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Does Methodology Matter? Revisiting the Energy-growth Nexus in Asia Pacific Economies

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Abstract

There have been many studies on the energy-growth nexus since the 1970s. However, the findings are mixed. Reasons for the inconsistent findings include different time spans and countries or regions examined, different frameworks, as well as different methodologies adopted, by various studies. In this paper, we examine how methodology affects findings regarding the energy-growth nexus employing a sample of Asia Pacific economies for the period of 1965–2019, using a supply-side framework that takes into consideration both physical capital and human capital in the production function. Methodologies considered in this paper include the widely used vector error correction model and autoregressive distributed lag model (ARDL) for time series and panel data, and Granger non-causality tests. Coefficients are estimated and compared using various methodologies including the cointegrating approach, Dynamic OLS, Fully-Modified OLS, and others. The conclusion obtained from this study will contribute to a better understanding of the varying findings in the literature and highlight the importance of choosing an appropriate methodology for the data analysis.

JEL Classifications: C10, O44, Q43.
Keywords: Energy-growth nexus, Asia Pacific, Granger causality, ARDL, panel data.

1. Introduction

The relationship between energy consumption and economic growth, known as the energy-growth nexus, has been a topic of significant interest for several decades. As energy is an essential input for economic production, understanding the relationship between energy consumption and economic growth is critical for policymakers, researchers, and practitioners alike.

The energy-growth nexus has been studied extensively since the energy crisis of the 1970s, with research initially focused on developed countries, where a positive relationship between energy consumption and economic growth was observed. However, later studies examining developing countries have yielded mixed results, indicating that the relationship between energy consumption and economic growth may be more complex than previously thought. One of the reasons for the mixed findings is the use of different time spans and countries or regions examined in various studies.

For instance, some studies have focused on developed economies (Stern 2000; Fatai *et al* 2002; Gozgor 2018), while others have analysed developing countries (Shahbaz *et al* 2013; Hamit-Haggar 2016; Abid *et al* 2020). Moreover, there are differences in the frameworks and methodologies adopted by various studies. For instance, some studies have used a demand-side approach (Li and Leung 2021), while others have used a supply-side approach (Fang and Chang 2016; Hassan *et al* 2023). Some studies have considered only two variables (Kraft and Kraft 1978), while others have used the multivariate framework (Narayan and Smyth 2009; Fang and Yu 2020). The choice of methodology also varies, with econometric methodologies developing over time, which can affect the results obtained and lead to different conclusions.

In recent years, the research on the energy-growth nexus has shifted towards examining the causal relationship between energy consumption and economic growth, as well as the role of renewable energy, institutions, trade, and technology in shaping the relationship (see surveys by Ozturk and Acaravci 2010; Payne 2010; Ahmad and Zhang 2020). Furthermore, the use of advanced econometric methodologies has allowed for a more nuanced understanding of the energy-growth nexus by addressing some of the limitations of traditional approaches. By accounting for heterogeneity, nonlinearity, and feedback effects, these methods have provided valuable insights into the causal relationship between energy use and economic development, as well as the impact energy conservation policies may have on economic growth.

This paper takes a different approach by examining the impact of methodology on the findings regarding the energy-growth nexus. Based on a sample of Asia Pacific economies for the period 1965–2019, we examine how methodology affects findings regarding the energy-growth nexus, using a supply-side framework that takes into consideration both physical capital and human capital in the production function. The Asia Pacific region is made up of economies with varying levels of economic development, energy resources, and policy approaches. It has also experienced substantial economic growth and energy sector transformations over the past decades, which could contribute to the robustness and relevance of the study. We also employ various methodologies, including the vector error correction model, the autoregressive distributed lag approach, and Granger non-causality tests for both time series and panel data, to estimate and compare the coefficients and Granger causal relationships.

The findings from this study indicate the presence of a cointegrating relationship between energy consumption, factor inputs, and GDP in several economies. The Granger causality analysis supports the presence of causal relationships between these variables. However, the results obtained using different methodologies, such as time series analysis and panel analysis, may vary, emphasising the need for careful interpretation and consideration of country-specific factors. The positive impact of physical capital and human capital on GDP is generally supported, while the impact of energy consumption on GDP appears to be less consistent across economies. These findings contribute to a better understanding of the energy-growth nexus and highlight the complexity of analysing this relationship using different methodological approaches. Conclusions drawn from the paper highlight the importance of selecting an appropriate methodology for data analysis, suggesting researchers need carefully to consider the advantages and limitations of each method before selecting one, or the need to consider a few appropriate methodologies and compare the results before reaching any conclusions and making any policy implications.

2. Literature review

The energy-growth nexus has been a topic of extensive research in the field of energy economics (see surveys by Ozturk 2010; Payne 2010; and Ahmad and Zhang 2020), because determining the causal relationship between energy and GDP is crucial for the development of energy-related policy and supporting sustainable development. Four possible causation outcomes are identified in the literature when the two variables energy (E) and output (Y) are taken into account. They are:

i. Growth Hypothesis: implying that energy causes economic growth ($E \rightarrow Y$)
ii. Conservation Hypothesis: implying that economic growth drives energy use ($Y \rightarrow E$)
iii. Feedback Hypothesis: implying that there is bidirectional causality ($E \leftrightarrow Y$)
iv. Neutrality Hypothesis: implying that there is no interrelationship ($E \neq Y$)

The findings on the causal relationship between energy consumption and economic growth have important short-, medium-, and long-term policy implications. For instance, if a country were subject to the conservation hypothesis, an energy-saving programme would not adversely affect the wealth or rate of economic growth of the country. In the literature, a large number of empirical investigations have sought to establish this nexus, but their findings are conflicting and inconclusive. The results' variability may be explained by the different types of energy consumption the studies look into, different econometric approaches, the bias caused by omitted variables, and different study time frames. Table 1 shows a listing of empirical research based on one or more of our selected economies, organised by author, nation, time period, methodology, and findings. The papers included in Table 1 provide evidence for a general conclusion that the findings regarding the growth, conservation, neutrality, and feedback hypotheses are inconsistent among the investigations. In the case of China, for example, different methodologies may lead to very different results even when the sample periods are similar, as shown in Chang (2010), and Zhang and Ren (2011). The same can be found in other economies as well, where different research methodologies affect the conclusions of the causality directions.

Table 1: Summary of empirical studies on energy-growth nexus for some of the sample economies

