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Energy consumption, environmental contaminants, and economic growth: The G8 experience

Environmental pollution has increasingly become an issue of global concern because of climate change and consciousness for environmental sustainability. To this end, this paper investigates the relationship between energy consumption, carbon dioxide (CO₂) emissions and economic growth of the G8 countries over the period of 56 years spanning 1960 through 2015 using both the Fully Modified and Dynamic OLS estimation techniques. The empirical investigation establishes the critical roles played by energy consumption and CO₂ emissions on economic growth but in substantially opposite directions. While that of the former positively enhances economic growth, on the one hand, the latter negatively deters it. In addition, a long-run relationship is equally established but with the varied direction of causality. Finally, the study offers significant policy implications directed at using energy resource efficiently as well as curtailing environmental contaminants.

Keywords: energy consumption; environmental contaminants; economic growth.

JEL classification: E21; Q53; O44.

1. Introduction

That energy matters inexorably for growth is not a matter of empirical dispute among researchers, development economists, and policymakers. What is, yet to be resolved empirically, is the direction of causality between these two variables. While there are many empirical studies that have documented the impact of energy consumption on economic growth (Kraft, Kraft, 1978; Asafu-Adjaye, 2000; Stern, 2000; Morimoto, Hope, 2004; Lee, 2006; Lee, Chang, 2008; Balat, 2008; Acaravci, Ozturk, 2010; Dogan, 2016) on the one hand, the impact of energy on environment has equally enjoyed a widespread research attention on the other hand. This notwithstanding, the emanating issue of concern till date, still centers on tracing the level and degree of interconnectedness among economic growth, energy, and environment. Of a greater concern, however, is the excruciating problem of environmental pollution. Specifically, carbon emissions which constitute the major by-product of economic growth processes, are arguably the most driving forces behind global warming and ozone layer depletion. It is worth noting, however, to state that fossil fuels combustion remains the main source of carbon emissions. According to Mehrara (2007), global warming which is caused by greenhouse gas emissions, especially carbon

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dioxide (CO₂) emissions, are mostly generated from the consumption of fossil fuels. In light of this, Jamel and Derbali (2016) thus argued that «the relationship between economic growth and the environment is complex». On a lighter note, they equally aver that the size and composition of the economy, particularly, the share of the service sectors to gross domestic product (GDP), as opposed to primary industries, manufacturing, and technological changes, have the potential to reduce the environmental impacts of both production and consumption decisions, which at the same time help driving economic growth. On the whole, the issue bordering on energy-growth-environment nexus is still largely contentious and thus, far from being resolved.

In view of the ambivalent positions regarding energy consumption-growth nexus on the one hand, the growing concern of the environmental impact of energy consumption in recent times on the other hand, there have persistent attempts thereafter, at extending the probe into examining the tripartite relationships, see (Selden, Song, 1994; Jumbe, 2004; Al-Iriani, 2006; Ang, 2007; Halicioglu, 2009; Menyah, Wolde-Rufael, 2010a,b; Tiwari, 2011; Sheinbaum-Pardo et al., 2012; Arouri et al., 2012; Salami et al., 2012; Saidi, Hammami, 2015; Jamel, Derbali, 2016). Notwithstanding, the empirical findings are yet filled with mixed outcomes. The possible channel of disagreements may be attributed to omitted variable bias in the tripartite relationship.

Against this backdrop, this paper focuses on examining the relationship between energy consumption, environmental degradation and economic growth in G8² countries, but specifically take account of capital investment variable as the main transmitting channel of environmental contaminants. In light of this, the motivations for the study as well as for the selection of G8 countries as a candidate representative sample of focus are based on the following points: first, the world's nations have committed to holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C pre-industrial levels. This is considered necessary to avert incalculable risks as well as move the 2030 Sustainable Development Goals beyond reach. Second, the G8 countries make up the huge portion of world energy consumption. For instance, the thirteen 'G8+5'³ countries account for about 70% Gigatonnes of carbon per year emitted globally from fossil-fuel combustion (Energy Information Administration, 2007). Third, at the G8 summit at Gleneagles held in Scotland on July 6–8, 2005, the heads of state and governments issued a declaration and an Action Plan centered on climate change, clean energy, and sustainable development. Lastly, the US Energy Information Administration had projected that atmospheric carbon dioxide concentrations will approach 450 ppm by 2030 if global energy-related CO₂ emissions grow as projected. Thus, prompt and aggressive action are required to curb energy-related CO₂ concentrations below the 450 ppm threshold, as this is considered to be «safe zone» for avoiding the most dangerous effects of climate change.

Given the foregoing, our study adds to the extant stock of literature in the following ways. First, while many of the previous empirical research on the issue is conducted for country-specific and cross-country studies, we are not aware of any study (aside from the work of Rahman et al. (2016) which is limited to inter-regional analysis) conducted specifically on the G8 economies vis-a-vis the key variables of interest, namely: energy consumption, environmental contaminants, and economic growth. Second, the analysis in relation to G8 economies becomes funda-

² The countries are as follows: Canada, France, Germany, Italy, Japan, Russia, UK, and the USA.

³ The countries include China, India, Brazil, South Africa and Mexico plus the eight other countries listed in footnote 2.

mentally germane given the fact that the group consists of the most industrialized and developed economies of the world. This apart, the role of these economies in setting the pace towards ensuring a greener, cleaner, and non-renewable energy independent economies is equally unparalleled. Third, we control for the role of gross fixed capital formation in order to test the extent to which industrial activities are perceived as being more capital than labor intensive in nature in these economies. Fourth, we explore the use of a battery of estimators to probing the relationship between the variables of interest to be able to make a valid conclusion devoid of any form of qualification(s). Lastly, focusing on G8 economies require that we account for their inherent heterogeneity. To this end, the study also employs second generation unit root tests like the cross-sectionally augmented ADF (CADF) and cross-sectionally augmented IPS (CIPS) panel unit root tests. The failure to recognizing the problem of cross-sectional dependence can result in unreliable estimates and cause econometrically dangerous consequences.

In sum, the empirical fallouts from study's findings support a long run relationship between energy consumption, CO₂ emission, gross fixed capital formation and economic growth in the G8 economies. Similarly, the panel results support the existence of a statistically significant relationship between/among the variables of interest. Both CO₂ emission and gross fixed capital formation exhibit negative impacts while energy exerts positive and significant influence. The variation in results is indicative of the dynamic nature of these economies. More importantly, carefully and well-tailored economic policies needed to manage the rate of energy consumption and degree of CO₂ emissions both in the medium and longer terms are seen to be inexorable if these economies must continue to thrive and play its leading roles in driving the global economy.

2. Literature review

The section is not intended to conduct a full-scale review of previous empirical studies on the relationship between energy consumption, CO₂ emission, and economic growth but to selectively undertake the review of some selected empirics considered central to this strand of literature. This is forewarned in what follows.

To start with, in no particular order, Lee and Chang (2008) and Lee et al. (2008) adopt a panel approach to co-integration in examining the correlation between energy, gross domestic product (GDP) and capital in 16 Asian economies and 22 OECD (Organisation for Economic Co-operation and Development) countries spanning through a period of over 30 years and 40 years respectively. While the empirical results from Lee and Chang (2008) support a long run causal relationship running from energy to GDP in the sample of Asian countries, on the one hand, those of Lee et al. (2008) on the other hand, find a bidirectional relationship in the OECD sample. Using a panel co-integration technique, Kahia and Ben (2014) also explore the relationship between renewable and non-renewable energy consumption and economic growth in a sample of 11 Net Oil Importing Countries of Middle East and North Africa region (MENA) covering the period 1980–2012. Results from the panel co-integration tests support the existence of a long-run equilibrium relationship between real GDP, renewable energy consumption, nonrenewable energy consumption, real gross fixed capital formation, and the labor force with elasticities, and thus find a positive and statistically significant relationship in the long-run. Wolde-Rufael (2005) investigates the long run relationship between energy use per capita and per capita real GDP for 19 African countries for the period 1971–2001 using the bound testing ap-

proach to long-run relationship. While the empirical results support the existence of a long-run relationship between the two variables for only eight countries, evidence of causality is further established in ten countries.

