

# Revisiting Energy Consumption-economic Growth Hypothesis: Do Slope Heterogeneity and Cross-sectional Dependence Matter?

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Received: 20 September 2020 / Revised: 30 October 2020 / Accepted: 06 January 2020 / Published: 19 January 2021

## ABSTRACT

In this paper, the long-term nexus between energy consumption and economic growth is investigated using a panel data of 80 countries from World Bank data base for the period 1970 to 2017. In order to check for the issues of endogeneity, slope heterogeneity, and cross-sectional dependence present in errors of panel data, the study applied cross-sectional augmented autoregressive distributed lag (CS-ARDL) and cross-sectional augmented distributed lag (CS-DL) models to examine the long-term impact of energy consumption on economic growth. The empirical results revealed that energy consumption has a positive and significant long-run effect on economic growth and that cross-sectional dependence, slope endogeneity and heterogeneity are issues that should be on the watch when dealing with panel data of developing and developed countries' analysis. Furthermore, the outcomes indicated that the impact of energy consumption on economic growth is stronger in less developed countries than in advanced economies. Technological progressions that give rise to the advancement of clean and efficient energy and substitution of low-quality fuels with high quality fuels are some of the possible channels that weaken the link between energy consumption and economic growth in advanced economies. Importantly, from a policy perspective, based on the study findings, energy conservation policies aimed at promoting environmental quality may worsen economic growth in developing countries, thereby adversely affecting their long-run economic growths.

**Keywords:** Energy consumption; Economic growth; developing and developed countries; panel data.

## 1 Introduction

Long run impact of energy consumption on economic growth and its implications for environmental quality has gained renewed interest in recent years (see, e.g., Alam and Paramati 2015; Arora and Shi 2016; Nguyen et al. 2017; Acheampong 2018; Shahbaz et al. 2018; Sierra and Scavia 2018; Koengkan, Fuinhas, & Rosa, 2020; Rahman & Velayuthan, 2020; Chen, Pinar & Stennegos, 2020; Ajmi \* Inglesi-Lotz, 2020). One of the major channels through which economic growth affects environmental quality via carbon dioxide emissions is energy consumption. In the light of this, the nexus between energy and economic growth has been an important topic in previous researches on economic development, and it has recently reemerged as a subject of extensive debate in academic and policy circles. The long-run impact of energy consumption on economic growth has drawn considerable attention in an international debate as society has faced the challenge of achieving sustainable development while fighting against climate change and environmental degradation. It is documented in the literature that energy is an important input needed for goods and services to be produced, hence, several economists conjecture that energy use is an important factor that drives economic growth. If the impact of energy use on long-run economic growth is a positive one, then cutting carbon dioxide emissions through a reduction in energy consumption could be detrimental to economic growth especially in less developed countries that solely depend on energy for growth. In the literature, this view is called the "growth hypothesis." Proponents of the growth-hypothesis argue that a

major factor in promoting economic growth either directly as an input in the production function or indirectly as a complement to other factors of production, such as capital and labor is energy consumption. In line with this, many economies are not ready to reduce their energy consumption because of the fear that a reduction in energy-use will harm their economic growth. Yet, conclusive robust evidence in support of this hypothesis from empirical studies finds it difficult to arrive at. From the studies of Apergis and Payne (2009); Belke et al. (2011); Alper and Oguz (2016), proponents of the “conservation hypothesis,” on the other hand, argue that policies aimed at energy-use reduction may have little or no detrimental impact on real GDP.

Despite the numerous studies on the nexus between energy-use and economic growth, findings have been mixed and inconclusive evidence on the long-run impact of energy-use on economic growth. Therefore, examining the long-run effect of energy-use on economic growth is of principal interest to policy makers. The major questions underpinning this study are: Does energy consumption matter for long-run growth? What is the direction of causality between energy-use and economic growth? The broad objectives include: examining whether energy consumption matters for long run growth of the economy and to investigate the direction of causality between energy consumption and long run economic growth. Answers to these questions have important policy implications as policy makers face a dilemma: there is a need to accelerate growth, but at the same time, there is a need to fight against climate change.

One of the major issues for the discrepancy in the literature’s empirical results is the use of homogeneous models that impose the assumption of cross-sectional independence. Such methods ignore cross-country heterogeneity in production technologies and the spillover effects arising from common global shocks, which may result in cross-sectional dependencies in errors. Most of the previous studies on this subject use unit root tests and a cointegration analysis with strong assumptions of slope homogeneity and cross-sectional independence in cross-country regressions. Studies that focus on a single country are also impaired by a short data span that results in low statistical power. Moreover, a cointegration analysis requires that variables have to be non-stationary and integrated of the same order, typically  $I(1)$ . Smyth and Narayan (2015) provide an interesting literature on the recent advancements in applied econometrics and their implications on research in energy economics. The authors state that energy variables are stationary in most countries, and empirical results on the direction of causality in energy-use and economic growth provide mixed evidence.

In order to fill the above mentioned literature gap, this paper employs novel econometric techniques that address econometric issues in the estimation of cross-country production functions for a broad panel of countries using annual data from 1970 to 2017.

The following summary constitutes the paper’s contributions to the extant body of knowledge. First, the study shows that modeling heterogeneity in production technology is important in examining how energy-use affects economic growth. Second, the study lays emphasis on the importance of addressing global spillover effects and accommodating cross-sectional dependencies along with other features of dynamic panel data, such as endogeneity. Third, the study uses a rich dataset comprised of a broad panel of countries over a relatively long period of time than that of previous studies allowing us to estimate long-run impact of energy-use on growth by accounting for heterogeneity in slope parameters, as well as cross-sectional dependence in errors. Fourth, the study applies a non-conventional technique of variables causality known as the Dumitrescu and Hurlin (2012) Granger causality test for heterogeneous non-causality. This test is applicable except when  $T=N$ . It is built on vector autoregressive model (VAR) and robust even in the presence of cross-sectional dependency. In doing that, the study adopts the cross sectionally augmented autoregressive distributed lag (CS-ARDL) model advanced in Chudik and Pesaran (2015) and Chudik et al. (2017) that addresses dynamics, reverse causality, country heterogeneity, and cross-sectional dependencies. These estimation procedures are valid regardless of the integration order of the variables.