No	*Authors*	*Economies*	*Period*	*Methodology*	*Conclusions*
1	Hwang and Gum (1991)	Taiwan	1961-1990	Cointegration, ECM	Y ↔ E
2	Cheng and Lai (1997)	Taiwan	1954-1993	Granger causality	Y → E
3	Lee and Chang (2005)	Taiwan	1954-2003	Johansen-Jeselius, Cointegration, VECM	E → Y
4	Lee and Chang (2007)	Taiwan	1955-2003	Granger causality, Cointegration, VECM	E → Y
5	Glasure and Lee (1998)	South Korea	1961-1990	Hsiao's Granger causality	Y ↔ E
6	Oh and Lee (2004)	South Korea	1970-1999	Granger causality, Cointegration	Y ↔ E
7	Cheng (1998)	Japan	1952-1995	Hsiao's Granger causality	Y → E
8	Cheng (1999)	India	1952-1995	Cointegration, ECM, Granger causality,	Y → E
9	Paul and Bhattacharya (2004)	India	1950-1996	Granger causality, ECM	E → Y
10	Mandal and Madheswaran (2010)	India	1979-2005	Cointegration, ECM	Y ↔ E
11	Mahalik and Mallick (2014)	India	1971-2009	Cointegration, ARDL	E → Y
12	Fatai *et al* (2002)	New Zealand	1960-1999	Granger causality, ARDL, Toda and Yamamoto test	Y ≠ E
13	Bartleet and Gounder (2010)	New Zealand	1960-2004	Granger causality	Y → E
14	Ho and Siu (2007)	Hong Kong	1966-2002	Cointegration, VECM	E → Y
15	Ang (2008)	Malaysia	1971-1999	Johansen Cointegration, VECM	Y → E
16	Tang and Tan (2014)	Malaysia	1972-2009	Cointegration, Granger causality	Y ↔ E
17	Zhang & Cheng (2009)	China	1960-2007	Granger causality	Y → E
18	Chang (2010)	China	1981-2006	Multivariate causality test based on VECM	E → Y
19	Wang, Zhou, Zhou and Wang (2011)	China	1995-2007	Cointegration, VECM	Y ↔ E
20	Wang, Wang, Zhou Zhu and Lu (2011)	China	1972-2006	Cointegration, ARDL	E → Y
21	Zhang and Ren (2011)	China	1980-2008	Cointegration, Granger causality	Y ↔ E
22	Shahbaz *et al* (2013)	China	1971-2011	ARDL, Granger causality	E → Y
23	Jalil and Feridun (2014)	China	1952-2008	ARDL	E → Y
24	Kyophilavong *et al* (2015)	Thailand	1971-2012	Cointegration	Y ↔ E
25	Ahmed *et al* (2015)	Pakistan	1971-2011	Maximum entropy bootstrap	Y → E
26	Abid *et al* (2020)	Pakistan	1990-2017	FMOLS, Granger causality, VECM	Y ↔ E
27	Jafari *et al* (2012)	Indonesia	1971-2007	Toda and Yamamoto test, Granger causality	Y ≠ E

Notes: E → Y, Y → E, E ↔ Y, and E ≠ Y indicate the Growth Hypothesis, Conservation Hypothesis, Feedback Hypothesis, and Neutrality Hypothesis, respectively.

Another important observation from Table 1 is that there is a wide range of methodologies that have been employed to examine this relationship, including time series analysis, panel data analysis, Cointegration analysis, and Granger Causality Analysis. Each of these techniques has its strengths and limitations, and the choice of methodology depends on the nature of the research question and the data available. In the following section, we provide an overview of the key methods used to study the energy-growth nexus, highlighting some of the advantages and limitations of each method. We also provide examples of studies that have used each method to examine the relationship between energy consumption and economic growth.

Time-Series Analysis

Time-series analysis is a popular method used in the study of the energy-growth nexus. This approach involves analysing the time-series data of energy consumption and economic growth to identify the relationship between these two variables. A popular method in this category is the Autoregressive Distributed Lag (ARDL) model, which is used to investigate the long-run and short-run dynamics between the two variables. Ozturk and Acaravci (2010), for example, used the ARDL model to analyse the causal relationship between energy consumption and economic growth in Turkey. They found a positive and significant relationship between the two variables in both the long-run and short-run.

Another time-series method used in the study of the energy-growth nexus is the Vector Autoregression (VAR) model. This method allows for the analysis of the dynamic relationships between multiple variables, including energy consumption and economic growth. As an example, Shafiei and Salim (2014) used the VAR model to analyse the relationship between energy consumption, economic growth, and carbon dioxide emissions. They found bidirectional causality between energy consumption and economic growth, but unidirectional causality running from carbon dioxide emissions to energy consumption.

Panel Data Analysis:

Panel data analysis is another widely used methodology in the study of the energy-growth nexus. This approach involves analysing data on multiple countries or regions over time to identify patterns and relationships that may not be visible in cross-sectional or time-series data alone. Apergis and Payne (2009), for example, used panel data analysis to examine the relationship between energy consumption and economic growth across 10 Central and Eastern European countries. They found bidirectional causality between energy consumption and economic growth.

Another panel data method used in the study of the energy-growth nexus is the dynamic panel data model, which allows for the analysis of the dynamic relationships between multiple variables over time. As an example, Huang *et al* (2022) used the dynamic panel data model to analyse the relationship between energy consumption and economic growth in 30 provinces in China. They found that energy consumption had a positive impact on economic growth in the short run, but no significant impact in the long run.

Panel Cointegration Analysis

Panel cointegration analysis has been employed in several studies to investigate the long-run causal relationship between energy consumption and economic growth. This technique involves testing for the presence of cointegration in a panel data set, whilst the second generation of panel cointegration analysis allows for the possibility of cross-sectional dependence and heterogeneity among countries. A number of studies have used panel cointegration analysis to examine the energy-growth nexus, including those by Ghosh (2002), Apergis and Payne (2010), and Wang *et al* (2016). For example, Apergis and Payne (2010) used a panel data set of 54 countries over the period 1971–2005 to investigate the existence of a long-run relationship between energy consumption and economic growth, and found evidence of a positive long-run relationship.

Granger Causality Analysis

Granger causality analysis involves testing for the presence of causality in a time series data set or panel data setting, and has been used in studies to investigate the direction of causality between energy consumption and economic growth. Some notable studies that have used Granger causality analysis include those by Shahbaz *et al* (2011), Lin and Moubarak (2014), and Aydin (2018). For example, Aydin (2018) examined how natural gas consumption is related to economic growth over the period 1994–2015, for the top 10 natural gas-consuming countries using the panel Granger causality tests that allow for country-level heterogeneity. Their results suggest a significant and positive impact of natural gas consumption on economic growth in the long run. Lin and Moubarak (2014) studied the relationship between renewable energy consumption and GDP growth in China from 1977 to 2011. Their Granger causality test results show bi-directional long-term causality between renewable energy consumption and economic growth in that country.

The Vector Error Correction Model (VECM) can be used for the analysis of long-run relationships between multiple variables. Zhang *et al* (2021) used the panel VECM to analyse how three renewable energy sources are related to the sustainable economic growth of the South Asian Association for Regional Cooperation (SAARC) countries. Based on data from SAARC countries for 1995 to 2018, they found that the three renewable energy sources in these countries play a positive and significant role in impacting their economic development.

To sum up, the empirical evidence on the energy-growth nexus is mixed. The strength and direction of this relationship vary across countries and regions and are influenced by a range of factors such as the level of economic development, the structure of the economy, and the energy mix. More research is needed to better understand the factors that drive the energy-grow nexus.

3. Data

This study follows Fang and Chang (2016) and updates the dataset to 2019 to revisit the energy-growth nexus in Asia Pacific economies. Specifically, this study uses real GDP, physical and human capital from the Penn World Table (PWT) version 10.0 (Feenstra *et al* 2013), and primary energy consumption (million tons oil equivalent) from BPs 2020 statistical review of world energy. The index of human capital per worker has been made available since PWT version 8.0. It was constructed based on the average years of schooling in the most updated Barro-Lee Educational Attainment Dataset (Barro and Lee 2013) and an estimated rate of return to primary education, secondary education, and tertiary education. Details on the index construction can be found in Feenstra *et al* (2013) and Fang and Chang (2016).

Following Fang and Chang (2016), these variables, GDP, physical capital, human capital, and energy consumption, are examined in the multivariate supply-side model.[4] The sample includes 14 Asian Pacific economies, namely, Australia, China, China Hong Kong SAR, Indonesia, India, Japan, Malaysia, New Zealand, Philippines, Singapore, South Korea, Sri Lanka, Thailand, and Taiwan, for more than half a century from 1965–2019.[5] The selected time period encompasses a substantial duration, allowing us to capture long-term trends and assess the energy-growth relationship over time. Furthermore, the focus on the Asia Pacific economies contributes to a better understanding of the varying findings in the literature, as it represents a diverse group of economies with diverse levels of economic development, energy resources, and policy approaches.