Jamel and Derbali (2016) investigate the impact of energy consumption and economic growth on CO₂ emissions as a proxy for environmental degradation. The study finds the existence of a long run relationship among environmental degradation, energy consumption and economic growth along with financial development, trade openness, capital stocks, and urbanization as control variables. Similarly, results from fully modified ordinary least square method (FMOLS) confirm that economic growth and energy consumption have a positive and significant impact on environmental degradation. Rahman et al. (2016) adopt Toda Yamamoto technique in investigating the long-term relationship between industrial production and energy consumption together with an environmental degradation variable in developed and developing countries over a period of 40 years spanning 1971 through 2011. The empirical findings establish that both G8 and Southeast Asian countries are energy dependent based on unidirectional Granger causality running from energy consumption to industrial production. While cases of energy efficient with environmental friendly are recorded more among G8 countries than the developing countries.

Saidi and Hamammi (2015) investigate the impact of economic growth and CO₂ emissions on energy consumption on a global panel of 58 countries. Using the system Generalized Method of Moments (GMM) for the period 1990–2012, they find that CO₂ exerts a significant positive impact on energy consumption for four global panels. Similarly, economic growth has a positive impact on energy consumption but statistically significant only for the four panels. Zhang and Lin (2012) examine the impact of economic indicators on pollution (CO₂ emissions) in China during the period 1995–2010, employing the fixed effects model and the method of least square generalized linear regression. They utilize the demographic intensities, urbanization, GDP, industrial production, production of services, and energy consumption as economic indicators. The main results of their study show that the demographic intensities, GDP, industrial production, and energy consumption have impacts on CO₂ emissions. Tiwari (2011) also investigates whether there is causality between energy consumption, CO₂ emissions and economic growth in India using Granger approach in VAR framework. He finds that there exists a unidirectional causality running from energy consumption, capital, and population to economic growth and that CO₂ emission has a positive impact on energy use and capital but negative impact on population and GDP. The result also shows that energy consumption has a positive impact on CO₂ emissions and GDP but its impact is negative on capital and population.

A careful evaluation of the above brief literature reviewed pinpoints at three key messages: first, the existence of divergent empirical outcomes thus showing the level of inconclusiveness in the energy-growth and growth-environment debates. Second, the role of capital investment has scanty been considered in such relationships thus far. Third, on the methodological stance, most of the existing literature has relied exclusively on one technique at the expense of others. Leveraging on these identified gaps, the study adds to the existing stock of literature addressing the impact of energy consumption, the environment on economic growth through an intervening role of capital investment variable. We employ a variety of methodologies to enable us to determine the level of convergence or otherwise in the previously conducted empirics on the issue. It is equally worth noting that our sample of countries (G8), with the exception of the work of Rahman et al. (2016), has received a very scant attention particularly with respect to the variables of interest.

2.1. Stylized facts

The G8 originated in the early 1970s with two flag-bearer groups known as the Brussels Group (1971) and the Library Group (1973). Both represented a selection of certain developed and democratic countries that occasionally meet to deliberate on global issues, however, these meetings were largely kept indoors. Just 12 months to the existence of the Library Group (France, Germany, the United Kingdom, and the United States), Japan became a member. Consequently, the group metamorphosed to the G6 with a new member of Italy and in 1976, it became G7 when Canada joined. Incorporation of new members was put to stop with the admission of Russia in 1998 to make the G8. This group is perceived as an association of the most industrialized economies of the world. They are at the forefront of influencing global developments and mediating global crisis given their economic, political and military power.

From Fig. 1, the trends of country-specific and panel group depict the consistent reduction in fossil energy consumption⁴ by the G8 economies in the last 3 decades.

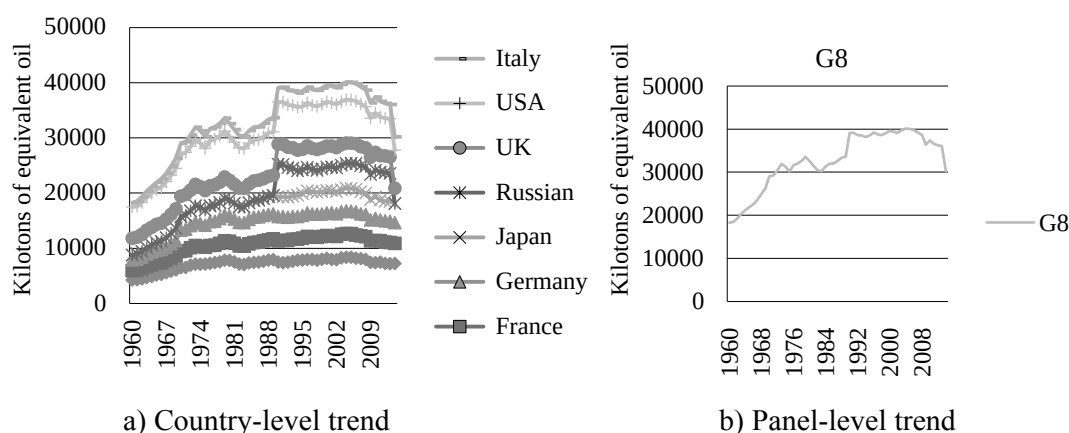


Fig. 1. G8 Energy consumption trend 1960–2015

Source: Authors' computation with underlining data from (WDI, 2016).

Since pre-industrial period, the world has witnessed an increasing trend in the atmospheric concentrations of CO_2 . According to Olivier et al. (2015), about half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (high confidence). This is further supported by the graph of the trend presented in Fig. 2 for both country-specific and panel group with a remarkable difference witnessed in 2013. Similarly, the wide difference between the USA and other G8 countries is suggestive of high level of CO_2 emissions recorded in the country in 2013 which consequently puts the country in the group of the 4 economies with the largest share of CO_2 ⁵.

⁴ Energy use as presented in the World Development Indicators (WDI) represents mainly energy consumption from the group of fossil fuel.

⁵ According to Olivier et al. (2015), CO_2 for the last decade had an annual increase of 4% on average, and nosedived to 1% for two years between 2012 and 2013 and the top 4 emitting countries/regions, which together account for almost two thirds (61%) of the total global CO_2 emissions are China (30%), the United States (15%), the European Union (EU-28) (10%) and India (6.5%).

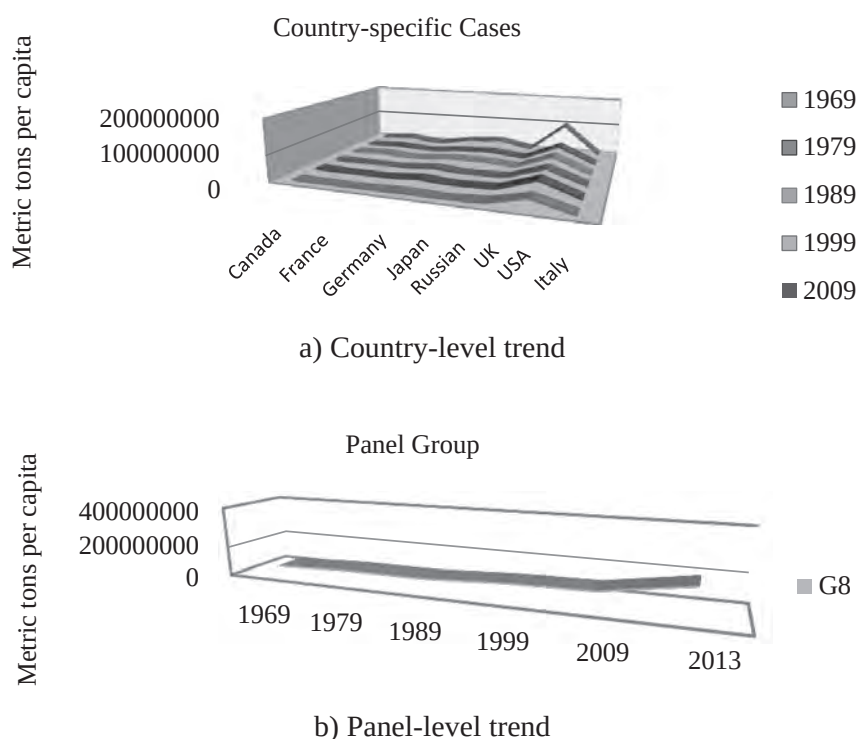


Fig. 2. G8 CO₂ emission trend 1969–2013

Source: Authors' computation with underlining data from (WDI, 2016).