The study uses data from samples of 80 countries from 1970–2017 in the analysis of the nexus between energy-use and long-run economic growth. The findings from the empirical analysis indicate that there is a positive and statistical long-run impact of energy-use on the growth of the economy. The effect is stronger

in developing countries compared to what is found in advanced economies. The results further indicate that environmental policies that aim to curb energy-use in developing economies may worsen economic growth, thereby adversely affecting long-run economic growth. Moreover, the study shows that models that ignore heterogeneity in production technology and global spillover effects in estimating cross-country production functions, assuming homogeneous technology and cross-sectional independence across countries, are specifically mis-specified. In such cases, the estimates of the production parameters are biased and inconsistent, yielding spurious inferences. This study addresses parameter heterogeneity, the interplay of endogeneity and commonality, to provide new evidence for the relationship between energy-use and long-run economic growth. Our study uses a more current set of data in a panel framework for the period 1970-2017 and applies an unconventional estimation technique. This differs from the conservative hypothesis established by Menagaki (2011) who applied a data set from 1997-2007 and claimed that inadequate spread an use of energy in the EU economies is responsible for the neutrality thesis. This shows that proper application of clean energy from renewable is a useful avenue of achieving economic growth and environmental sustainability in the long run. Consequently, proper guide for the corresponding energy consumption-economic growth policy implications across the globe particularly SSA countries could be obtained from our analytical results. Therefore, by using recent novel empirical methods to address issues in previous studies, this paper adds significant contributions to the literature, offering a fresh reexamination of the energy consumption–economic growth nexus while allowing for dynamics, heterogeneities, and cross-sectional error dependencies.

## **2 Empirical review of related literatures**

A plethora of empirical studies on the impact of energy-use on economic growth show evidence of mixed and conflicting findings. The most notable among recent contributions of this relationship is Salamaliki and Venetis (2013) who applied multiple horizons and sequential causality testing techniques. Their finding indicated that energy-use has no effect on real income in the G7 (Group of Seven) countries. Yildrima et al (2014) used a bootstrapped autoregressive metric causality to demonstrate that energy-use has no effect on economic growth in a sample of developing countries. Accordingly, they suggest that implementations of energy conservation-oriented policies do not undermine economic growth. Hence, the evidence is weak for the claim that energy conservation policies could prove harmful to economic growth in developed countries. Another strand of literature posits that energy consumption is a key factor to economic growth, and, hence, reduction in energy-use could pose detrimental effects on real income growth. In another development, Mohammadi and Parvaresh (2014) examined the nexus between energy-use and growth of the economy in 14 oil-exporting countries from 1980 to 2007. Their findings show that energy-use causes long-run economic growth and that environmental policies aimed at reducing energy use may have a significant detrimental effect on long-run economic growth. Alper and Oguz (2016) support this finding in their study, which employed a symmetric causality test analysis based on an ARDL (autoregressive distributed lag) approach in a sample of new European Union member countries from 1990 to 2009. The outcomes of their findings indicate that clean energy-use of renewables affect economic growth in a positive direction in all the samples considered. In line with this, Alam and Paramati (2015) analyzed the economies of developing countries and found a positive long-run impact of energy-use on growth of their economies. Using quantile-on-quantile method, Shahbaz et al. (2018) proved that energy-use is positively associated with economic growth in the economies indexed as the ten top energy-consumers countries. Other studies that find evidence in support of the ‘growth hypothesis’ are those of Soytas and Sari (2006), Lee and Chang (2008), Narayan and Smyth (2008), and Niu et al. (2011). Mohammadi and Amin (2015) use common correlated effects mean group estimators in a sample of 79 countries, which are classified into high, low and negative-growth countries. Their findings are mixed, indicating not only long-run linkage energy-use and output in all three categories but also unidirectional causality from output to energy in the negative-growth category. This means that growth causes energy use but not the other way round in negative-growth countries. However, Mohammadi and Amin’s (2015) methodology has some drawbacks. First, it does not

take into consideration the dynamism to capture the persistent nexus between energy-use and economic growth. Second, it does not address endogeneity bias. Third, categorization of the sample into negative- and positive-growth groups may induce selection bias. Acheampong (2018) employed panel vector autoregression (PVAR) and GMM (generalized method of moment) to examine the linkage between energy-use, economic growth and CO<sub>2</sub> emissions in a sample of 116 economies spanning the time frame, 1990–2014. He found out that energy-use affected growth in Sub Saharan African countries in a positive direction and a negative effect on the rest of the world. Shahbaz et al. (2017) applied a nonlinear ARDL bounds testing approach to investigate the asymmetric nexus between energy-use and economic growth in India. According to their findings, only negative shocks to energy-use have detrimental impacts on real income growth. Riti et al (2016, 2017a, 2017b and 2018) carried out separate studies on the links between energy-use, (renewable and non-renewable), economic growth and environmental quality using different econometric techniques in Nigeria, 90 countries classified on the basis of income possession, China and China respectively concluded that energy-use has a long term relationship with growth of economies of the investigated countries. The results particularly indicated that renewable energy is capable of ensuring long run economic growth in favour of environmental quality whereas non-renewable energy is capable of ensuring growth at the expense of the environment. Wang et al (2018) investigated the decoupling of greenhouse gas emissions, urbanization, energy and real income (real GDP) in China, using the technique of ARDL and VECM Granger causality from 1978-2015 concluded that in all the four models extracted from the analysis, energy is found to affects both real income and environmental quality proxied by greenhouse gas of CO<sub>2</sub> emissions. Shi et al (2019) estimated the role of energy mix and financial development in greenhouse emissions' reductions among the ten leading CO<sub>2</sub> emitting countries, applying FMOLS techniques and Panel Granger causality. The results showed that energy (renewable and non-renewable) are important for economic growth.