Firstly, the Asia Pacific region comprises some of the world's largest and fastest-growing economies, which have seen significant economic growth and undergone transformative changes in the energy sector in recent decades, making them key contributors to global energy consumption. Investigating the energy-growth nexus in this region provides valuable insights into the dynamics of energy use and its implications for economic development on a substantial scale. Secondly, the region encompasses a wide range of energy resources, comprising fossil fuels, renewables, and nuclear power, which presents unique challenges and opportunities for understanding the energy-growth relationship. Lastly, the Asia Pacific region features diverse policy approaches and initiatives aimed at addressing energy security, sustainability, and economic development. As a result, examining this region provides a broader perspective on the energy-growth relationship by balancing internal and external validity. By considering region-specific factors, policy approaches, and diverse energy landscapes, studies in this region contribute to filling gaps in the existing literature and provide insights that can inform policy decisions and sustainable development strategies in the Asia Pacific region and beyond.

4. Econometric methodologies

We first conduct the time series analysis for each of the 14 Asia Pacific economies individually, and next, perform the analysis on the whole panel of 14 economies, as well as the individual economies whenever possible, over the 55 years from 1965 to 2019. The observation period and variables have not been changed throughout this study.

The extended production model that considers physical capital (K), human capital (H) and energy (E) as factor inputs is specified as follows:

$$lnY = f(lnK, lnH, lnE)$$

where *Y* represents GDP, and the logarithms are used for each of the variables Y, K, H and E.

4.1 Time series analysis

For the time series part, we apply the following methods for each of the 14 Asia Pacific economies. First, we use the Augmented Dickey-Fuller (ADF) unit root test (Dickey and Fuller 1979) to examine whether the series of lnY, lnK, lnH, and lnE are stationary. It is noted, however, that there are many other tests that are often used in the literature as well, such as the Phillips-Perron (PP) test (Phillips and Perron 1988), and the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski *et al* 1992). Next, we apply the Johansen cointegration test (Johansen 1991, 1995) to test whether the four variables are cointegrated, under the assumption that they are all integrated of order one. If the variables are found to be cointegrated, the vector error correction model (VECM) is subsequently employed to investigate the long-term cointegrating relationship of the four variables, as well as the Granger causal relationship between energy consumption and economic growth in both the short run and long run. Specifically, the VECM is as follows:

$$\Delta lnY_t = \alpha_1 + \sum_{j=1}^{p-1} \beta_{1j}\Delta lnY_{t-j} + \sum_{j=1}^{p-1} \gamma_{1j}\,\Delta lnK_{t-j} + \sum_{j=1}^{p-1} \delta_{1j}\,\Delta lnH_{t-j} + \sum_{j=1}^{p-1} \theta_{1j}\,\Delta lnE_{t-j} + \rho_1 ECT_{t-1} + \varepsilon_t$$

$$\Delta lnK_t = \alpha_2 + \sum_{j=1}^{p-1} \beta_{2j}\Delta lnY_{t-j} + \sum_{j=1}^{p-1} \gamma_{2j}\,\Delta lnK_{t-j} + \sum_{j=1}^{p-1} \delta_{2j}\,\Delta lnH_{t-j} + \sum_{j=1}^{p-1} \theta_{2j}\,\Delta lnE_{t-j} + \rho_2 ECT_{t-1} + \varepsilon_t$$

$$\Delta lnH_t = \alpha_3 + \sum_{j=1}^{p-1} \beta_{3j}\Delta lnY_{t-j} + \sum_{j=1}^{p-1} \gamma_{3j}\,\Delta lnK_{t-j} + \sum_{j=1}^{p-1} \delta_{3j}\,\Delta lnH_{t-j} + \sum_{j=1}^{p-1} \theta_{3j}\,\Delta lnE_{t-j} + \rho_3 ECT_{t-1} + \varepsilon_t$$

$$\Delta lnE_t = \alpha_4 + \sum_{j=1}^{p-1} \beta_{4j}\Delta lnY_{t-j} + \sum_{j=1}^{p-1} \gamma_{4j}\,\Delta lnK_{t-j} + \sum_{j=1}^{p-1} \delta_{4j}\,\Delta lnH_{t-j} + \sum_{j=1}^{p-1} \theta_{4j}\,\Delta lnE_{t-j} + \rho_4 ECT_{t-1} + \varepsilon_t$$

where Δ is the first difference operator, *ECT* is short for the error correction term, and ε_t is the white noise. The lag order p is the optimal lag order determined by information criteria such as Akaike Information Criterion (AIC) and Schwarz Bayesian Criterion (SBC) in the vector autoregression (VAR) model. The short-run Granger causality test on energy use Granger causing GDP is determined by the (joint) test on $\{\theta_{1j}\}$, and that on GDP Granger causing energy use is tested by $\{\beta_{4j}\}$. The long-run Granger causal relationship is examined through the coefficient of the error correction term, ρ_1 or ρ_4 for either direction. A stronger version of the long-run Granger causality test is to look at both the coefficient of the error correction term and the coefficients of the lagged differences. More specially, a joint test on ρ_1 and θ_{1j} is applied to examine whether energy Granger causes GDP; and a joint test ρ_4 on β_{4j} and is applied to check whether GDP Granger causes energy consumption.

Besides the traditional time series analysis, we further apply the autoregressive distributed lag (ARDL) model for the cointegrating analysis. The ARDL bounds test for cointegration was first introduced by Pesaran *et al* (2001). Compared to the Johansen cointegration test and other earlier approaches such as Engle and Granger (1987), and Toda and Yamamoto (1995), the ARDL bounds test allows both I(0) and I(1) variables to co-exist in the model, and different lag orders for different variables. It also corrects for residual serial correlation and therefore has good small-sample performance. The reparameterised ARDL model is as follows:

$$\Delta lnY_t = \alpha_1 + \sum_{j=1}^{p_1} \beta_{1j} \Delta lnY_{t-j} + \sum_{j=0}^{p_2} \beta_{2j}\, \Delta lnK_{t-j} + \sum_{j=0}^{p_3} \beta_{3j}\, \Delta lnH_{t-j} + \sum_{j=0}^{p_4} \beta_{4j}\, \Delta lnE_{t-j} + \delta_1 lnY_{t-1}$$
$$+ \delta_2 lnK_{t-1} + \delta_3 lnH_{t-1} + \delta_4 lnE_{t-1} + \varepsilon_t$$

where p_i is the optimal lag. The coefficients $\{\beta_{ij}\}$ are short-run coefficients, and the long-run coefficients are derived by $-\frac{\delta_j}{\delta_1}(j = 2,3,4)$. The coefficient δ_1, the speed of adjustment coefficient, is expected to be negative, as it measures how fast lnY_t reacts to the deviation from the long-run equilibrium in the next period. Otherwise, the variables are not cointegrated and there is no long-term relationship among the variables.

In the ARDL model, the null hypothesis of no cointegrating relationship is tested by an F-test on the joint significance of $\{\delta_i\}$, and bounds on the critical values for the F-test are provided by Pesaran *et al* (2001). If the computed F-statistic is smaller than the lower bound, the variables are not cointegrated. If the computed F-statistic is greater than the upper bound, there is a cointegrating relationship among the variables. If the computed F-statistic is within the lower and upper bounds, it is inconclusive. If the variables are found to be cointegrated, the error correction model can be applied to get the dynamic relationship. Otherwise, the ARDL model is employed to explore the short-run and long-run relationship of the four variables. The only point to note is that no I(2) series are allowed in the ARDL model.

