and urbanization. There is much evidence that the increased prevalence of automobiles in many Asian cities, which has accompanied growing urbanization and rising incomes, has exacerbated pollution emissions. Mishra et al. [43] and Zhang and Cheng [68] include urbanization as a variable when examining the energy consumption-economic growth nexus, but neither study considers the role of automobile ownership. Similarly, a large literature exists which examines the long-run relationship between health expenditures and GDP, while Narayan and Narayan [44] examine the influence of pollution emissions and GDP on health expenditure. This could be extended to consider the relationship between economic growth, health expenditure and alternative forms of pollution emissions within a multivariate Granger causality setting.

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