Rodríguez-Caballero and Ventosa-Santaul'ariab (2016) employed a vector error correction specification that allows for structural breaks to examine the relationship between electricity-use per capita and income in the USA, Canada, and 17 Latin American countries. They conclude that energy use caused growth in eight of the sample countries; there is evidence that supports the conservation hypothesis in three countries and inconclusive evidence for the remaining five countries in their sample. The most recent study that is closest to ours in terms of methodology is that of Osman et al. (2016). These researchers examined the nexus between electricity-use and economic growth but apply their methodology to a narrow range of samples of the Gulf Corporation Council (GCC) countries. For these countries, the authors find a bi-directional causality in the energy–growth relationship. Mezghani and Haddad (2017) used a time-varying parameter vector autoregressive (TVP-VAR) model with stochastic volatility to investigate the dynamic relationship between GDP and electricity-use in Saudi Arabia. Their findings show that volatility in energy consumption matters for GDP. Earlier studies on the energy– growth nexus also provide inconclusive evidence. Stern (2000), Lee (2006), and Belke et al. (2011) proved feedback causality is spotted between energy-use and real GDP. A comprehensive review of the literature on the linkage between energy-use and economic growth is available in Ozturk (2010) and Kalimeris et al. (2014).

In sum, the studies on the energy consumption–economic growth nexus provides mixed evidence. The main limitations in previous studies include the lack of mechanisms to account for all the key features of panel data—namely, dynamics heterogeneity, cross-sectional dependence, and endogeneity. Economic theories provide a justification for heterogeneous production functions. Accordingly, empirical evidence on the importance of differences in production technologies across countries is available in the growth empirics' literature (see for instance, Durlauf et al. 2001; Eberhardt and Teal 2011; Mundlak et al. 2012). Nevertheless, the majority of existing studies in the literature on the nexus between energy-use and economic growth assume homogeneous technology across countries and do not account for slope heterogeneity in their analyses.

It is equally important to address the cross-sectional dependence that arises from interdependence in the political, trade, social, and cultural ties among economies. As Eberhardt and Teal (2011) maintain,

traditional panel data models that impose cross-sectional independence in errors may lead to biased empirical results. In a move to address this econometric issue, recent developments in panel data techniques propose the adoption of a multi-factor error structure allowing for unobserved factors that are common and country-specific (Chudik and Pesaran 2015; Chudik et al. 2017).

Aside from addressing technological heterogeneity in production technologies and cross-sectional dependence, our empirical analysis accounts for all specification issues that have occupied the standard literature on growth empirics, such as endogeneity. Our aim is to address the above mentioned issues in previous studies by utilizing a recently innovated CS-ARDL approach that allows for endogeneity, heterogeneity, and cross-sectional dependencies, which are key features of a dynamic panel data analysis.

### 3 Methodology

In this section, a glimpse of empirical methodologies, techniques of estimation, and data employed in this paper are presented. The analysis of the section began with an exploration of the econometric methods adopted to deal with cross-country issue of heterogeneous nature and cross-sectional dependency of the data.

#### 3.1 Issues of heterogeneity and cross-sectional dependence

The study begins the analysis with traditional panel ARDL models to explore the importance of heterogeneities, dynamics, and simultaneous determination of energy consumption and economic growth in a broad panel of countries. Specifically, we begin by considering the following model:

$$\Delta y_{it} = \alpha_i + \sum_{l=1}^p \varphi_{il} \Delta y_{it-l} + \sum_{l=1}^p \beta'_{il} \Delta x_{it-l} + \mu_{it} \dots \dots (1)$$

where  $y_{it}$  is the log of per capita real GDP for country  $i$  at time  $t$ ,  $x_{it} = (E_{it}, I_{it})'$ ,  $E_{it}$  is the log of real per capita energy consumption, and  $I_{it}$  is the log of investment as percent of GDP. Following the literature, we use a maximum lag order of 3, which is assumed to be sufficient to fully account for the short-run dynamics in a moderately large time dimension ( $T = 48$  in our case; the rule of thumb is  $p = T^{1/3} \approx 3$ ). We estimate the models for different lags in the range of 1 to 3, while the same lag order ( $p$ ) is used for all variables and countries in a particular estimation. The baseline panel ARDL model in equation (1) can be written as an error correction model (ECM) representation, as follows:

$$\Delta y_{it} = \alpha_i - \lambda_i (y_{it-1} - \theta x_{it-1}) + \sum_{l=1}^{p-1} \varphi_{il} \Delta y_{it-l} + \sum_{l=0}^{p-1} \beta'_{il} \Delta x_{it-l} + \mu_{it} \dots \dots \dots (2)$$

where  $\Delta y_{it} = y_{it} - y_{it-1}$ ,  $\Delta x_{it} = (\Delta E_{it}, \Delta I_{it})'$ ,  $\lambda_i = 1 - \sum_{l=1}^p \varphi_{il}$ ,  $\varphi_{il} = - \sum_{k=l+1}^{p-1} \varphi_{ik}$

for  $1 \leq l \leq p-1$ ,  $\theta_i = 1 - \sum_{l=1}^p \beta_{il} / \lambda_i$  and  $\beta_{it} = - \sum_{k=l+1}^{p-1} \beta_{ik}$  for  $1 \leq l \leq p-1$

Equation (2) can be estimated using mean group estimators under the assumption of cross-sectional independence in the residuals. Chudik and Pesaran (2015) have shown that ARDL methodology can be used to estimate a long-run relationship between economic variables. The resulting long-run estimates are valid even in the presence of endogenous regressors and regardless of the order of integration, that is, for either order one,  $I(1)$ , or order zero,  $I(0)$ , processes.