4.2 Panel data analysis

For the panel data, there are many methods proposed in the econometrics literature to conduct the unit root test, the cointegration test, and the Granger causality test. They can be divided into two generations. The first generation does not take into account the cross-sectional dependence (Levin *et al* 2002; Im *et al* 2003), while the second-generation methodologies assume the cross-section units are dependent (Pesaran 2007). In this paper, we first examine whether the four variables are all cross-sectional dependent using the Pesaran (2004) CD-test statistic $\sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right)$ where $\hat{\rho}_{ij}$ are correlation coefficient estimates, and N and T are the number of units and time periods, respectively. It is proved to follow a standard normal distribution. Next, we use the cross-sectionally augmented IPS (CIPS) test to test for the presence of unit root. This is the second-generation panel unit root test proposed by Pesaran (2007). If they are integrated of order one, we proceed to use the Westerlund (2007) test to test for the presence of a cointegrating relationship in the panel data. If the results show the variables are cointegrated, we move on to estimate the long-run relationship using the panel heterogeneous fully-modified OLS (Pedroni 2001), and the dynamic OLS (Kao and Chiang 2001).

Furthermore, we apply the panel ARDL method to examine the cointegrating and dynamic relationship among all four variables. The panel ARDL (p, q_1, q_2, q_3) model is specified as follows:

$$lnY_{it} = \sum_{j=1}^{p}\alpha_{ij}lnY_{i,t-j} + \sum_{j=0}^{q_1}\beta_{ij}\,lnK_{i,t-j} + \sum_{j=0}^{q_2}\gamma_{ij}\,lnH_{i,t-j} + \sum_{j=0}^{q_3}\delta_{ij}\,lnE_{i,t-j} + \varphi_i + e_{it}$$

where φ_i denotes the fixed effect. If there is a cointegrating relationship among the variables, the panel ARDL can be re-parameterised to the error correction model as follows:

$$\Delta lnY_{it} = \rho_i\left(lnY_{i,t-1} - \theta_{1i}lnK_{i,t-1} - \theta_{2i}lnH_{i,t-1} - \theta_{3i}lnE_{i,t-1}\right) + \sum_{j=0}^{p-1}\lambda_{ij}\,\Delta lnY_{i,t-j}$$
$$+ \sum_{j=1}^{q_1-1}\eta_{ij}\,\Delta lnK_{i,t-j} + \sum_{j=1}^{q_2-1}\tau_{ij}\,\Delta lnH_{i,t-j} + \sum_{j=1}^{q_3-1}\upsilon_{ij}\,\Delta lnE_{i,t-j} + \varphi_i + e_{it}$$

where ρ_i is expected to be negative and significant, suggesting the speed of adjustment to its long-run equilibrium. In the bracket is the long-run relationship and the coefficients before the difference operators show the short-run relationship between the regressors and lnY.

Lastly, to uncover the Granger causal relationship between energy consumption and economic growth, we use panel Granger causal tests proposed by Emirmahmutoglu and Kose (2011), and Dumitrescu and Hurlin (2012).

For the EK Granger causal test, the null hypothesis is the absence of a Granger causal relationship between the variables. The EK approach proposes the Fisher test statistic $\lambda = -2\sum_{i=1}^{N} lnP_i$, where P_i is the p-value of the Wald statistic of unit *i*. It follows a chi-square distribution of 2N degrees of freedom when the cross-sections are independent, and an empirical distribution to be obtained by the bootstrap method when the cross-sections are dependent. Besides allowing for cross-sectional dependence, it allows heterogeneity and avoids the pretest bias (Emirmahmutoglu *et al* 2016). It has been applied in studies such as Cowan *et al* (2014), Yao and Chang (2014), Yao and Chang (2015), Fang and Chang (2016), and Fang and Yu (2020).

For the DH Granger causal test, the null hypothesis is no Granger causality for any units of the panel, while the alternate hypothesis is the presence of a Granger causal relationship for at least some units. It has a good small-sample property and allows heterogeneity and cross-sectional dependence. Empirical applications refer to Herrerias (2013), and Chen and Fang (2018).

5. Empirical results

5.1 Results from the time series analysis

We analyse the cointegrating relationship between economic growth, physical capital, human capital, and energy consumption, as well as the Granger causal relationship between economic growth and energy consumption in each of the 14 Asia Pacific economies over the period 1965–2019.

Table 2 shows the results of the ADF unit root tests for lnY, lnK, lnH, and lnE in levels and in first differences in two models, one with only the constant, and the other with both the constant and the trend. The findings are summarised in Table 3. Looking at the four variables individually, we find that at the 5 per cent significance level, there is some evidence that lnY is integrated of order one for all economies except Japan and the Philippines, and lnE is I(1) for all economies except Australia and Japan. For the other two variables, physical capital and human capital, lnK is found to be stationary after first difference only in Indonesia, Malaysia, and New Zealand, while lnH is integrated of order one for most economies (except Hong Kong, Indonesia, Japan, and Thailand).

To sum up, only two countries, Malaysia and New Zealand, have all four series that are non-stationary in levels but become stationary after first differencing, which then allows us to proceed with the Johansen cointegration test in the next step. However, it is noteworthy that researchers of empirical studies usually perform other unit root tests such as the Phillips-Perron (PP) test (Phillips and Perron 1988), the Kwiatkowski-Phillips-Schmidt-Shin (KPSS) test (Kwiatkowski *et al* 1992), and the Augmented Dicky-Fuller Generalised

Table 2: Results of ADF unit root tests

	log_1gdp				log_1k			
	level		first difference		level		first difference	
	constant	with trend	constant	with trend	constant	with trend	constant	with trend
Australia	-1.662	-1.628	-3.722***	-3.890**	-1.836	-0.637	-1.947	-2.452
China	0.718	-2.179	-4.829***	-4.724***	1.829	-1.870	-2.834*	-3.022
China Hong Kong SAR	-3.259**	-0.749	-3.008**	-4.366***	-2.663*	1.053	-1.666	-3.041
India	3.042	-0.646	-3.067**	-5.163***	1.339	-1.655	-1.648	-2.299
Indonesia	-0.886	-2.203	-3.555**	-3.558**	-0.731	-2.175	-2.975**	-2.835
Japan	-3.265**	-2.634	-3.062**	-3.240*	-3.755***	-2.946	-2.328	-2.966
Malaysia	-1.956	-2.458	-3.325**	-3.641**	-2.395	-1.137	-2.600*	-3.609**
New Zealand	0.118	-1.914	-4.146***	-4.073***	-1.679	-2.345	-3.444**	-4.066**
Philippines	0.961	-0.422	-2.876*	-3.177	0.028	-2.008	-2.384	-2.334
Singapore	-4.100***	-2.538	-2.680*	-3.819**	-4.263***	-3.279*	-1.975	-4.119**
South Korea	-3.779***	0.563	-2.604*	-4.653***	-2.120	0.269	-1.577	-2.186
Sri Lanka	1.158	-1.750	-3.077**	-3.276*	0.513	-1.414	-2.673*	-2.793
Taiwan	-4.297***	0.313	-2.574	-5.083***	-2.771*	-0.921	-1.413	-2.754
Thailand	-2.193	-1.924	-3.334**	-3.827**	-2.325	-0.986	-2.186	-2.828