3. Data, variable description, and econometric modeling

The scope of this paper is limited to annual series data straddling a time period of 1960–2015 collected for the 8 most industrialized economies regarded as the G8⁶. The scope and coverage are constrained by data availability. The dataset on annual GDP per capita, energy use per capita in kilotons, CO₂ emissions (metric tons per capita) and gross fixed capital formation are obtained from the World Development Indicators (WDI, 2016).

3.1. Panel unit root tests

Prior to panel co-integration tests, it is conventionally plausible to first carry out a panel unit root test to probe the order of integration of panel data series. The rationale behind panel unit root tests lies in the fact that the tests instantaneously estimate data from time series and cross-sectional units. It is equally pertinent to note that the combination of cross-sectional deviation to time series deviation improves the efficiency of the estimation by obtaining smaller standard

⁶ The group is presently reformatted as G7 (Canada, France, Germany, Italy, Japan, United Kingdom, United States) due to Russia's suspension as at 2014.

errors and higher t-ratios. Similarly, recent literature has advanced that panel-based unit root tests have higher power and are more reliable than unit root tests based on individual time series. Hence, about five types of panel unit root tests have been empirically and statistically proposed. These include Levin et al. (2002), Breitung (2000), Im et al. (2003), Fisher-type tests using ADF and PP tests (Maddala, Wu, 1999; Choi, 2001), and Hadri (2000), respectively.

Levin et al. (2002) proposed a set of heterogeneous dynamics, fixed effects, and an individual-specific determinant trend. In addition to these, the test accounts for homogeneity of autoregressive series root under the alternative hypothesis. Im et al. (2003), on the other hand, differ by estimating panel unit root test for a heterogeneous autoregressive coefficient under the alternative hypothesis. Breitung (2000) panel unit root differs from the former tests in that it estimates substantially higher power and smaller size distortions and hence free of reliance on bias correction. Maddala and Wu (1999) and Choi (2001) proposed a combination of the probability values from individual unit root tests based on Fisher type which is neither conditioned on a balanced panel nor identical lag lengths as the case may be.

Based on the foregoing, this study is keen to test the presence of a unit root in a panel of GDP per capita (a proxy for economic growth) energy use (kg of oil equivalent per capita), CO₂ emissions (metric tons per capita) and gross fixed capital formation (% of GDP). We employ both the first and second-generation tests of stationarity on all the variables across our sample of G8 countries.

In specifying the equation procedure for the LLC and IPS, we consider the autoregressive mechanism used to find the ADF test for each series in the panel. Hence, based on the assumption that there are N such series. The IPS specification holds,

$$\Delta y_{it} = \rho_i y_{i,t-1} + \sum_{j=1}^{p_i} \beta_{i,j} \Delta y_{i,t-j} + \alpha_i d_{it} + \varepsilon_{it}, \quad (1)$$

where d_{it} are the deterministic components. Also, while $\rho_i = 0$ indicates the y process has a unit root for individual i , $\rho_i < 0$ implies that the process is stationary around the deterministic part.

Taking inferences from IPS, the test statistic can be computed after deciding on d_{it} and the p_i , hence, the t -ratios for the α_i , t_{α_i} can, therefore, be calculated along with its arithmetic average, $\bar{t}_{NT} = \sum_{i=1}^N t_{\alpha_i} / N$ are estimate. IPS show that t_{NT} may be adjusted to yield an asymptotic $N(0,1)$ statistic under the null hypothesis as $\mathbf{H}_0 : \alpha_i = 0$ vs. $\mathbf{H}_1 : \alpha_i < 0$:

$$\bar{t}_{NT}^* = \frac{N^{1/2} \left(\bar{t}_{NT} - N^{-1} \sum_{i=1}^N E(t_{\alpha_i}) \right)}{\left[N^{-1} \sum_{i=1}^N \text{Var}(t_{\alpha_i}) \right]^{1/2}}. \quad (2)$$

The $E(t_{\alpha_i})$ and $\text{Var}(t_{\alpha_i})$ have been obtained by simulation⁷.

⁷ For the purpose of precision, this study is limited by the mathematical equation to LLC and IPS panel unit roots. For details on the other types panel unit roots, see (Levin et al., 2002; Im et al., 2003; Breitung, 2000; Maddala, Wu, 1999).

3.2. Panel co-integration tests

The panel co-integration techniques aimed at obtaining series of relevant information on mutual long-run relationships among a set of variables while allowing for short-run dynamics and fixed effects to be non-homogeneous across the different samples of the panel. This is patently essential since it is obvious that vectors of co-integration across all the individuals of the panel are unidentical. Hence, taking consideration of such heterogeneity becomes inexorable. We adopt two different tests of panel co-integration namely; Pedroni (1999, 2004) and Kao (1999).

To examine whether there exists or not a long-run co-integration among our variables of interest, we first employ the seven panel co-integration tests suggested by Pedroni (1999, 2004) which is based on the residuals of the Engle and Granger (1987) co-integrating regression in a panel data model which similarly estimates the degree of heterogeneity in the sample panel of the model:

$$y_{i,t} = \alpha_i + \delta_i t + \beta_{1i} x_{1i,t} + \beta_{2i} x_{2i,t} + \dots + \beta_{Mi} x_{Mi,t} + e_{i,t}, \quad (3)$$

given $t = 1, \dots, T$; $i = 1, \dots, N$. In this case, T is the number of observations over time, while N is the number of cross-sectional units in the panel. Similarly, M denotes the number of regressors. In this model, α_i denotes the member-specific intercept or fixed effects parameter which diverges across individual cross-sectional units. The same is similar to the slope coefficients and member-specific time effects $\delta_i t$.

In an extended version of this model, Pedroni (1999, 2004) suggests both the heterogeneous panel and heterogeneous group mean panel statistics to test for panel co-integration which includes two sets of statistics. The first set of four statistics stated is based on the pooled residuals along the within the dimension of the panel which is expressed as thus:

$$T^2 N^{3/2} Z_{\hat{v}_{N,T}} = T^2 N^{3/2} \left(\sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} \hat{e}_{i,t-1}^2 \right)^{-1}, \quad (4)$$

$$T \sqrt{N} Z_{\hat{\rho}_{N,T-1}} = T \sqrt{N} \left(\sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} \hat{e}_{i,t-1}^2 \right)^{-1} \sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} (\hat{e}_{i,t-1} \Delta \hat{e}_{i,t} - \hat{\lambda}_i), \quad (5)$$

$$Z_{t_{N,T}} = \left(\hat{\sigma}_{N,T}^2 \sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} \hat{e}_{i,t-1}^2 \right)^{-1/2} \sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} (\hat{e}_{i,t-1} \Delta \hat{e}_{i,t} - \hat{\lambda}_i), \quad (6)$$

$$Z_{t_{N,T}}^* = \left(\hat{s}_{N,T}^{*2} \sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} \hat{e}_{i,t-1}^{*2} \right)^{-1/2} \sum_{i=1}^N \sum_{t=1}^T \hat{L}_{11i}^{-2} \hat{e}_{i,t-1}^* \Delta \hat{e}_{i,t}^*, \quad (7)$$

given that $\hat{e}_{i,t-1}$ is the residual vector of the OLS estimation of equation (3) and where the other terms are properly defined in Pedroni.