These features of the panel ARDL approach are considered important advantages in our model as a remedy for possible biases from reverse causality and the omission of relevant variables. Moreover, the ARDL estimation approach allows for slope heterogeneity and controls for cross-country differences in geography, history, institutions, and other time-invariant determinants of economic growth and energy consumption. Following the estimation of equation (2) and under the assumption that the unobserved common factors

are not only serially uncorrelated but are also uncorrelated with the regressors, the long-run effects,  $\hat{\theta}_i$ , can be obtained from the OLS estimates of the short-run coefficients,  $\hat{\beta}_{il}$  and  $\hat{\varphi}_{il}$ , as follows:

$$\theta_i = \frac{\sum_{l=0}^p \beta_{il}}{1 - \sum_{l=1}^p \varphi_{il}}$$

The estimate for  $\lambda_{il}$  captures the long-run cointegration of covariates and the speed of convergence toward the long-term equilibrium of a steady state in our ARDL estimation approach, which is in the form of an ECM representation. The main drawback of using traditional panel ARDL methodology is the strong assumption of cross-sectional independence in the error terms. The traditional ARDL approach does not account for residual cross-country dependencies that might be present due to a number of factors. For instance, exposures to common shocks could exist, such as world business cycles, financial crises, and oil price shocks. When unobserved common factors are correlated with the regressors, the least square estimates of ARDL models are no longer consistent. Estimating long-run effects using ARDL without accounting for these issues may result in biased and misleading estimates.

To address these problems, we employ mean group estimators based on the cross-sectionally augmented ARDL (CS-ARDL) approaches advanced in Chudik and Pesaran (2015) and Chudik et al. (2017). This estimation procedure allows for heterogeneity in coefficients. It also allows for cross-sectional dependence in residuals by augmenting the ARDL regressions with cross-sectional averages of the regressors and the dependent variable with a sufficient number of lags in a dynamic multifactor framework; these lags act as proxies for spillovers and un-observables. The CS-ARDL models are given by equation (3):

$$y_{it} = \alpha_i + \sum_{l=1}^p \varphi_{il} y_{it-l} + \sum_{l=1}^p \beta' x_{it-l} + \sum_{l=0}^3 \psi'_{il} \bar{z}_{t-l} + e_{it} \dots \dots \dots (3)$$

where  $\bar{Z}_t = (\bar{y}_t, \bar{x}_t)$  denotes the simple cross-sectional averages of  $y_{it}$  and  $x_{it}$  in year  $t$ , and all the other variables are as defined as in equation (2). The ECM representation of the model is given by

$$y_{it} = \alpha_i - \lambda_i (y_{it-1} - \theta x_{it-1}) + \sum_{l=1}^{p-1} \varphi_{il} \Delta y_{it-l} + \sum_{l=1}^{p-1} \beta' \Delta x_{it-l} + \sum_{l=0}^3 \psi'_{il} \Delta \bar{z}_{t-l} + e_{it} \dots \dots \dots (4)$$

where  $\Delta \bar{Z}_t = (\Delta \bar{y}_t, \Delta \bar{x}_t)$  denotes the simple cross-sectional averages of  $\Delta y_{it}$  and  $\Delta x_{it}$  in year  $t$ .

### 3.2 Data

Data on per capita real GDP (Y), energy consumption (E) in kilograms of oil equivalent per capita, and investment as percent of GDP (I) are from the World Bank’s data base/World Development Indicator (2016). All variables are in natural logarithms and are in real US dollars (USD). We use annual panel data for a sample of 80 countries spanning from 1970 to 2017. Table 1 presents the descriptive statistics of the series for the sample period.

**Table 1: Descriptive statistics**

	Obs	Mean	Std. Dev.	Min	Max
<b>Full sample</b>					
Y	3758	141018	17769.1	339.3	113079.3
I	3645	23.6	8.0	3.1	110.7
E	3492	2074.3	2153.9	96.6	13134.9
<b>Advanced Economies</b>					
Y	1266	35247.9	16979.2	5807.2	112079.3
I	1263	25.2	7.1	22.5	100.7
E	1211	4335.1	2090.0	774.9	13134.9
<b>Developing Economies</b>					
Y	2604	4451.1	5052.5	339.3	34245.8
I	2493	22.9	8.2	3.0	70.7

E	2392	984.0	901.4	96.6	6943.8
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Source: Authors' computation

As shown in Table 1, there are significant variations in energy consumption across economies. The mean value of energy consumption in advanced economies is more than three times the mean value for developing economies. The standard deviations indicate large cross-country differences in the level of energy consumption. The same trend is observed in investment a ratio of GDP and real GDP per capita where statistics from developed countries surpass those of developing economies.

#### 4 Empirical Results and Discussion

This section presents empirical results derived from the baseline ARDL model and the mean group estimates, which are based on CS-ARDL approaches, for the full sample, as well as for advanced and developing economies. We report the baseline ARDL (Panel A) and CS-ARDL (Panel B) estimation results for each sample group in Tables 2–4. The estimates for each model are reported for three cases: (a), (b), and (c). The results are presented in case (a) when only energy consumption is included in the model, in case (b) when only the investment-to-GDP ratio is included, and in case (c) when both variables are included. Each panel gives the average estimates of the long-run effects of energy consumption (E) and investment (I) on per capita real GDP growth and the mean estimate of the coefficients for the error correction term are denoted by  $\hat{\lambda}$ .

##### 4.1 Full sample

Table 2 presents the estimation results for the full sample. Panel A presents the mean group estimates based on the traditional ARDL approach, which allows for slope coefficients to vary across countries, and Panel B presents estimates of the cross-sectional augmented ARDL (CS-ARDL) approach, which allows for both heterogeneity in slopes and cross-sectional dependence in errors. We report the results for estimations with different lag orders:  $p = 1, 2, \text{ and } 3$ . The results in Panel A of the table show that the coefficient of energy consumption is positive and statistically significant in all specifications, indicating that energy consumption has a positive long-run effect on growth. The coefficient of energy consumption in the mean group estimations based on the baseline ARDL approach is approximately 0.4. The result shows that a 1% increase in energy consumption leads to an increase in economic growth of about 0.4%.