	log_1hc				log_1energy			
	level		first difference		level		first difference	
	constant	with trend	constant	with trend	constant	with trend	constant	with trend
Australia	-1.478	-2.295	-4.795***	-4.971***	-3.222**	-2.105	-2.580	-3.149
China	-2.902*	-0.400	-1.424	-3.549**	-1.977	-2.988	-4.195***	-4.28***
China Hong Kong SAR	-2.277	-1.044	-2.061	-2.540	-2.509	-1.918	-4.094***	-4.613***
India	-1.362	-1.675	-3.061**	-3.240*	0.939	-2.063	-3.493**	-3.636**
Indonesia	-1.355	-1.056	-2.170	-2.444	-2.198	-1.356	-3.523**	-4.151***
Japan	0.381	-2.431	-2.843*	-2.840	-3.077**	-2.406	-3.100**	-3.223*
Malaysia	-0.837	-1.497	-3.214**	-3.274*	-2.278	-0.268	-3.597***	-4.459***
New Zealand	-1.137	-2.271	-3.657***	-3.623**	-2.719*	-1.191	-3.977***	-5.014***
Philippines	-1.199	-1.214	-4.988***	-5.181***	-1.386	-3.022	-3.135**	-3.060
Singapore	0.641	-2.662	-4.989***	-5.077***	-1.103	-1.844	-5.631***	-5.552***
South Korea	-3.205**	-1.292	-3.147**	-4.300***	-3.307**	-0.275	-2.253	-3.741**
Sri Lanka	-1.013	-1.507	-4.238***	-4.264***	-1.013	-3.855**	-4.436***	-4.426***
Taiwan	-2.069	-0.712	-3.350**	-3.960**	-4.076***	-0.031	-3.026**	-5.362***
Thailand	-0.974	-1.687	-2.314	-2.358	-1.731	-1.594	-3.263**	-3.388*

Note: ADF test results are based on the model specifications with 2 lags.
*** Significant at 1% level. ** Significant at 5% level. * Significant at 10% level

Table 3: A summary of integration order of the variables
(Results of stationarity at the 5% significance level)

	log_1gdp		log_1k		log_1hc		log_1energy	
	constant	with trend	constant	with trend	constant	with trend	constant	with trend
Australia	I(1)	I(1)			I(1)	I(1)	I(0)	
China	I(1)	I(1)				I(1)	I(1)	I(1)
Hong Kong	I(0)	I(1)					I(1)	I(1)
India	I(1)	I(1)			I(1)		I(1)	I(1)
Indonesia	I(1)	I(1)	I(1)				I(1)	I(1)
Japan	I(0)		I(0)				I(0)	
Malaysia	I(1)	I(1)		I(1)	I(1)		I(1)	I(1)
New Zealand	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)	I(1)
Philippines					I(1)	I(1)	I(1)	
Singapore	I(0)	I(1)	I(0)	I(0)	I(1)	I(1)	I(1)	I(1)
South Korea	I(0)	I(1)			I(0)	I(1)	I(0)	I(1)
Sri Lanka	I(1)				I(1)	I(1)	I(1)	I(0)
Taiwan	I(0)	I(1)			I(1)	I(1)	I(0)	I(1)
Thailand	I(1)	I(1)					I(1)	

Note: The findings are based on the ADF test results for the specifications with 2 lags, at the significance level of 5%, in Table 1.

Least Squares (ADF-GLS) test (Elliott *et al* 1996), or even more advanced versions that allow for structural breaks such as the Perron (1997) test and the Zivot and Donald (1992) test, together with the ADF test. It is not uncommon that findings vary across the different unit root tests, and one can always find some evidence of I(1) to some extent. Therefore, in the next step, we continue to perform the Johansen cointegration test on each of the 14 economies, though our ADF unit root test results only support the I(1) of all four variables in Malaysia and New Zealand.

Table 4 summarises the cointegration ranks found from the trace statistic and the max eigenvalue statistic in the Johansen cointegration tests for every economy, at the 5 per cent significance level. Since the Johansen cointegration test is sensitive to the lag order used in the VAR model, we first select the optimal lag order based on three information criteria, namely the Akaike information criterion (AIC), Hannan-Quinn information criterion (HQIC), and Schwartz information criterion (SIC). It is found that the optimal lag order is two for the VAR model in all the 14 economies except Thailand, where the optimal order of lag is 3. For the two countries where the series are found to be integrated of order one, results from the Johansen cointegration test show that the four variables are cointegrated in New Zealand, but there is no long-term

Table 4: A summary of Johansen cointegration test results

	Lag order	Order of cointegration	
		Trace statistic	Max eigenvalue statistic
Australia	2	2	1
China	2	0	0
China Hong Kong SAR	2	2	1
India	2	1	1
Indonesia	2	0	0
Japan	2	1	1
Malaysia	2	0	0
New Zealand	2	1	1
Philippines	2	0	0
Singapore	2	1	1
South Korea	2	3	3
Sri Lanka	2	0	0
Taiwan	2	2	1
Thailand	3	1	1

Note: The optimal lag order is chosen based on AIC, HQIC, and SBIC. The order of cointegration is determined at the 5% significance level.

relationship among the four variables in Malaysia. For other economies, results suggest the existence of a long-run relationship between GDP, physical capital, human capital, and energy consumption in Australia, Hong Kong, India, Japan, Singapore, South Korea, Taiwan, and Thailand, while in China, Indonesia, the Philippines, and Sri Lanka there is no evidence of a linear cointegrating relationship at the 5 per cent significance level.

Although, theoretically, only when the non-stationary variables are cointegrated do they have an ECM representation (Engle and Granger 1987), we still use the VECM to estimate the long-term relationship among the four variables and establish the Granger causal relationship between GDP and energy consumption for every country. This is to enable us to compare findings from various econometric methodologies. Table 5 reports the estimated coefficients and standard errors for lnK, lnH, and lnE, as well as the constant in the long-term cointegrating relationship with lnY. In New Zealand, where the VEC model is legitimate, we find that in the long run, a 1 per cent increase in physical capital is associated with a 1.03 per cent increase in GDP, while surprisingly a 1 per cent increase in human capital is associated with a 1.11 per cent reduction in GDP. Moreover, energy consumption is found to be negatively associated with economic growth in New Zealand.

For other economies where we enforce the VECM regression, the significant and positive relationship between physical capital and GDP is found in almost

Table 5: Cointegrating relationships based on the VEC model

	log_k		log_hc		log_e		constant
Australia	1.668***	(0.220)	-3.253***	(0.912)	0.365	(0.288)	18.614
China	0.518***	(0.115)	0.668***	(0.223)	0.113	(0.203)	14.046
Hong Kong	2.651***	(0.405)	0.178	(0.626)	-2.405***	(0.451)	11.804
India	0.997***	(0.372)	2.597***	(0.839)	-0.792	(0.736)	14.752
Indonesia	0.924***	(0.054)	-0.295***	(0.090)	-0.032	(0.051)	14.142
Japan	0.691***	(0.059)	0.195	(0.192)	-0.362***	(0.094)	13.098
Malaysia	-2.301***	(0.531)	1.559**	(0.755)	2.420***	(0.543)	6.226
New Zealand	1.029***	(0.085)	-1.107***	(0.262)	-0.740***	(0.116)	11.445
Philippines	0.513	(0.649)	1.133	(1.030)	-1.560***	(0.395)	4.332
Singapore	0.243***	(0.074)	0.199	(0.161)	0.418***	(0.140)	11.994
South Korea	0.154**	(0.066)	1.083***	(0.189)	0.369***	(0.070)	11.062
Sri Lanka	-2.604	(1.600)	-24.017***	(5.001)	14.410***	(2.838)	64.641
Taiwan	1.099***	(0.137)	0.748***	(0.162)	-0.898***	(0.204)	12.466
Thailand	0.691***	(0.150)	1.235***	(0.227)	-0.375**	(0.151)	11.226

Note: All economies (except Thailand) use the lag order of 2 in the VAR model; For Thailand, we use the lag order of 3 in the VAR model.

every country (except in Malaysia where it is significantly negative, and in the Philippines and Sri Lanka where it is insignificant). Next, the surprising negative relationship between human capital and GDP is also found in Australia, Indonesia, and Sri Lanka, but it is significantly positive in China, India, Malaysia, South Korea, Taiwan, and Thailand. As for the relationship between energy consumption and economic development, they are found to be significantly positive in Malaysia, Singapore, South Korea, and Sri Lanka, while significantly negative in Hong Kong, Japan, the Philippines, Taiwan, and Thailand. Overall, the long-term relationship varies across economies.

