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Nuclear Energy-Economic Growth Nexus in OECD Countries: A Panel Data Analysis

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ABSTRACT

In this study, our purpose was to analyze the relationship between nuclear energy consumption and economic growth in 13 OECD countries from 1980 to 2012, based on the framework of panel cointegration and causality analyses. The panel causality results supported the feedback hypothesis in both the short-run and long-run. In other words, there is a positive relationship between nuclear energy consumption and economic growth. As such, nuclear energy consumption and economic growth complement and reinforce each other, and thus nuclear energy conservation policies may negatively affect the economic growth rates of OECD countries under study. Besides, the long-run estimation results indicated that nuclear energy consumption has a positive and significant impact on real GDP in 6 out of 13 countries, namely Germany, Netherlands, Sweden, UK, Switzerland, and South Korea. Also, for the whole OECD panel set, the long-run results indicated that labor force, physical capital and nuclear energy consumption have positive and significant impacts on the economic growth. Based on the findings, important policy implications were also provided.

JEL Classification: C50; Q42; Q43.

Keywords: Nuclear Energy; Economic Growth; Panel Causality Test; Panel Cointegration Test.

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1. INTRODUCTION

While it is expected that global energy demand will grow strongly in the coming years, many questions are waiting to be answered about the future of energy supply, the economic competitiveness of different energy sources, and the concerning environmental effects (World Energy Council, 2007). As such, producing energy in a more efficient and durable way and reducing its environmental effects is of critical importance for the future of the planet while energy is, and will be, an essential factor of development in the 21st century (Fiore, 2006). Based on the increasing importance of energy demand, a transition from fossil fuels to renewable (i.e. hydroelectricity, solar, wind, and biomass) and to nuclear energy types is one of the main priorities of long-term energy and environmental policies. Further, recent developments and debates have revitalized interest in the role of nuclear energy as a viable energy source (Apergis and Payne, 2010; Chu and Chang, 2012; Naser, 2013; Nazlioglu et al., 2011; Tsou and Huang, 2012), such as the existence of high levels of greenhouse gas (GHG) emissions produced from fossil fuel energy sources, the high volatility of oil and gas prices on international markets, questions about sustainability of oil reserves, the uncertainty surrounding the political stability of oil-producing countries, increasing energy demand all over the world, and energy safety. These factors are forcing countries to find clean, stable, and safe energy in order to end the dependence on fossil fuel, to enhance global energy security, to promote economic growth, and to prevent climate change (Toth and Rogner, 2006; Tsou and Huang, 2012; Wolde-Rufael, 2010).

As countries sought to reduce their dependence on fossil fuels, nuclear capacity grew rapidly in the 1970s and 1980s, especially after the oil crises in the 1970s (IEA, 2010). Oil prices doubled and even tripled in many countries during the energy crises in the 1970s, and economic performance and international competitiveness of imported energy–dependent countries deteriorated because their production costs increased and export competitiveness declined (Lee and Chiu, 2011b). Thus, as stated by Lee and Chiu (2011a), many oil-importing countries began to pay special interest to the stability of their oil supplies after the energy crises in the 1970s. They took politic precautions against the fluctuations of prices and the instability of oil supplies, such as oil reservation mechanisms, the improvement of energy consumption efficiency, and the development of substitute energy for oil, e.g., nuclear energy. Today, more than 430 commercial nuclear power reactors are operating in 31 countries and almost 70 more reactors are under construction (World Nuclear Association, 2014b). About 6% of the world's energy and 13–14% of the world's electricity are provided by nuclear power plants (Energy.gov., 2013).

Because of the above-mentioned developments in the nuclear energy area, it is insightful to investigate the relationship between nuclear energy consumption and economic growth to understand why countries need to invest in nuclear energy for economic, environmental, and social concerns (Chu and Chang, 2012; Nazlioglu et al., 2011). As such, it is expected that nuclear energy will be an important part of the strategy towards sustainable energy development and meet a significant part of the energy needs in many countries (Wolde-Rufael and Menyah, 2010). Therefore, there is a clear revival of nuclear energy in long-term projections to fill the gap between the current capacity and the world future energy needs without increasing GHG emissions (Vaillancourt et al., 2008). However, some analysts believe that nuclear energy does not fulfill all essential requirements for creating sustainable energy paths (Toth and Rogner, 2006), and there are doubts and risks surrounding the nuclear energy sector, such as the risk of proliferation of nuclear material, the peril of terrorism, operational safety, and radioactive waste disposal (Apergis and Payne, 2010; Toth and Rogner, 2006; Vaillancourt et al., 2008). These shortcomings contribute to a generally low social acceptance of nuclear energy and a negative public perception.

In the empirical analyses, there is a lack of consensus on the direction of causality between nuclear energy consumption and economic growth. In this paper, we aim to fill this gap in the literature by analyzing the economic growth–nuclear energy nexus within a panel data framework in 13 OECD countries. We contribute to the literature in two aspects: First, to our knowledge, there is only one panel study (Apergis and Payne, 2010) using the same model in this study and employing the panel cointegration test and panel error correction model to analyze the nuclear energy consumption-economic growth nexus. Second, we differ from them using different panel unit root and cointegration tests allowing for cross-sectional dependency. Taking into account the cross-sectional dependency across OECD countries is of critical importance. They are highly integrated and correlated with each other due to globalization and international linkages, and thus they can transmit their shocks to each other. In other words, "a shock that affects one country may spillover on other countries" (Nazlioglu et al., 2011, p. 6618).