**Table 2: Long run effect of energy consumption on economic growth**

<b>Panel A: Mean group estimates of the long-run effects based on ARDL approach</b>									
	ARDL (Lag 1)			ARDL (Lag 2)			ARDL (Lag 3)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
E	0.446*		0.385*	0.437*		0.393*	0.414*		0.480*
	(0.044)		(0.042)	(0.045)		(0.044)	(0.068)		(0.094)
I		0.142*	0.117*		0.171*	0.122*		0.171*	0.057
		(0.015)	(0.013)		(0.018)	(0.014)		(0.040)	(0.054)
$\lambda$	-0.784*	-0.745*	-0.824*	-0.839*	-0.765*	-0.869*	-0.841*	-0.699*	-0.849
	(0.027)	(0.028)	0.027)	(0.031)	(0.032)	(0.034)	(0.038)	(0.030)	(0.039)
N	3229	3376	3131	3153	3297	3052	3077	3218	2973
<b>Panel B: Mean group estimates of the long-run effects based on the CS-ARDL approach</b>									
	ARDL (Lag 1)			ARDL (Lag 2)			ARDL (Lag3)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
E	0.380*		0.323*	0.359*		0.343*	-0.005		0.432
	(0.048)		(0.042)	(0.057)		(0.057)	(0.289)		(0.255)
I		0.124*	0.109*		0.139*	0.155*		0.103*	0.184*
		(0.018)	(0.017)		(0.024)	(0.026)		(0.049)	(0.072)
$\lambda$	-0.773*	-0.707*	-0.842*	-0.837*	-0.703*	-0.875*	-0.850*	-0.639*	-0.080*
	(0.029)	(0.029)	(0.033)	(0.037)	(0.038)	(0.044)	(0.047)	(0.036)	(0.072)

N	3132	3242	3043	3131	3230	3042	3077	3218	2973
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**Note:** The dependent variable is the growth rate of per capita real GDP. Standard errors are in parentheses.

\*\* and \* indicate significance at the 5% and 1% levels, respectively.

Furthermore, Table 2 reported the estimated error correction term which shows the speed of adjustment of the model from short run distortions to long run equilibrium. The result shows that the estimated error correction term is inversely significant at 1% level across all the estimated models. The result further shows that energy consumption and economic growth have a merging point and a long-run equilibrium association. In terms of the overall sample, and of the three-lagged estimates of the short-run error correction term, the coefficients range from 0.7 to 0.8. In addition, the findings suggest that real GDP model's yearly adjustment from the short-run to the long-run convergence is corrected with about 70-80% mechanism. This further confirms that, the presence of a constant co-integration between economic growth and its factors in the long-run. Unlike the estimates of the error correction terms found by Apergis and Payne (2010b) and which ranges between 11-14%, our estimates of the error correction terms from the models with lagged 3 values are in contrast in absolute values.

Panel B of Table 2 presents the estimates when we account for both heterogeneity and cross-sectional dependencies using the CS-ARDL approach. The results from eight out of the nine specifications, on the basis of lag choice, show that energy consumption has a positive and statistically significant effect on long-run growth. Our results support the growth hypothesis in the energy consumption–economic growth nexus. That is, energy consumption is a key factor in promoting economic growth either directly as an input in the production function or indirectly as a complement to other factors of production, such as capital and labor. As a result, a reduction in the use of energy consumption may have an adverse effect on long-run economic growth. The CS-ARDL estimation results show that the output elasticity of energy consumption is estimated to be 0.3 to 0.4. That is, a 1% increase in energy consumption leads to an increase in real GDP growth of about 0.3%–0.4%. The coefficient of investment is consistently positive and statistically significant in all the specifications except for the model with three lags in Panel A, where both E and I are included as explanatory variables. Finally, the results given in Table 2 indicate that all the error correction coefficients,  $\hat{\lambda} = \sum_{l=0}^p \phi_{il} - 1$ , are negative and statistically significant, which suggests a dynamically stable long-run equilibrium between energy consumption and economic growth. The coefficients of the error correction term range between -0.7 and -0.85, which indicate that the system corrects its previous period disequilibrium annually at a speed of between 70% and 85% to reach a steady state except the coefficient of adjustment of ARDL lag 3 of model C which is as low as 0.080 (8%).

## 4.2 Developing economies

Table 3 presents the empirical results for the sample of developing economies. Panels A and B present estimation results for baseline ARDL and CS-ARDL estimation approaches, as discussed in Section 4.1.1. As shown in Panel A of Table 3, the estimates of the coefficient of energy consumption for the mean group estimators based on the traditional ARDL model are both positive and statistically significant at the 1%-significance level in all specifications.

Panel B of Table 3 presents the mean group estimators based on the CS-ARDL approach, which accounts for both slope heterogeneity and cross-sectional dependencies. The results indicate that the coefficient of energy consumption is positive and statistically significant in all specifications, suggesting that energy consumption has a positive long-run effect on growth in developing countries. More precisely, the output elasticity of energy consumption in developing countries ranges from about 0.4 to 0.7, indicating that a 1% increase in energy consumption leads to an increase in per capita real GDP growth of 0.4% to 0.7%. Furthermore, investment shows a positive and statistical significance in all the models except lag 3 of model C which shows insignificance of investment at the 0.01 and 0.05 levels respectively. The speed of adjustment from short run distortions show that all the models correct short run dynamic between 0.69 to 0.86 (69%-86%).