The second set considers the pooled residuals along the between the dimension of the panel which accounts for a heterogeneous autocorrelation parameter across samples. The model is stated as thus:

$$TN^{-1/2}\tilde{Z}_{\hat{\rho}_{N,T}-1} = TN^{-1/2} \sum_{i=1}^N \left(\sum_{t=1}^T \hat{e}_{i,t-1}^2 \right)^{-1} \sum_{t=1}^T \left(\hat{e}_{i,t-1} \Delta \hat{e}_{i,t} - \hat{\lambda}_i \right), \quad (8)$$

$$N^{-1/2}\tilde{Z}_{t_{N,T}} = N^{-1/2} \sum_{i=1}^N \left(\hat{\sigma}_i^2 \sum_{t=1}^T \hat{e}_{i,t-1}^2 \right)^{-1/2} \sum_{t=1}^T \left(\hat{e}_{i,t-1} \Delta \hat{e}_{i,t} - \hat{\lambda}_i \right), \quad (9)$$

$$N^{-1/2}\tilde{Z}_{t_{N,T}}^* = N^{-1/2} \sum_{i=1}^N \left(\sum_{t=1}^T \hat{s}_i^{*2} \hat{e}_{i,t-1}^{*2} \right)^{-1/2} \sum_{t=1}^T \hat{e}_{i,t-1}^* \Delta \hat{e}_{i,t}^* \quad (10)$$

These models estimate the group means of the individual conventional time series statistics. With this in mind, the asymptotic distribution of each of the seven models can be stated as follows:

$$\frac{X_{N,T} - \mu\sqrt{N}}{\sqrt{\nu}} \Rightarrow N(0,1), \quad (11)$$

where $X_{N,T}$ is the analogous form of the test statistics, while μ and ν denote the mean and the variance of each test respectively. Their estimates are provided in Table 2 in Pedroni (1999). Similarly, considering the stated alternative hypothesis panel ν statistics which diverges to positive infinity, it can be inferred that the statistic is a one-sided test where large positive values reject the null of no cointegration. The corresponding statistics diverge to negative infinity deducing that large negative values reject the null.

In a supplementary estimation of the long run relationship, we further adopt the Kao (1999) tests of co-integration which specifically utilizes both DF and ADF to test for cointegration in a panel and similarly adopts the standard approach of the EG-step procedures given the stated panel regression model of the form:

$$Y_{it} = X_{it} + Z_{it} + e_{it}, \quad (12)$$

where Y and X are unconditionally non-stationary.

3.3. Panel co-integration estimation

3.3.1. Theoretical architecture

To examine the role of gross fixed capital formation (per capita) in the relationship between GDP per capita, energy use (kg of oil equivalent per capita) and CO₂ emissions (metric tons per capita) on G8 countries over the period 1960–2015, our empirical strategy rely on the theoretical model proposed by Solow (1956) whose work centers on factors affecting economic growth. Solow draws a line of distinction between two dimensions of growth regressors called the endogenous and exogenous variables. In his model, the exogenous variable with a central focus on technology plays a significant role in the growth prospects of every economy. Abundant empirical studies have made series of improvements on this model (especially, since the 1798 Malthus's propositions) with the classicalists and neo-classicalists playing prominent roles using

varied propositions. Whereas the classical theorists are more inclined to capital as a key driver of growth, the neoclassical pursued an extension of the Harrod–Domar classical formulation through the inclusion of labor and technology to the growth model (Solow, 1956).

Let's consider the basic Solow growth model of the form:

$$Y(t) = K(t)^\alpha A(t)L(t)^{1-\alpha}. \quad (13)$$

The above equation (13) states that the long-run economic growth is a function of capital (K), labor (L), and technological progress (A), which is exogenously determined and also implies knowledge or effectiveness of labor. The equation (13) does not consider the pertinent roles of natural resources and environmental pollution. Nevertheless, the roles of natural resources and its ensuing effects on the environment have become imperative in explicating the rate of economic growth. This is evident from the fact that the continuous increase in production activities are known to have depleting effects on natural resources, and by extension, contaminate the human environment. This narrative seems logical considering that the stock of energy and other natural resources on earth are mostly fixed in nature and thus any unfettered usages may tend to deplete them. Also, production activities in its continued form may further surpass what the land can accommodate and by implication, may result in pollution in its divergent forms (Romer, 2012; Gardoňová, 2016).

The extended version of the Solow–Swan growth model which incorporates natural resources and land as additional factors of production is credited to Nordhaus (1992). The production function of his model follows the form:

$$Y(t) = F(K(t), A(t)L(t), T(t), R(t)), \quad (14)$$

where T is the stock of land and R is the flow of natural resources used in production.

Since the amount of land on earth is fixed by nature, in the long run, the quantity used in production cannot be growing. Hence, we assume that the stock of land is fixed:

$$\dot{T}/T = 0. \quad (15)$$

Likewise, since the resources used in production are assumed to be fixed, it implies that over time, resource use must eventually decline as the stock becomes exhausted so that

$$\dot{R}/R = -\rho, \quad (16)$$

where $\rho > 0$. Hence, we make an assume that technical progress and population grow at constant rates given by

$$\dot{A}/A = g \quad (17)$$

$$\text{and } \dot{L}/L = n. \quad (18)$$

Nordhaus (1992) assumes a constant return to scale Cobb–Douglas production function of the form

$$Y = K^\alpha T^\beta R^\gamma (AL)^{1-\alpha-\beta-\gamma}, \quad (19)$$

$$\alpha > 0, \beta > 0, \gamma > 0 \text{ and } \alpha + \beta + \gamma < 1.$$

Taking logarithms of (19), we have

$$\log Y = \alpha \log K + \beta \log T + \gamma \log R + (1 - \alpha - \beta + \gamma) \log(AL). \quad (20)$$

According to the model, resource and land limitations can cause output per worker to eventually fall. The declining quantities of resources and land per worker are thus regarded as drags on growth while technological progress acts as a spur on growth. If the impact of spurs outweighs that of drags, then there will be sustained growth in output per worker. This is precisely what has happened over the past few centuries (Romer, 2012).

3.3.2. Empirical model

To incorporate non-renewable energy in our model, we follow the theoretical foundation laid in the preceding section and equally adopts that of the existing literature (Asafu-Adjaye, 2000; Mohammed et al., 2012; Saibu, 2012; Gardoňová, 2016; Eregha, Mesagan, 2017). Hence, energy consumption E can represent natural resource N used in the Cobb–Douglas production function given as thus:

$$Y = AK^\alpha E^\beta L^{1-\alpha-\beta}, \quad (21)$$

where α and β values lie between zero and one, and $\alpha + \beta < 1$, human, physical capital, energy consumption and exogenous technology are L , K , E and A respectively. Going by the assumption of Solow model, exogenous technology is used to multiply the whole production function rather than the labor inputs. We follow the proposition of constant return to scale. Hence, we infer that any proportionate increase in L , K , and E lead to the proportionate increase in the real GDP. Extending the model to cater for the pollution effects, we include CO₂ emission to proxy the consequential effects of energy usage as well as that of land limitation on production activities. For the purpose of consistency, we follow the assumption that labor is constant, to enable us to determine the total output based on the level of capital, energy resources (Eregha, Mesagan, 2017) and carbon oxide emissions.