Using the VEC model, we also explore the short-run and the long-run Granger causal relationship between GDP and energy consumption. The results at the 5 per cent significance level are summarised in Table 6. In the long run (both from the error correction term and the combined test), the conservation hypothesis is supported in Australia, Hong Kong, Malaysia, New Zealand, and South Korea, while the feedback effect is evidenced in Japan, Singapore, Sri Lanka, and Thailand. In other economies, results from the two tests are not consistent. As for the short-run Granger causality, eight of the 14 economies show no evidence of causality from both directions, and five of them (Australia, Hong Kong, New Zealand, Taiwan, and Thailand) show short-run Granger causality running from GDP to energy consumption, and only one (the Philippines) presents evidence of short-run Granger causal relationship from energy consumption to GDP.

Table 6: A summary of Granger causal relationship between GDP and energy consumption based on the VEC model

	Short-run	Long-run ECT	Long-run combined
Australia	Conservation	Conservation	Conservation
China	Neutrality	Feedback	Growth
China Hong Kong SAR	Conservation	Conservation	Conservation
India	Neutrality	Growth	Growth
Indonesia	Neutrality	Growth	Neutrality
Japan	Neutrality	Feedback	Feedback
Malaysia	Neutrality	Conservation	Conservation
New Zealand	Conservation	Conservation	Conservation
Philippines	Growth	Growth	Neutrality
Singapore	Neutrality	Feedback	Feedback
South Korea	Neutrality	Conservation	Conservation
Sri Lanka	Neutrality	Feedback	Feedback
Taiwan	Conservation	Conservation	Feedback
Thailand	Conservation	Feedback	Feedback

Note: The findings are made at the significance level of 5%.

Next, we use the ARDL approach to investigate the cointegrating relationship among GDP, physical capital, human capital, and energy consumption. In our analysis, the optimal lag order is determined by the AIC. The selected model and the associated F-test statistic of the ARDL bounds testing for each of the 14 economies are shown in Table 7. The upper and lower bounds of the critical values of the F test at the 1 per cent, 5 per cent, and 10 per cent significance levels are reported at the bottom of Table 7. Comparing the F-test statistics with the bounds at the 5 per cent significance levels, we conclude that the long-run cointegrating relationship among the four variables exists in Hong Kong, India, Japan, Singapore, South Korea, and Thailand, while there is no evidence of cointegration in the other economies. Nonetheless, it should be noted that only the findings for Malaysia, New Zealand, and Singapore are credible, as the ARDL approach allows for only I(0) and I(1) series in the model, and only these three economies meet this requirement based on results summarised in Table 3.

Assuming the ARDL bounds testing results support the presence of the cointegrating relationship between GDP, physical capital, human capital, and energy consumption for all 14 economies, we subsequently obtain the long-run coefficient estimates using the ARDL model, and the results are shown in Table 8. For Singapore where the estimates are more credible, we find that a 1 per cent increase in physical capital is associated with a 0.58 per cent

Table 7: Bounds test results and the cointegrating relationship based on the ARDL model

	F-statistic	Lags	Cointegration? (at a 5% significance level)
Australia	2.961	(1,2,0,1)	
China	2.383	(1,1,0,1)	
Hong Kong	10.685	(2,2,0,0)	V
India	6.667	(2,2,2,1)	V
Indonesia	1.041	(1,2,2,0)	
Japan	12.074	(2,2,4,4)	V
Malaysia	1.398	(2,2,0,1)	
New Zealand	1.565	(1,2,2,1)	
Philippines	1.986	(2,2,0,1)	
Singapore	4.8	(2,2,2,0)	V
South Korea	11.774	(2,2,0,2)	V
Sri Lanka	1.768	(1,2,0,1)	
Taiwan	2.81	(1,2,2,2)	
Thailand	4.79	(1,2,0,2)	V
	I(0)	I(1)	
Bounds at 1%	4.29	5.61	
Bounds at 5%	3.23	4.35	
Bounds at 10%	2.72	3.77	

Table 8: Estimated long-run coefficients using the ARDL model

Country	log_k		log_hc		log_e	
Australia	0.748***	(0.238)	0.430	(0.892)	-0.595	(0.369)
China	0.522***	(0.080)	0.087	(0.173)	0.103	(0.146)
China Hong Kong SAR	-0.084	(0.210)	1.456***	(0.257)	0.552***	(0.203)
India	0.742***	(0.194)	0.673	(0.608)	-0.001	(0.393)
Indonesia	0.832***	(0.129)	-0.158	(0.233)	-0.022	(0.115)
Japan	0.682***	(0.040)	0.03	(0.152)	-0.341***	(0.090)
Malaysia	0.292	(0.573)	2.162**	(0.960)	-0.454	(0.696)
New Zealand	0.967***	(0.247)	-0.809	(0.788)	-0.497*	(0.252)
Philippines	0.727	(0.735)	0.307	(1.244)	-1.035	(0.805)
Singapore	0.577***	(0.048)	0.148	(0.093)	0.266***	(0.084)
South Korea	0.213**	(0.080)	1.028***	(0.178)	0.301***	(0.090)
Sri Lanka	1.044**	(0.439)	1.585	(1.373)	-0.804	(0.959)
Taiwan	0.335*	(0.199)	1.253***	(0.213)	0.044	(0.285)
Thailand	0.155	(0.106)	0.556***	(0.168)	0.425***	(0.093)

increase in GDP, and a 1 per cent increase in energy use is associated with a 0.27 per cent increase in GDP, while human capital is insignificantly related to economic growth. Comparing these estimates with those reported in Table 5, the magnitude of the impacts varies but the significance and direction of the impacts are similar. However, the consistency of the qualitative conclusion is rare and only seen in two other countries: Japan and South Korea. In all other economies, the long-run estimates obtained from the ARDL model are quite different from those from the VECM, even though only the signs are considered.

While it is not uncommon to reach different findings when different methodologies are used, it is crucial to follow the proper procedures or best implementation strategies for each methodology (Menegaki 2019). Strictly speaking, for the VECM analysis, only the findings for New Zealand are credible; and for the ARDL analysis, only the findings for Hong Kong, India, Japan, Singapore, South Korea, and Thailand, are credible. If there is further evidence to support these findings, policy implications drawn from these results become more convincing.

5.2 Results from the panel data analysis

Table 9 shows the results of the cross-sectional dependence test (CD-test) proposed by Pesaran (2004). As expected, the CD-test statistics reject the null hypothesis of cross-sectional independence at the 1 per cent significance level, suggesting that all four variables present strong interdependence across economies.

Table 9: Cross-sectional dependence test results

	ln_gdp	ln_k	ln_hc	ln_energy
CD-test statistic	67.08	68.34	67.58	64.98
p-value	0.000	0.000	0.000	0.000

Since our data are cross-sectional dependent, we apply the second-generation panel unit root test, the CIPS statistic developed by Pesaran (2007), to examine whether the data are stationary. Table 10 shows the panel unit root test results using the CIPS test for two models with and without the trend term, for both the level variables and the first difference variables. The results for the model with only the intercept suggest that all four variables have unit roots, and become stationary after first difference, at least at the 5 per cent significance level. However, in the model with both the intercept and the trend terms, results suggest the three variables (lnY, lnH, and lnE) are integrated of order one at the 1 per cent significance level, while lnK is stationary (i.e. I(0)). Therefore, we can either proceed to perform the panel cointegration analysis based on results from the intercept model, or we can move on to the panel ARDL model without any concern.