**Table 3: Long run effect of energy consumption in developing countries**

<b>Panel A: Mean group estimates of the long-run effects based on ARDL approach</b>									
	ARDL (Lag 1)			ARDL (Lag 2)			ARDL (Lag 3)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
E	0.478*		0.442*	0.484*		0.450*	0.448*		0.601*
	(0.059)		(0.055)	(0.059)		(0.060)	(0.095)		(0.129)
I		0.121*	0.092*		0.159*	0.098*		0.178*	0.007
		(0.017)	(0.013)		(0.021)	(0.015)		(0.055)	(0.076)
$\Lambda$	-0.792*	-0.733*	-0.817*	-0.833*	-0.758*	-0.863*	-0.846*	-0.695*	-0.862*
	(0.036)	(0.037)	(0.036)	(0.042)	(0.042)	(0.044)	(0.049)	(0.039)	(0.049)
N	2175	2270	2077	2122	2214	22021	2069	2158	1965
<b>Panel B: Mean group estimates of the long-run effects based on the CS-ARDL approach</b>									
	ARDL (Lag 1)			ARDL (Lag 2)			ARDL (Lag3)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
E	0.456*		0.412*	0.464*		0.579*	0.411*		0.723*
	(0.057)		(0.051)	(0.063)		(0.146)	(0.118)		(0.182)
I		0.119*	0.082*		0.140*	0.049		0.142*	-0.044
		(0.018)	(0.016)		(0.020)	(0.064)		(0.030)	(0.146)
$\Lambda$	-0.814*	-0.767*	-0.839*	-0.896*	-0.789*	-0.875*	-0.958*	-0.751*	-0.925*
	(0.036)	(0.035)	(0.038)	(0.044)	(0.046)	(0.050)	(0.052)	(0.045)	(0.070)
N	2122	2183	2033	2121	2171	2032	2069	2158	1965

Note: The dependent variable is the growth rate of per capita real GDP. Standard errors are in parentheses.

\*\* and \* indicate significance at the 5% and 1% levels, respectively.

**Table 4: Long run effect of energy consumption in developed countries**

<b>Panel A: Mean group estimates of the long-run effects based on ARDL approach</b>									
	ARDL (Lag 1)			ARDL (Lag 2)			ARDL (Lag 3)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
E	0.389*		0.282*	0.343*		0.275*	0.336*		0.216*
	(0.054)		(0.042)	(0.058)		(0.044)	(0.069)		(0.086)
I		0.178*	0.157*		0.190*	0.164*		0.157*	0.169*
		(0.031)	(0.030)		(0.035)	(0.026)		(0.046)	(0.042)
$\lambda$	-0.763*	-0.762*	-0.830*	-0.842*	-0.767*	-0.876*	-0.823*	-0.699*	-0.833*
	(0.031)	(0.039)	(0.040)	(0.040)	(0.044)	(0.052)	(0.054)	(0.044)	(0.063)
N	1050	1101	1050	1026	1077	1026	1002	1053	1002
<b>Panel B: Mean group estimates of the long-run effects based on the CS-ARDL approach</b>									
	ARDL (Lag 1)			ARDL (Lag 2)			ARDL (Lag3)		
	(a)	(b)	(c)	(a)	(b)	(c)	(a)	(b)	(c)
E	0.146*		0.082*	0.105		0.033	0.002		-0.133
	(0.056)		(0.041)	(0.079)		(0.063)	(0.105)		(0.140)
I		0.134*	0.142*		0.150*	0.206*		0.143*	0.191*
		(0.026)	(0.030)		(0.038)	(0.040)		(0.047)	(0.054)
$\lambda$	-0.766*	-0.808*	-0.829*	-0.828*	-0.824*	-0.879*	-0.752*	-0.757*	-0.743*
	(0.053)	(0.049)	(0.049)	(0.049)	(0.049)	(0.059)	(0.054)	(0.032)	(0.051)
N	1005	1053	1005	1005	1053	1005	1002	1053	1002

Note: The dependent variable is the growth rate of per capita real GDP. Standard errors are in parentheses.

\*\* and \* indicate significance at the 5% and 1% levels, respectively.

### 4.3 Advanced economies

Table 4 presents estimation results for our sample of advanced economies. The mean group estimates in Panel A of Table 4 shows that energy consumption has a positive and statistically significant effect on long-run growth in advanced economies. The coefficient of energy consumption in mean group estimations, based on the baseline ARDL model, ranges from 0.2 to 0.4 across various specifications. However, when we account for cross-sectional dependence in the CS-ARDL model, the results show no strong evidence on the positive effect of energy consumption on economic growth in advanced economies (Table 4, Panel B). Our results indicate the importance of accounting for cross-sectional dependence to capture a country's complex production processes in consideration of global interdependence among advanced economies.

The assumption of cross-sectional independence in previous studies is unrealistic because economies interact in many ways, such as political ties and international trade. Furthermore, common global shocks, such as oil price shocks or financial crises, may affect all economies but at different magnitudes, which creates interdependencies in cross-sectional errors in standard panel data specifications. Taking these into account, the coefficients of energy consumption are statistically insignificant in all specifications except for those with an ARDL of one lag. By inference, an energy conservation hypothesis that promotes environmental quality thereby reducing energy consumption may have little or no effect on long-run economic growth in advanced economies.

Our findings on the effect of energy consumption on growth in advanced economies surpass the results of Arora and Shi (2016). Using time-varying multivariate model, they find that energy consumption plays insignificant effect on US real GDP in 2000s.

### 4.4 Robustness check using the CS-DL model

Although the ARDL and CS-ARDL approaches have several advantages, as outlined in the previous section, they also have drawbacks. Mainly, the sampling uncertainty could be large when the time dimension is moderate (as in our case), and the performance of the estimators depends on a correct specification of the lag orders of underlying ARDL specifications. Conversely, the direct approach to estimating long-run relationships proposed by Chudik et al. (2017) namely, the CS-DL method is more generally applicable to address these issues and only requires a truncation lag order to be selected. Therefore, to check the robustness of our results, we perform estimations based on the CS-DL model.

Table 5 presents the results from the CS-DL model, which includes up to three lags. As shown in the Table, energy consumption has a positive and significant effect on long-run growth. The coefficient of energy consumption is quantitatively larger for developing economies than it is for developed economies, suggesting that developing countries are heavily dependent on energy use as an input in their economy. The results from the CS-DL model confirm the robustness of our main results from the CS-ARDL model.