The transformed regression version of this model is given as thus:

$$GDPPC = f(ECP, CO_2, GFCP). \quad (22)$$

This is further extended in the form:

$$GDPPC_{it} = \alpha_0 + \alpha_1 ECP_{it} + \alpha_2 CO_{2it} + \alpha_3 GFCP_{it} + \ell_{it}, \quad (23)$$

where $GDPPC$ is gross domestic product per capita as a proxy for economic growth, ECP for energy consumption, environmental degradation by CO₂ and gross capital formation as a ratio of GDP ($GFCP$) is used to proxy capital in the model and ℓ is the stochastic residual term that is white noise. Both the Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) techniques are used to estimate the model.

Given that:

$$y_{it} = \alpha_i + x'_{it}\beta + e_{it}, \quad x_{it} = x_{i,t-1} + \varepsilon_{it}, \quad (24)$$

where $\xi_{it} = [e_{it}, \varepsilon'_{it}]$ denotes stationary series with covariance matrix Ω_i with an estimator β which is categorically consistent when the co-integration assumption between y_{it} and x_{it} is satisfied by this error process $\omega_{it} + [e_{it}, \varepsilon'_{it}]'$. The OLS estimator may be constrained depending on parameters of the

error terms. However, a semi-parametric correction to the OLS estimator has been suggested as a possible solution because it automatically eliminates the presence of second-order bias going by the endogenous nature of the regressors. With this in mind and following Pedroni (1996, 2000), the FMOLS estimator is constructed as follows:

$$\hat{\beta}_{NT}^* - \beta = \left(\sum_{i=1}^N L_{22i}^{-2} \sum_{t=1}^T (x_{it} - \bar{x}_i)^2 \right)^{-1} \sum_{i=1}^N \hat{L}_{11i}^{-1} \hat{L}_{22i}^{-1} \left(\sum_{t=1}^T (x_{it} - \bar{x}_i) \mu_{it}^* - T \hat{\gamma}_i \right), \quad (25)$$

where $\hat{L}_i$ is the lower triangular decomposition of a consistent estimator of the idiosyncratic asymptotic covariance matrix given as $\Omega_i = \Omega_i^0 + \Gamma_i + \Gamma_i'$ with $\hat{L}_i$ normalized such that $\hat{L}_i = \hat{\Omega}_{i22}^{-1/2}$

and where μ_{it}^* is given by $\mu_{it}^* = \mu_{it} - \frac{\hat{L}_{21i}}{\hat{L}_{22i}} \Delta x_{it}$ and the serial correlation adjustment parameter $\hat{\gamma}_i = \hat{\Gamma}_{21i} + \hat{\Omega}_{21i}^0 - \frac{\hat{L}_{21i}}{\hat{L}_{22i}} (\hat{\Gamma}_{22i} + \hat{\Omega}_{22i}^0)$.

Conversely to the non-parametric FMOLS estimator, a between-dimension group means panel DOLS estimator is explored to further probe the empirical relationship between the variables of interest⁸.

In terms of theoretical priors, energy consumption is expected to exert a positive impact on economic growth. This is based on the fact that the aggregate level of production in a given period is enhanced by the consumption pattern in energy demand. For instance, production activities are driven by energy consumption in terms of: electricity, coal, gas, petroleum oil, wind, and solar energy among others. This positive or direct relationship between energy consumption and growth as envisaged in this paper has been well documented in the previous empirical studies (Li et al., 2011; Shahbaz, Lean, 2012; Omri, 2013; Shabbir et al., 2014; Saidi, Hammami, 2015; Eregha, Mesagan, 2017).

Gross fixed capital formation equally expected to trigger growth positively since production activities in large scale is capital-driven (intensive), the accumulation of capital is therefore hypothesized to exert a positive impact on economic growth (Saidi, Hammami, 2015; Lee et al., 2008; Bartleet, Gounder, 2010).

The relationship between CO₂ emission and its squares are also tested. The intent is to test whether EKC (environmental Kutznet curve) hypothesis holds or not. Hence, a negative relationship is hypothesized. This is evidently in line as environmental degradation poses a major threat to human existence in the wake of the recent global warming.

4. Empirical results

The Table 1 below encapsulates descriptive statistics of all variables of interest to this paper. We employed annually panel data of the G8 countries (Canada, France Germany, Japan, Italy, Russia, United Kingdom, and USA) spanning 1960–2015.

⁸ DOLS is a modification of the FMOLS model by supplementing the co-integrating regression with lead and lagged differences of the regressors. This enables correction for endogeneity and serial correlation parametrically. See Pedroni (2001) for mathematical details.

Table 1. Descriptive statistics

	Mean	Max	Min	Skewness	Kurtosis	Probability	Observations
CO ₂	139	580	0.00	2.01	5.53	0.00***	185
GDPPC	228	208	184	2.39	6.83	0.00***	185
ECP	480	837	0.00	0.78	2.39	0.00***	185
GFCP	21.1	31.6	14.4	0.97	4.66	0.00***	185

Note. *** means level of significance at 1%.

A cursory glance reveals the mean values of 139, 228, 480 and 21.1 for CO₂, GDPPC, ECP, and GFCP in that order. Going by the shape of the dataset employed as depicted by skewness (asymmetry) and kurtosis (leptokurtic), it can be inferred that all the variables are not normally distributed as the positive signs indicate that they are not far from being symmetric. Similarly, the kurtosis coefficient which is greater than 1 shows that the distribution is more clustered around the mean than in a mesokurtic or platykurtic distribution.

4.1. Panel cross-section dependence test

Many panel data models are often placed on the assumption that disturbances across individual observations are independent. The reality of economic phenomenon has however shown that cross-sectional dependence is often present in panel regression settings. Hence, failure to account for cross-sectional dependence in estimation may result in the inefficiency of the estimator and invalid test statistics. There are a variety of tests for cross-section dependence in the literature. As observed by Eregha and Mesagan (2017), that prior to testing for panel unit root, one has to ascertain whether it is the first generation or second-generation panel unit tests⁹ that are applicable. In this study, two types of cross-sectional dependence tests are employed, namely: the Breusch–Pagan (1980) Lagrange Multiplier (LM) test and Pesaran (2004) cross-sectional dependence (CD) test.

Breusch–Pagan LM. The Breusch–Pagan LM test statistic is undeniably the most common diagnostic cross-section dependence test. The model assumes the null hypothesis of no cross-section dependence among the stated terms of the correlations between the disturbances in different cross-section units. The model is stated as thus:

$$LM = \sqrt{\frac{1}{N(N-1)}} \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^N (T\tilde{\rho}_{ij}^2 - 1), \quad (26)$$

where $\tilde{\rho}_{ij}$ are the correlation coefficients obtained from the residuals of the model as described above.

Pesaran CD. To address the challenges faced with size distortion as evident in the LM models, Pesaran (2004) suggests a different statistic based on the average of the pairwise correlation coefficients $\tilde{\rho}_{ij}$:

⁹ The first-generation panel unit root tests assume cross-sectional independence while the second generation panel unit root tests propose the possibility of cross-sectional dependence.

$$CD = \sqrt{\frac{2}{N(N-1)}} \cdot \sum_{i=1}^{N-1} \sum_{j=i+1}^N T_{ij} \rho_{ij}^2, \quad (27)$$

which is asymptotically standard normal for $T_{ij} \rightarrow \infty$ and $N \rightarrow \infty$ in any order. The tests' results are provided in Table 2.

Table 2. Cross-sectional dependence test

Test	Statistic	Probability
Breusch–Pagan LM	19.94	0.11
Pesaran CD	0.39	0.70

Based on the tests' results in Table 2, it can be inferred that the set of observations are cross-sectionally independent. This is evidenced by the insignificant level of the two results. Hence, we fail to reject the null hypothesis of cross-sectional independence thus suggesting the adoption of the first-generation panel unit root tests. Consequently, we proceed to test the stationarity of the series using the first-generation panel unit root tests.