Table 10: Panel unit root test results (Pesaran, 2007)

	Level		First difference	
	Intercept	Intercept and trend	Intercept	Intercept and trend
ln_gdp	-1.403	-1.851	-5.029***	-5.481***
ln_k	-2.092	-3.323***	-2.365**	-2.528
ln_hc	-2.128	-2.864**	-4.809***	-5.087***
ln_energy	-1.991	-2.770	-6.003***	-6.146***

Notes: (i) The maximum lag length to be included in the model is set to 4; (ii) *** and ** denote the significance level of 1% and 5%, respectively.

We perform the panel cointegration test proposed by Westerlund (2007) for the cross-sectionally dependent data. The null hypothesis in Westerlund's (2007) test is the absence of cointegration, while there are two versions of the alternative hypothesis: one is that some units are cointegrated, and the other is a stronger version that states all units are cointegrated. Therefore, we have in total four test statistics for models without the trend and with the trend term, which, together with their associated p-values, are reported in Table 11. The test statistic -1.467 suggests the presence of cointegration in some panels at the 10 per cent significance level for the model without the trend, while the other three test statistics suggest that there is no cointegration in the panel data.

Table 11: Panel cointegration test results with cross-sectional dependence (Westerlund 2007)

Test	Some	All	Some	All
			Trend	Trend
Test statistic	-1.467 (0.071)	-1.011 (0.156)	-0.180 (0.429)	-0.633 (0.263)

Notes: In parentheses are p-values. Ho: no cointegration. Ha: Some panels are cointegrated, or all panels are cointegrated.

Next, we employ the panel ARDL model to investigate whether the data are cointegrated. The optimal lag orders are first determined using the most common lags across all 14 economies for each of the four variables, which are ARDL(1,2,0,0). Estimates of the long-run relationship for each economy and the whole panel are reported in Table 12. Physical capital is found to have a significant impact on economic growth, especially in Australia, China, India, Indonesia, Japan, the Philippines, Singapore, and Sri Lanka. Human capital is overall not significantly related to economic growth, except in Hong Kong, Japan, Malaysia, South Korea, and Taiwan. Energy consumption is driven by economic growth in Hong Kong, Singapore, South Korea, and Thailand.

Table 12: Long-run coefficient estimates from Panel ARDL model

	lnK		lnH		lnE		ECT	
Australia	0.514**	(0.223)	1.448	(1.042)	-0.878	(0.543)	-0.095*	(0.069)
China	0.517***	(0.084)	-0.0393	(0.165)	0.151	(0.153)	-0.236**	(0.018)
Hong Kong	0.0605	(0.176)	1.338***	(0.238)	0.429**	(0.182)	-0.310***	(0.000)
India	0.704***	(0.256)	-0.244	(0.556)	0.316	(0.510)	-0.195*	(0.065)
Indonesia	0.884***	(0.096)	-0.273	(0.188)	-0.0133	(0.103)	-0.252**	(0.036)
Japan	0.649***	(0.066)	0.413**	(0.194)	-0.145	(0.104)	-0.297**	(0.018)
Malaysia	0.329	(0.476)	1.618***	(0.575)	-0.273	(0.505)	-0.099*	(0.088)
New Zealand	0.946	(0.662)	-0.764	(2.150)	-0.220	(0.745)	-0.057	(0.532)
Philippines	1.108**	(0.540)	-0.218	(0.833)	-0.989*	(0.554)	0.086**	(0.030)
Singapore	0.581***	(0.051)	0.134	(0.098)	0.285***	(0.090)	-0.349***	(0.001)
South Korea	0.197*	(0.109)	0.826***	(0.249)	0.388***	(0.135)	-0.325***	(0.000)
Sri Lanka	0.844**	(0.372)	0.630	(0.933)	-0.152	(0.569)	-0.046	(0.428)
Taiwan	0.0219	(0.226)	1.122***	(0.232)	0.564*	(0.338)	-0.264***	(0.001)
Thailand	0.256	(0.178)	0.362	(0.274)	0.403**	(0.166)	-0.245***	(0.005)
Dynamic FE	0.478***	(0.057)	0.181	(0.138)	0.257***	(0.083)	-0.064***	(0.000)

Note: The results are based on ARDL (1,2,0,0). MG estimates are reported for the individual economy; DFE estimates are reported for the panel.

The coefficients of the long-run relationship estimated from FMOLS and DOLS are reported in Table 13. Similar to the findings from the panel ARDL model, results from both FMOLS and DOLS show that physical capital is found to be significantly and positively related to regional economic growth. Nonetheless, different from the panel ARDL results where the relationship between human capital and regional economic growth is insignificant, FMOLS and DOLS results show that human capital exerts an almost equally important effect on economic growth. As for the impact of energy consumption on regional economic growth, results from FMOLS and DOLS show differing findings. The FMOLS estimate shows that a 1 per cent increase in energy consumption is associated with a 0.11 per cent increase in economic growth, while the DOLS estimate finds no significant impact from energy consumption.

Table 13: Panel estimation results

	FMOLS	DOLS
lnK	0.51***	0.52***
	(48.61)	(86.53)
lnH	0.43***	0.45***
	(14.90)	(18.76)
lnE	0.11***	0.04
	(5.63)	(-0.59)

Note: In the parentheses are t-values.

Table 14 shows results from the EK Granger causality test. The number of bootstrap replications is 1000, and the optimal lag order is determined by the Schwarz information criteria and the maximum lag length of 10. For each direction (i.e. Energy $\nrightarrow$ GDP, and GDP $\nrightarrow$ Energy), the Wald test statistics and the associated p-values are reported for the individual economy, and the Fisher test statistics and the critical values generated from the bootstrap method are shown for the whole panel. The last column summarises findings at the 5 per cent significance level. It is found that the neutrality hypothesis is supported in most economies, except in Australia where GDP is found to Granger cause energy use, and in South Korea where energy use Granger causes GDP. For the whole panel of 14 economies, the Fisher test statistics show that there is no Granger causal relationship between lnY and lnE at the 5 per cent significance level. However, there is some weak evidence that lnY Granger causes lnE at the 10 per cent significance level, suggesting the conservation effect.

Table 14: Panel Granger non-causality test using Emirmahmutoglu and Kose (2011)

		Energy Granger not-cause GDP?		GDP Granger not-cause energy?	
	k	Wi	Pi	Wi	Pi
Individual Economy					
Australia	2	1.537	0.464	7.965	0.000
China	3	0.742	0.863	0.601	0.896
Hong Kong	1	0.520	0.471	0.778	0.378
Indonesia	1	0.052	0.820	0.007	0.933
India	1	0.756	0.384	1.192	0.275
Japan	1	0.880	0.348	0.081	0.775
South Korea	1	6.325	0.012	1.696	0.193
Sri Lanka	6	2.319	0.888	9.178	0.164
Malaysia	1	0.002	0.962	0.191	0.662
New Zealand	1	0.407	0.523	0.531	0.466
Philippines	1	0.061	0.805	3.488	0.062
Singapore	1	0.572	0.449	0.103	0.748
Thailand	7	7.196	0.409	2.357	0.089
Taiwan	1	3.114	0.078	0.080	0.778
Panel					
Fisher test statistic lambda		27.16		44.101	
Bootstrap critical values	***1%	54.667		56.373	
	**5%	46.642		45.809	
	*10%	41.517		41.227	

Note: The number of bootstrap replications is 1000. The max lag length is 10. Lag procedure: SBC

Comparing the results with those of Fang and Chang (2016), who use the same Granger causality test, and the same dataset but a shorter period of time (1970–2011), we find that the findings are consistent for the panel of countries, as well as for most countries individually, except India and Thailand. Specifically, our results using data from 1965–2019 support the neutrality hypothesis in India, while Fang and Chang (2016) found evidence of the feedback effect in India. In addition, we evidence GDP Granger causing energy use in Thailand at the 10 per cent significance level, but Fang and Chang (2016) found no Granger causal relationships in either direction in Thailand. The discrepancy of findings suggests that the EK Granger causality test results are sensitive to the time frame under study, and the time frame is one of the reasons for the inconclusive findings across studies in the energy-growth literature.