**Table 5:** CS-DL estimates of the long-run effects of energy consumption on growth

	ARDL (lag 1)		ARDL (lag 2)		ARDL (Lag 3)	
	(a)	(b)	(a)	(b)	(a)	(b)
<b>Panel A: Full sample</b>						
E	0.407*	0.331*	0.455*	0.391*	0.465*	0.436*
	(0.040)	(0.037)	(0.046)	(0.049)	(0.049)	(0.067)
I		0.113*		0.112*		0.122*
		(0.012)		(0.015)		(0.020)
N	3132		3131	3030	3077	2973
<b>Panel B: Developing economies</b>						
E	0.439*	0.422*	0.492*	0.481*	0.518*	0.511*
	(0.052)	(0.052)	(0.061)	(0.060)	(0.072)	(0.092)
I		0.078*		0.086*		0.067*
		(0.013)		(0.015)		(0.025)
N	2122	2033	2121	2010	2069	1965
<b>Panel C: Advanced economies</b>						

E	0.198* (0.043)	0.123* (0.038)	0.214* (0.066)	0.135** (0.057)	0.173** (0.075)	0.104 (0.065)
I		0.167* (0.025)		0.158* (0.029)		0.159* (0.039)
N	1005	1005	1005	1005	1002	1002

Note: The dependent variable is the growth rate of per capita real GDP. Standard errors are in parentheses.

\*\* and \* indicate significance at the 5% and 1% levels, respectively.

Our main conclusion is that energy consumption is an important input that drives long-run growth, especially in developing countries. The estimates are quantitatively larger when we account for heterogeneity and cross-sectional dependence, which implies that failure to consider heterogeneity and cross-sectional dependence may result in biased results. The effect of energy consumption on long-run growth is stronger in developing countries than it is in advanced economies. This might be attributed to the structural difference between the two types of economy as developing countries obviously depend on primary and traditional energy sources for economic activities. Once we accounted for cross-sectional dependence using the CS-ARDL model, we discovered a weak long-run relationship between energy consumption and economic growth in advanced economies. This might be due to the emergence of positive global technology shocks with common effects across developed countries in promoting economy-wide energy efficiency. This suggests that less energy per unit of economic output is required in many advanced economies due to the following factors: significant technological progress and a shift from using low quality fuels, such as coal, to using higher quality energy sources, such as electricity and thermal energies. Our findings of strong positive effect of energy consumption on long-run growth support the findings of recent studies by Menagaki (2011); Alam and Paramati (2015); Acheampong (2018).

#### 4.5 Granger-causality analysis of panel data set

The analysis of Granger-causality approach of panel data set is estimated with the use of Dumitrescu and Hurlin (2012) Granger-causality test which account for the issue of heterogeneity of non-directional cause-effect. The application of the technique is possible when  $T=N$ . The technique accounts for the issue of cross-sectional dependence and produce robust result which is constructed on VAR (vector autoregressive model). The test comprises two definite distributions which exist in the analysis. These distributions are the asymptotic which is applied in the case of  $T > N$  and the semi-asymptotic when  $N > T$ . The formulation of the linear model is presented thus:

$$y_{i,t} = \sum_{l=1}^L \lambda_i^{(l)} y_{i,t-l} + \sum_{l=1}^L \alpha_i^{(l)} x_{i,t-l} + \varepsilon_{i,t} \dots \dots \dots (5)$$

$L$  in this case describes the lag length,  $\lambda_i^{(k)}$  portrays estimate of auto-regression, while the estimate of the regression that guaranteed the variation within the cross-sections is represented by  $l(k)$ . The cause-effect analysis is assumed to have a normal distribution and guarantees the solution of heterogeneous nature of the data. The heterogeneous nature of the model causality is solved by applying the homogeneity nature of the unit-root thesis. The two hypotheses ( $H_0$  and  $H_1$ ) used in the homogeneous unit root hypothesis are formulated thus:

$$H_0: \delta_i = 0 \quad \Lambda_i = 1 \dots N$$

$$H_1: \delta_i = 0 \quad \Lambda_i = 1 \dots N_1$$

$$\delta_i \neq 0 \quad i = N_1 + 1, N_1 + 2 \dots N$$

In this case, the unknown estimate is described by  $N_1$ , which meets the requirement  $0 \leq N_1/N < 1$ . The proportion  $N_1/N$  in any case should be necessarily  $< 1$ . However, the test is assume to have no causal relationship across the groups if  $N_1/N = 1$ . In this situation, null hypothesis of homogeneous unit root thesis is not rejected. On the other hand, the aggregate panel is said to possess a causal relationship if  $N_1/N = 0$ .

We conduct the Granger causality test of Dumitrescu and Hurlin (2012) method in order to augment the ARDL valuation outcome and the result are presented in Table 6. According to the statistical significance of the Wald test, the following results emerged: (1) a feedback effect exists between real GDP and energy

consumption consistent with the findings of (Apergis and Payne, 2010b), (2) there is the existence of a feedback effect between per capita GDP and investment, a ratio of GDP, also consistent with the study of (Apergis and Payne, 2010a), (3) the feedback effects among the variables demonstrate a long-term interconnection among real GDP, energy consumption and other growth stimulus especially investment in both the developing and developed countries. The finding is in keen contradiction to the conclusions of Menegaki (2011) which assumes a conservative and a neutrality proposition between energy consumption and economic growth in the European countries and draws the conclusion that the conservative hypothesis exists in European region. The result therefore gives claims in support of feedback effects in all the categories of country including the full sample.