4.2. Panel unit root test results

Table 3 presents the results of the panel unit root tests. Following the proposition of Im et al. (2003), Maddala and Wu (1999) and Choi (2001), the stationarity status of the variables was tested using Levin–Lin–Chu (LLC) test, Im–Pesaran–Shin (IPS) test, Breitung (UB) test, Fisher-ADF test, and Fisher-PP test. The tests of this nature are expedient in confirming whether

Table 3. First generation panel unit root

Series	GDPPC		CO ₂		ECP		GFCP	
	No trend	Trend	No trend	Trend	No trend	Trend	No trend	Trend
<i>Levels</i>								
LLC	–0.65	1.08	1.08	0.84	4.74	1.90	–1.56**	–3.21***
UB	—	1.28	—	5.44	—	7.29	—	–3.01***
IPS	–0.04	1.97	1.92	0.70	4.74	5.11	–0.94	–4.03***
Fisher-ADF	16.87	25.47*	13.25	28.77**	3.26	4.87	18.67	45.03***
Fisher-PP	14.35	76.17*	17.35	83.93***	7.64	3.83	14.96	21.20***
<i>First difference</i>								
LLC	–9.96***	–10.17***	–2.21***	–15.28***	0.5	12.07***	–1.56085	–11.90***
UB	—	–1.78**	—	–9.81***	—	0.31253	—	–9.04***
IPS	–5.50***	–9.45***	–4.08***	15.61***	–2.80***	13.71***	–6.12***	–10.38***
Fisher-ADF	59.88***	107.26***	47.52***	183.49***	37.01***	174.12***	66.58***	119.09***
Fisher-PP	56.17***	97.22***	130.62***	185.34***	111.88***	175.20***	71.46***	101.39***

Note. ***, **, * indicate the level of statistical significant at 1, 5 and 10%, in that order. (#) Null hypothesis: the series are stationary.

the variables follow $I(0)$ or $I(1)$ process. To perform this test, we utilized both the first generation (Levin–Lin–Chu and Breitung tests) and second generation (Im–Pesaran–Shin test, Fisher-ADF test, and Fisher-PP test) panel unit root tests for the two equations with an intercept, and with an intercept and a linear trend. While most of the tests jointly suggest that all the variables are non-stationary at levels, but stationary at their first differences, the Fisher-ADF, and Fisher-PP statistics narrowly reject the null of non-stationary at the trend. Generally, the results validate the presence of a unit root at the level and the absence of any of their first differences. Consequently, the panel data tests lead to the empirical conclusion of stationarity of the series at their first differences mostly at 1% conventional level of statistical significance.

4.2.1. Robustness check: second generation panel unit root

The results of panel unit roots of the first generation estimated in Table 3 under the assumption that the time series $y_{it} = (1 - \alpha_i)\mu_i + \alpha_i y_{i,t-1} + \varepsilon_{it}$ are independent across i and t (Breitung, Pesaran, 2005), have been associated with a number of limitations in the literature. First, it is observed over time that country or regional data are usually characterized by interdependence among individual series. Second, according to Phillips and Sul (2003), the assumption of cross-sectional independence among macroeconomic variables is perceived as rather restrictive and somewhat unrealistic. Thus, estimates based on these results usually lead to size distortions and low power (Banerjee et al., 2004, Strauss, Yigit, 2003).

In light of the foregoing, we employ the second-generation tests as robustness check to Table 3 in order to exploit the inherent co-movements among the group of cross-sectional variables as proposed by Bai and Ng (2004), Phillips and Sul (2003), Moon and Perron (2004), Choi (2001), Ploberger and Phillips (2002), Moon, Perron and Phillips (2003), Chang (2002) and Pesaran (2004) respectively.

Table 4. Second generation panel unit root

Variable	CADF		CIPS	
	Level	First difference	Level	First difference
GDPPC	-1.45	-2.85***	-2.25	-4.45***
CO ₂	-1.64	-2.67***	-1.32	-3.89***
ECP	-1.95	-3.03***	-1.82	-3.83***
GFCP	-1.69	-3.22***	-1.65	-2.86***

Note. *** indicates the level of statistical significant at 1%. Critical values are from Pesaran (2007). (#) Null hypothesis: the series are stationary.

Table 4 reports the results of Pesaran's CADF and CIPS panel unit root tests for the sake of cross-sectional dependence. We find that GDPPC, CO₂, ECP, and GFCP are not stationary at their levels; but are stationary at their first differences. Thus, we have enough evidence to reject the null hypothesis of unit roots. We can thus conclude that GDPPC, ECP, CO₂, and GFCP are series of integrated of order one.

4.3. Panel co-integration results

The confirmation of the panel variables being stationary at first difference, rather than at levels, avail us the opportunity to proceed to conduct the panel co-integration test. This is considered necessary in order to determine whether there exists a long-run equilibrium relationship among the empirical variables. Hence, we adopt the Pedroni and Kao co-integration tests to examine the long run relationship among economic growth, energy consumption and environmental contaminants with the intervening variable of the gross fixed capital formation. This is estimated by accounting for both 'with time' and 'without time' effects. These trend-effects are expedient to enable the model captures any disturbance that is common to different members of the panel, such as worldwide instabilities, crises, as well as international business cycles. Finally, while the Pedroni test comprises two dimensions (four within-dimension and three between-dimension), Kao co-integration test is based on ADF *t*-statistic.

Table 5. Results of panel co-integration (dependent variable: economic growth)

Pedroni co-integration	Model 1. Time effects			Model 2. No time effects		
	Within-dimension		Between-dimension	Within-dimension		Between-dimension
	<i>Statistics</i>	<i>Weighted Statistics</i>	<i>Statistics</i>	<i>Statistics</i>	<i>Weighted Statistics</i>	<i>Statistics</i>
Panel v-Statistic	0.83	-5.01	—	-0.954476	-1.897448	—
Panel rho-Statistic	0.65	0.53	—	1.952557	1.668594	—
Panel PP-Statistic	0.70	-3.31***	—	3.010491	2.174544	—
Panel ADF-Statistic	-0.35	-3.95***	—	1.802800	1.646518	—
Group rho-Statistic	—	—	1.80	—	—	3.726755
Group PP-Statistic	—	—	0.70	—	—	4.635006
Group ADF-Statistic	—	—	-0.45	—	—	3.701809

Note. *** indicates the level of statistical significant at 1%. (#) Null hypothesis: co-integration does not exist.

Table 5 presents the panel co-integration results for both the within and between dimensions under time and no time effects. It is pertinent to note that except for the panel variance (no time effects), the panel PP and panel ADF statistics significantly reject the null of no cointegration. Notwithstanding the amount of acceptance of the null hypothesis by other statistics, we give high preference to the panel PP and panel ADF¹⁰. Hence, we come to the empirical conclusion that there is a long-run equilibrium relationship between energy consumption, CO₂, gross fixed capital and GDP for a cross-section of G8 economies. The outcome is furthered corroborated with the result of the Kao residual co-integration test in Table 6.

Table 6. Kao residual co-integration test

ADF	-3.07***
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Note. *** indicates the level of statistical significant at 1%. (#) Null hypothesis: co-integration does not exist.

¹⁰ The panel-ADF and group-ADF tests have better small-sample properties than the other tests, and hence, they are more reliable (Pedroni, 1999). This also aligned with the empirical result of Lee and Chang (2008).

The result of Kao co-integration test in Table 6 fails to accept the null hypothesis of no co-integration in the panel. Hence, we can conclude that energy consumption, CO₂, gross fixed capital and GDP are co-integrated for the panel of G8 countries. It is intuitively plausible to state that economic progress of these industrialized nations appears to recline more on energy consumption, CO₂ and gross fixed capital formation.