Table 15 presents the panel Granger causality test results using the Dumitrescu and Hurlin (2012) approach. The results show that there is a feedback effect between energy consumption and economic growth in the region, as the null hypothesis of non-Granger causality is rejected by both the Z statistic and Z-Tilda statistic for both directions, at the 5 per cent significance level. The finding is completely different from that of the Emirmahmutoglu and Kose (2011) approach.

Table 15: Panel Granger non-causality test using Dumitrescu and Hurlin (2012)

	Z	Z-tilda	lag order
lnE->lnY	4.049 [0.0001]	3.671 [0.0002]	1
lnY->lnE	2.704 [0.007]	2.332 [0.020]	2

Note: the lag order is determined by BIC.

Table 16 summarises the findings from the time series analysis and panel analysis. Combining the findings for the long-run Granger causal relationship obtained from the VECM in Table 6, the findings from time series and panel ARDL analysis in Table 8 and Table 12, and the findings from employing the Emirmahmutoglu and Kose (2011) and Dumitrescu and Hurlin (2012) methodologies for the panel data in Table 14 and Table 15, we can see clearly the conflicting results on the energy-growth nexus for New Zealand, where time series VECM supports the conservation hypothesis, while the EK and DH methods support the neutrality hypothesis. The significant relationship obtained from the time series and the panel ARDL analysis is consistent for almost all economies, apart from Japan (where time series ARDL shows a significant negative sign, while panel ARDL shows an insignificant relationship), when looking at the 5 per cent significance level. Caution should therefore be exercised in drawing any concrete conclusion on the Granger causal relationship between energy use and economic growth in any specific country based on one single methodology.

Table 16: A summary of the relationship between GDP and energy consumption using various methods

	Time series			Panel	
	VECM	Time series ARDL	Panel ARDL	Emirmahmutoglu & Kose (2011)	Dumitrescu & Hurlin (2012)
Australia				Conservation	Conservation
China				Neutrality	Neutrality
Hong Kong		***	**	Neutrality	Growth
India				Neutrality	Neutrality
Indonesia				Neutrality	Neutrality
Japan		*** (negative)		Neutrality	Growth
Malaysia				Neutrality	Neutrality
New Zealand	Conservation	*		Neutrality	Neutrality
Philippines			*	Neutrality	Neutrality
Singapore		***	***	Neutrality	Neutrality
South Korea		***	***	Growth	Neutrality
Sri Lanka				Neutrality	Growth
Taiwan			*	Neutrality	Neutrality
Thailand		***	**	Neutrality	Neutrality
Panel			***	Neutrality	Feedback

Note: The summary is based on results obtained from Table 6, Table 8, Table 12, Table 14, and Table 15, but only valid findings are presented here. *, **, and *** indicate that the coefficient estimate of lnE is significant at 10%, 5% and 1% significance levels in the ARDL models.

6. Discussion and Conclusion

From the time series analysis, we find solid evidence that there is a cointegrating relationship among the variables in New Zealand (via the Johansen test), Hong Kong, India, Japan, Singapore, South Korea, and Thailand (via the ARDL bounds test). This suggests that there exists a long-run equilibrium relationship between energy consumption, factor inputs (physical capital and human capital), and GDP in these economies. The presence of cointegration implies that changes in energy consumption and factor inputs have a long-lasting impact on GDP. Furthermore, the Granger causality analysis based on the vector error correction model (VECM) supports the presence of causal relationships between the variables.

Regarding the panel analysis, we observe differences in the results obtained using different methodologies. Results using the Emirmahmutoglu and Kose (2011) method support the neutrality hypothesis, which suggests that changes in energy consumption do not have a significant impact on GDP in the panel of economies. On the other hand, results using the Dumitrescu and Hurlin

(2012) approach find evidence of a feedback effect, indicating that changes in energy consumption affect GDP and vice versa. These contrasting findings are not uncommon in studies using these two methodologies. Shahbaz *et al* (2018) highlight the need to re-examine and re-evaluate policy recommendations based on these methodologies before considering them seriously. This implies that caution should be exercised in drawing policy implications solely based on the results from a single methodology, as different approaches may yield different conclusions.

Regarding the impact of factor inputs on GDP, the time series analysis reveals that physical capital and human capital have a positive impact on GDP in most economies. The ARDL model, which is considered more reliable due to the unit root test results, consistently supports this positive relationship. However, the VECM results show a significant negative impact of human capital on GDP in New Zealand, which contradicts the findings in other economies. This inconsistency emphasises the importance of carefully interpreting results and considering country-specific factors that may contribute to these variations.

In the panel analysis, the panel ARDL results provide a more consistent picture. They align with the established evidence in the literature, suggesting that physical capital, human capital, and energy consumption either have no significant impact on economic growth or are positively related to economic growth, at the 5 per cent significance level. This implies that these factor inputs play a crucial role in promoting economic growth across the panel of economies examined.

The comparison of results and findings from the various methodologies of time series analysis and the panel analysis illustrate two important points. First, it is crucial to follow the proper procedures of the particular methodology. For instance, if the variables are a mix of I(0) and I(1), the preferred methodology should be ARDL (Menegaki 2019). Second, it is suggested to perform the robustness check by using more than one methodology, so the conclusion could be more convincing. This is just like the case for the unit root tests, where it has become the practice to use ADF, PP, and KPSS tests together to confirm the order of integration of the series.

In summary, the findings from this study indicate the presence of a cointegrating relationship between energy consumption, factor inputs, and GDP in several economies. The Granger causality analysis supports the presence of causal relationships between these variables. However, the results obtained using different methodologies, such as time series analysis and panel analysis, may vary, emphasising the need for careful interpretation and consideration of country-specific factors. The positive impact of physical capital and human capital on GDP is generally supported, while the impact of energy consumption on GDP appears to be less consistent across economies. These findings contribute to a better understanding of the energy-growth nexus and highlight the complexity of analysing this relationship using different methodological approaches.

While this paper contributes to the literature by examining how methodology affects findings regarding the energy-growth nexus, it has some limitations. First, the methodologies considered in this paper are well-adopted approaches in the energy-growth nexus literature. There are constantly new and more advanced econometric methodologies that have been developed and applied in this area, such as non-linear cointegration and Granger causality tests (Xiao 2009; Troster *et al* 2018;), and time-varying Granger causality tests (Shi *et al* 2020), that are not covered in this study. Second, this paper only uses data from the Asia Pacific economies. While this choice makes it possible to conduct the time series analysis for the individual economy, it does not provide the full picture of the whole world. Nevertheless, the conclusion from this paper still holds, that researchers should choose the right econometric methodology based on the data properties, follow the proper procedures of the selected econometric methodology, and conduct some robust analysis before drawing any conclusions and policy implications.

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Endnotes

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4. The supply-side model is appropriate when the variables GDP (Y), physical capital (K), human capital (H) and energy consumption (E) are considered, as the extended production function enables the specification of the relationship between GDP and K, L, and E.

5. "The term *country*, used interchangeably with economy, does not imply political independence but refers to any territory for which authorities report separate social or economic statistics" (World Bank, https://datahelpdesk.worldbank.org/knowledgebase/articles/906519).

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