**Table 6:** Dumitrescu and Hurlin (2012) Panel Granger causality test results for Developed and Developing

Null hypothesis (H <sub>0</sub> )	W-stat	P-value	Causality	Direction
<b>Full sample</b>				
E→Y	3.831*	0.000	Yes	
Y→E	2.680*	0.000	Yes	Feedback
I→Y	3.604*	0.000	Yes	
Y→I	3.204*	0.000	Yes	Feedback
E→I	0.108**	0.011	Yes	
I→E	0.101**	0.021	Yes	Feedback
<b>Developing countries</b>				
E→Y	2.760*	0.000	Yes	
Y→E	2.008*	0.000	Yes	Feedback
I→Y	4.858*	0.000	Yes	
Y→I	3.760*	0.000	Yes	Feedback
E→I	0.122**	0.031	Yes	
I→E	0.027**	0.041	Yes	Feedback
<b>Developed</b>				
E→Y	2.301*	0.000	Yes	
Y→E	2.121*	0.000	Yes	Feedback
I→Y	2.602*	0.000	Yes	
Y→I	4.221*	0.000	Yes	Feedback
E→I	2.081**	0.033	Yes	
I→E	4.209**	0.020	Yes	Feedback

**Note:** the notation ≠ for null hypothesis implies that the variables do not Granger cause one another, against its alternative hypothesis that, the variables Granger-cause one another for at least one panel-VAR (id).

#### 4.6 Factors that weaken the linkage between energy and economic growth in advanced economies

While the results for developing countries are as expected and are in line with the existing literature, our findings for the energy consumption–economic growth nexus differ from those of the mainstream literature. In this section, we present explanations for possible economic mechanisms that could weaken the relationship between energy consumption and economic growth in advanced economies. Our findings are in line with emerging theories that emphasize the decoupling of economic growth and energy use, indicating that there has been a permanent change in the relationship between energy consumption and economic growth in developed countries (for instance, Riti et al, 2017b; Stern, 2011; Arora and Shi, 2016). Among the central factors that can weaken the link between energy consumption and economic growth is the substitution of energy with other inputs, such as capital, technological change, and shifts in the composition of inputs and outputs in the production technologies across countries. These all indicate the paramount importance of accounting for differences in production technologies in an empirical model, which signifies a departure in our study from the existing literature. Evidence from previous studies reinforces the view that energy inputs and capital are substitutes in the long run (Apostolakis, 1990; Frondel and Schmidt, 2002; Arora and Shi, 2016). Our empirical results lend support to this strand of literature: our findings show that the coefficient of investment is consistently significant in all models, while the coefficient of energy

consumption is also statistically significant in all the specifications in the CS-ARDL model for advanced economies though with less elasticities than those of developing economies. Technological change could be another important channel that can explain the weak linkage between energy consumption and economic growth in advanced economies. Previous studies, such as that of Newell et al. (1999), show that technological progress leads to the development of energy-saving techniques used by households and firms. The increase in energy prices in the last few decades due to the surge in aggregate demand, as well as disruptions in oil production in the Middle East (caused by ongoing conflicts), has accelerated the development of more efficient, energy-saving technologies in advanced economies (Stern, 2011).

The composition of energy inputs tends to evolve over time in the course of technological change and economic growth. With continuous improvements in technical innovations, low-quality inputs tend to be substituted by high-quality energy saving inputs, which necessitates less consumption of energy per unit of output. Evidence has already been presented in previous studies on the importance of the changing composition of energy inputs as a shift to higher quality fuels reduces the amount of energy required to produce a unit of output in advanced economies (for example, Berndt 1990; Berndt et al. 1993; Stern 2011). Even though energy use remains an important issue in modern economies, continued technological innovations and the shift from low- to high-quality energy inputs play a central role in weakening the linkage between the quantity of energy consumption and the degree of economic growth in advanced economies. That is, technical progress and the availability of high-quality energy inputs have made it possible that less energy is required per unit of output. By extension, policies for energy conservation and against climate change can be promoted in developed countries with less effect on economic growth, implying a favorable situation for environmental management. However, energy conservation policies that curb energy consumption in developing countries may exacerbate poverty levels in these countries, thereby adversely affecting their national economies in the long run.

## **5 Conclusions**

This paper investigates the long-run effect of energy consumption on economic growth using the most recent techniques in panel time-series literature, accounting for heterogeneity in production technology, cross-sectional dependence, and endogeneity. Our findings accord with the structural changes in the global economy, including the shift toward a more service-intensive economy, as well as the adoption of technologies that promote energy efficiency in advanced economies. Our results are consistent in the sense that technical progress and the development of high-quality energy inputs have allowed less energy to be used per unit of output, thus minimizing the adverse effects of a reduction in energy consumption on economic growth in developed countries. Our findings have important implications for energy policies in developing and developed countries seeking to realize not only long run economic growth but the emission reductions they agreed to in the Paris Convention on Climate Change. Our results suggest that those energy policies may have differing impacts on long-run growth depending on the economies based on income group. On the one hand, the main implication of our findings is that environmental policies and agreements aimed at reducing energy consumption in developing countries may worsen the development conditions in these countries, thereby harming their long-run economic growth. On the other hand, our results indicate that developed countries can promote energy conservation policies, as these policies have little adverse effect on their long-run economic growth. Therefore, from a policy perspective, our results suggest that developed countries can promote energy conservation policies that improve global environmental quality without adversely affecting their economic performance. Policies that impose limits on energy use in developing countries should be accompanied by benefit packages that may compensate the loss in output in these poor economies.

## 6 Declarations

### 6.1 Study Limitations

The limitation of the paper stems from the fact there are other variables that can be included such as energy efficiency to make the model a robust one which are missing in this present paper.

### 6.2 Acknowledgement

The authors wish to thank the proposed anonymous reviewers of this manuscript.

### 6.3 Competing Interests

The authors declare that there is no competing interest regarding the manuscript.

## 7 How to Cite this Article:

Kamah, M., & Riti, J. S. (2021). Revisiting Energy Consumption-economic Growth Hypothesis: Do Slope Heterogeneity and Cross-sectional Dependence Matter?. *Advanced Journal of Social Science*, 8(1), 10–24. <https://doi.org/10.21467/ajss.8.1.10-24>

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