Having established the existence of long-run relationship among these empirical variables, we proceed to estimate the model using the residual-based panel Fully Modified OLS (FMOLS) and Dynamic OLS (DOLS) estimators as advanced by Phillips and Moon (1999), Pedroni (2000, 2001), Kao and Chiang (2000). These estimators are confirmed to possess the quality of producing asymptotically unbiased and normally distributed coefficient estimates.

Table 7a. Fully modified OLS

	CO ₂	ECP	GFCP
Canada	-0.16***	10.83***	36.26***
France	-0.03***	-5.66***	16.29***
Germany	-0.13***	2.17	-0.82
Italy	-0.26***	53.45***	-3.12
Japan	-0.05	27.81**	-20.40***
Russia	1.00***	3.85E-13	-1.7E-11***
United Kingdom	-0.21***	18.23***	-17.30*
USA	0.03***	-18.79***	9.58**
Panel	-0.15***	10.31***	33.39***

Note. ***, **, * indicate the level of statistical significant at 1, 5 and 10%, in that order. (#) Null hypothesis: no significant relationship.

Table 7a presents both country-specific and panel FMOLS tests on the impactful roles of energy consumption, environmental degradation and gross fixed capital formation on economic growth of the G8 economies.

The panel result at the bottom of Table 7a depicts statistical significances of CO₂, ECP, and GFCP on economic growth. This occurs at the conventional 1% level. Both ECP and GFCP bear a positive relationship with GDPPC while CO₂ carries a negative sign, thus conforming to theoretical a priori of negative sign between economic growth and environmental degradation. The economic intuition is that a 1% increase in CO₂ emission tend to drag the pace of economic growth by 0.15%, while a 1% increase in energy consumption and gross fixed capital formation lead to corresponding increase 10.31 and 33.39% in GDP per capita of G8 economies. The observed positive relationship in energy-growth nexus is not in sync with recent empirical studies that have probed into the same level of relationship across developed and developing economies (Li et al., 2011; Shahbaz, Lean, 2012; Omri, 2013; Shabbir et al., 2014; Saidi, Hammami, 2015; Eregha, Messagan, 2017).

The negative sign in regard to CO₂-growth nexus duly conforms to the EKC hypothesis which has been well established in the empirical literature. Similarly, the positive impact of the capital variable on economic growth is in tandem with the previous strand of empirical growth literature for developed countries (Lee et al., 2008; Bartleet, Gounder, 2010; Saidi, Hammami, 2015).

Furthermore, at a country-specific level, we find CO₂ emissions to bear a negative relationship with economic growth of such countries like Canada, France, Germany, Italy, and United

Kingdom. This is suggestive of the need for these countries to accommodate more environmentally friendly and pollution-resistant policies in order to suppress the negative externalities caused by CO₂ emissions. In contrast, the positive statistical significance recorded for both Russia and USA is indicative of the effectiveness of policy measures enacted by these countries to minimize environmental pollution. For instance, the recent growth experience in the USA is a case in point as it has been able to decouple the country's economic growth from environmental degradation. That is, carbon emissions have tended to decline in the face of sustainable economic growth. To buttress this, the Economic Report of the USA (ERP-2017), suggests that CO₂ emissions from the energy sector fell by 9.5% while the economy grew by over 10%. Similarly, the signs on ECP and GFCP coefficients equally suggest that the use of energy and capital investment (in terms of accumulation and employment in production processes) significantly raise the level of outputs in these countries with the exception of Germany and Russia with statistically insignificant impacts. The negative statistical significance is also recorded for the USA. By and large, it is ostensibly clear that gross fixed capital formation exerts a significant impact on all the economies with the exception of Germany and Italy. While these impacts have divergent signs, it can arguably be said that gross fixed capital formation plays a crucial role in the growth process of the G8 countries. It can, therefore, be argued that the considered empirical variables exert significant influence on the economic growth of the G8 countries.

Table 7b. Dynamic OLS

	CO ₂	ECP	GFCP
Canada	-0.21***	12.98***	57.93***
France	-1.10	-0.11***	21.1**
Germany	-0.28*	55.20**	20.41
Italy	-0.24***	50.33***	-4.52
Japan	-0.05	27.81**	-20.4**
Russia	1***	3.33E-12	-3.8E-12
United Kingdom	-0.16***	17.88**	-20.9018**
USA	0.03***	-18.26***	8.86**
Panel	-0.11***	27.80***	-7.02**

Note. ***, **, * indicate the level of statistical significant at 1, 5 and 10%, in that order.

(#) Null hypothesis: no significant relationship.

The results in Table 7b do not significantly differ from that of FMOLS results. The panel result in the table displays a positive and significant impact of energy consumption on economic growth, while contrary signs are associated with CO₂ emissions and GFCP. Hence, a 1% increase in CO₂ emissions and GFCP will reduce output per capita by 0.11 and 7.02% respectively, while a 1% increase in energy will increase per capita GDP by 27.80%. In terms of CO₂, the same level of statistical significance and negative a-priori signs are observed for the G8 countries with the exception of Russia and USA. It is counterintuitive to observe that CO₂ in Japan has a positive but insignificant impact on her economic growth. Energy consumption is statistically significant for 7 of the G8 countries. Similarly, the results indicate that increased energy consumption is analogous to increased output in all the 7 countries with the exception of France and USA where the contrary results are obtained. A further examination of Table 7b re-

veals that GFCP exerts a positive and significant impact on output in Canada, France, and the USA but contrary signs are credited to Italy and UK. Conclusively, our estimation results from DOLS concur to both country-specific and panel group using FMOLS.

Summarily, the results of FMOLS and DOLS both confirm the statistical significance of the variables of interest in explaining variation observed in economic growth across the G8 countries. In view of our empirical results, we next test for causality among the variables by estimating a panel-based error correction model to test for the existence of short-run and long-run causality between energy consumption, CO₂ emission, GFCP and economic growth.

Table 8. Granger causality based on panel VECM estimations

Dependent variable	Source of causation (independent variable)				
			Short run		Long run
	GDPPC	CO ₂	ECPP	GFCP	ECT
GDPPC	—	0.373 (0.830)	1.305 (0.521)	5.057* (0.080)	−0.0002 (0.395)
CO ₂	0.0446 (0.978)	—	1.4362 (0.488)	0.234 (0.890)	0.0007 (0.674)
ECPP	1.634 (0.442)	56.721*** (0.0000)	—	1.335 (0.513)	0.000510 (0.975)
GFCP	4.389 (0.111)	2.496 (0.287)	0.681 (0.712)	—	−0.0557*** (0.0008)

Note. ***, * indicate the level of statistical significant at 1 and 10%, in that order. (#) Null hypothesis: no causal relationship.

The panel Granger causality results in Table 8 reveal variations in the causal relationships among the variables for G8 countries. From the results, it is apparent that while the majority of the estimates fail to reject the null hypothesis of no causality, a unidirectional causal relationship is observed in the following pairs of the considered variables.

There is a unidirectional causality running from GFCP to GDPPC, implying that capital formation induces a positive influence on economic growth in the G8 countries. This is intuitively plausible going by the level of industrialization in these countries which had foisted on them the most industrialized economies. This outcome further substantiates the earlier results obtained.

Similarly, a unidirectional causality is also observed between CO₂ and ECP, denoting that CO₂ emission causes the level of energy consumption in the G8 countries. This further supports the fact that the desire to maintain a healthy environment and minimizing the negative environmental pollutions tend to dictate the choice of energy type to be consumed in these countries. This is inconsonant with the green revolution being advocated and massively adopted in the developed economies like the G8. Worthy of note is the fact that the error correction term (ECT) for all the four models except the gross capital model does not conform to the a-priori expectation of negative and significant coefficient. This suggests the inexorable role of capital investment in explicating the relevance of energy consumption and CO₂ emission in the development process of the G8 economies. This undoubtedly validates the findings that G8 economies depend heavily on capital formations for their continued economic strides.

To account for individual country specific owing to their economic heterogeneities and peculiarities, we conduct a country-specific Granger causality test in Table 9.

Table 9. Country-level Granger causality estimations

Null hypothesis	Canada F-stat	France F-stat	Germany F-stat	Italy F-stat	Japan F-stat	Russia F-stat	UK F-stat	USA F-stat
CO ₂ does not Granger Cause GDPPC	5.55***	1.18	1.60	3.01*	1.60	1.60	1.67	0.78
GDPPC does not Granger Cause CO ₂	6.58***	3.67**	1.89	3.49**	0.55	0.55	4.62**	0.86
ECP does not Granger Cause GDPPC	2.47*	1.54	0.20	3.43**	1.81	1.81	1.28	0.49
GDPPC does not Granger Cause ECP	8.26***	1.68	6.22***	2.08	0.46	0.46	5.92***	1.97
GFCP does not Granger Cause GDPPC	0.85	0.56	2.16	0.24	1.68	1.68	0.12	0.46
GDPPC does not Granger Cause GFCP	0.03	0.49	4.23*	5.72***	3.24**	3.24**	4.03**	4.68**
ECP does not Granger Cause CO ₂	1.33	0.91	1.98	0.38	1.12	1.12	1.81	1.90
CO ₂ does not Granger Cause ECP	139.53	1.61	1.17	0.31	1.20	1.10	2.50*	2.20
GFCP does not Granger Cause CO ₂	1.45	1.77	1.64	0.45	0.11	0.11	0.23	0.81
CO ₂ does not Granger Cause GFCP	0.47	4.35**	0.64	3.57**	3.23**	3.27**	3.03*	1.80
GFCP does not Granger Cause ECP	1.17	3.70**	0.96	1.21	0.76	0.76	0.97	0.25
ECP does not Granger Cause GFCP	2.12	0.76	2.06	3.01*	3.68**	3.68**	1.37*	1.24

Note. ***, **, * indicate the level of statistical significant at 1, 5 and 10%, in that order. (#) Null hypothesis: no causal relationship.

From Table 9, it can be inferred that the existence of bidirectional causality is evident in the relationship between CO₂ and GDPPC for Canada and Italy; GDPPC and CO₂ for France and UK. For other levels of relationship, a unidirectional causality is palpable; between ECP and GDPPC in Canada; GDPPC and ECP in Germany and UK; ECP and GDPPC in Italy; GDPPC and GFCP in Germany, Italy, Japan, Russia, UK and USA. A related level of causality is evident between CO₂ and ECP in the UK; CO₂ and GFCP in France, Italy, Japan, Russia, and the UK; GFCP and ECP in France, Japan, Russia, and the UK. The overall estimation supports the existence of at least minimum causal relationships in each country.

Table 10. Diagnostic tests results

	χ^2 -statistic	Probability
Jarque–Bera test	4.34	0.11
Wald test	13.62	0.00
Breusch–Godfrey serial correlation test	6.28	0.179
White heteroskedasticity test	9.29	0.597

The model for the underlying regression as stated in Table 10 fulfills the stated criteria examined by the diagnostic tests. The serial correlation estimated by the Breusch–Godfrey test suggests that the model is free from serial correlation indicating that the model is reliable in explaining the relationship the regressors and the explanatory variables. Similarly, the White heteroscedasticity test reveals that the disturbance term in the equation is equally homoscedastic. Going by the result of the Jarque–Bera test, the null hypothesis of normally distributed residuals cannot be rejected. The combined significance of the variables specified in the model as indicated by the Wald test further strengthens our overall conviction concerning the validity and correctness of the results obtained.

Table 11. Empirical findings at a glance

Empirical inquiry	Variable of interests	Estimation technique	Null hypothesis	Overriding results	Reference points
Cross-section dependence tests	CO ₂ , ECPP, GDPPC, GFCP	Breusch–Pagan LM test Pesaran CD test	No cross-sectional dependence	We fail to reject the null hypothesis	Table 2
Stationarity at level		Levin–Lin–Chu test, Im–Pesaran–Shin test, Breitung test, Fisher-ADF test, Fisher-PP test	The series is stationary	We fail to reject the null hypothesis	Table 3
Stationarity at first difference		Levin–Lin–Chu test, Im–Pesaran–Shin test, Breitung test, Fisher-ADF test, Fisher-PP test	The series is stationary	We reject the null hypothesis	Table 3
Panel co-integration test		Pedroni tests	Co-integration does not exist	We reject the null hypothesis	Table 5
		Panel co-integration test Kao co-integration test	Co-integration does not exist	We reject the null hypothesis	Table 6
Panel co-integration estimation		Residual-based panel Fully Modified OLS	No significant relationship	We reject the null hypothesis	Table 7a
		Dynamic OLS	No significant relationship	We reject the null hypothesis	Table 7b
Panel causal test		Granger Causality based on panel VECM estimations	No causal relationship	We reject the null hypothesis	Table 8
Country-level causality test		Pairwise Granger Causality tests	No causal relationship	We reject the null hypothesis	Table 9
Diagnostic tests		Jarque–Bera test Wald test	Residuals are normally distributed Coefficients of equal to zero	We fail to reject the null hypothesis We reject the null hypothesis	Table 11

5. Conclusion and policy implications

The study investigates the impact of energy consumption, CO₂ emission and gross fixed capital formation on economic growth of the designated G8 countries. Prior to estimation, the variables are tested for stationarity and found not to be stationary at levels but at their first differences. We also estimate the panel unit root tests under the assumption of cross-sectional dependence and independence. The panel co-integration based on Pedroni (1999) and Kao (1999) are equally deployed to ascertain if a long-run relationship exists or not among these variables. We find long run co-integration to exist among these variables. This avails the study the opportunity to estimate the causal relationships among the series using both Fully Modified and Dynamic OLS estimators. Also, a residual based panel vector error correction model (VECM) is employed to further uncover the short-run dynamics over the period spanning 1960 through 2015. Keeping the primary goal of the study in mind, we find the co-integration test of Pedroni and Kao endorsing the existence of a long run relationship among the variables. Both the Fully Modified OLS and Dynamic OLS jointly support the existence of statistically significant relationships among the variables of interest. While both the CO₂ and GFCF bear negative signs in the panel of Dynamic OLS on the one hand, only CO₂ appears to be negative in the panel of the Fully Modified OLS on the other hand. The positive and significant relationship exert by energy consumption on economic growth in G8 countries are suggestive of the energy-dependent nature of these economies. The direction of causality is divergent both from the panel and country-specific estimates. In conclusion, the error correction term of the panel VECM appears to be negative and statistically significant only for gross fixed capital formation thus suggesting its useful role in the development process of the respective economies.

Policy implications emanating from this study are: first, since capital investments remain one of the avenues that contribute substantially to environmental degradation in the G8 countries, it is thus advised that energy efficient capital investments should be embraced. This is considered important as governments in the G8 countries need more pragmatic measures of minimizing environmental pollutants that will further support the ongoing campaign on carbon emissions control. Second, the G8 economies should also embrace some incentive-based policy frameworks in order to encourage industries to adopt a cleaner and greener source of energy in their daily production activities. Third, the G8 economies should totally key into renewable sources of energy as they are still currently relying on environmental unfriendly sources of generating electricity. This is particularly so as they are considered to be cheaper as compared to renewable energy sources. The use of these environmentally damaging sources of energies can be discouraged using carbon taxes and use their proceeds to subsidize the installation of alternative, renewable energy sources like the windmill, solar and biomass. Lastly, there should be a massive investment into public awareness programs on the need to reduce dependence on fossil fuels and why the green economy should be enhanced using green technologies and investments.

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