The remainder of this paper is organized as follows: Sub-section 1.1 provides a short explanation about the hypotheses relating to the energy consumption-economic growth nexus and the structure of nuclear energy sector in the selected OECD countries. In Sub-section 1.2, a brief literature review is provided. Data and model are explained in Section 2, while methodology is presented in Section 3. Section 4 describes the empirical findings in details, and Section 5 concludes the study with important policy implications.

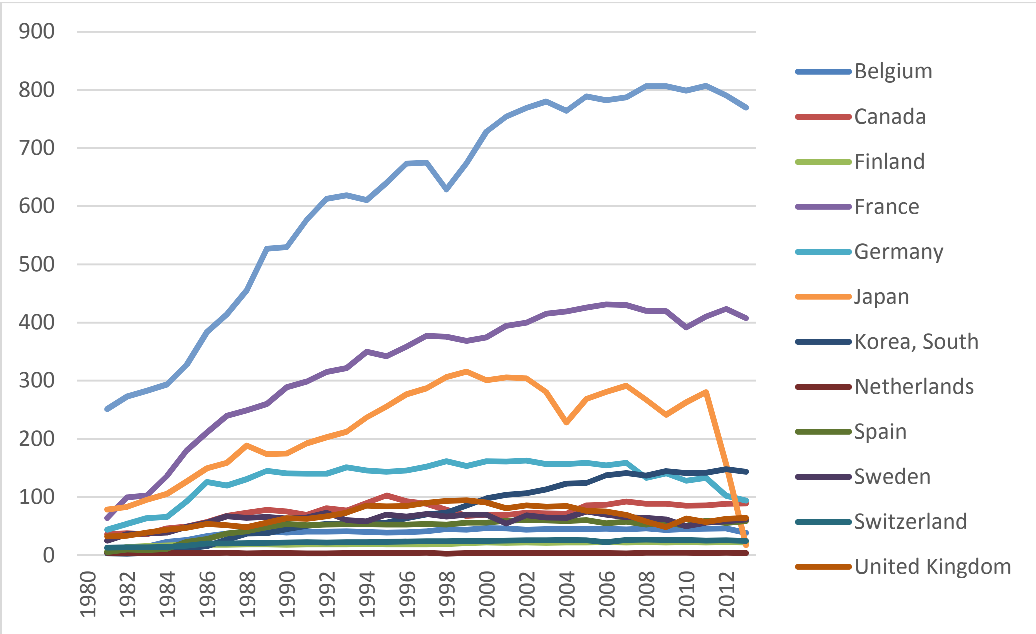
1.1 Related Hypotheses and the Nuclear Energy Sector in the Selected OECD Countries

Regarding the theoretical base, four hypotheses concern nuclear energy consumption-economic growth nexus; growth hypothesis, conservation hypothesis, feedback hypothesis, and neutrality hypothesis. The growth hypothesis indicates a unidirectional causality running from nuclear energy consumption to economic growth. This hypothesis assumes that energy consumption can have a direct and/or indirect impact on economic growth as a complement to labor and capital in the production process (Apergis and Payne, 2010). In this case, reducing nuclear energy consumption could lead to a fall in economic growth. The conservation hypothesis is confirmed if there is a unidirectional causality from economic growth to nuclear energy consumption. In this case, policies aimed at reducing nuclear energy consumption may be implemented with little or no adverse effect on economic growth. The feedback hypothesis is supported if there is a bidirectional causality between nuclear energy consumption and economic growth, and in this case, nuclear energy and growth complement and reinforce each other. The neutrality hypothesis postulates that there is no significant relationship running in any direction. In this case, reducing nuclear energy consumption may not affect economic growth, and nuclear energy conservation policies may be implemented without damaging the economic growth. Thus, evidence of a significant relationship in any direction has a significant bearing upon policy.

OECD countries are of special interest owing to their high levels of nuclear energy dependence. According to the World Nuclear Association (2014), the electricity power from nuclear energy is around three quarters in France and more than one quarter in Japan. Besides, Belgium, Czech Republic, Hungary, Slovakia, Sweden, Switzerland, Slovenia, and Ukraine obtain one-third or more of their power from nuclear energy; South Korea, Bulgaria, and

Finland normally get more than 30%; and the US, UK, Spain and, Russia obtain one-fifth of their power from nuclear. Therefore, we chose the following 13 OECD countries based on the data availability: Belgium, Canada, France, Germany, Netherlands, Spain, Sweden, United Kingdom (UK), United States (US), Japan, Switzerland, Finland and South Korea. Of these countries, the US has more nuclear capacity and obtains more electricity from nuclear power than any other nation. France has the second highest nuclear capacity and relies on nuclear power for nearly 80% of its electricity generation (EIA, 2012).

Figure 1 shows the nuclear electricity generation for 13 OECD countries under study from 1980 to 2012. As illustrated, the US, France, Japan and Germany have the four highest levels of nuclear electricity net generation. As of June 2015, the number of nuclear units in the US, France, Belgium, Canada, Germany, Netherlands, Spain, Sweden, UK, Japan, Switzerland, Finland and Korea Republic are 99, 58, 7, 19, 9, 1, 7, 10, 16, 43, 5, 4 and 24, respectively (World Nuclear Association, 2015).



Source: Energy Information Administration (EIA), (access date: 02.06.2015 at www.eia.gov.tr)

Figure 1.
Nuclear Electricity, Net Generation (Billion Kilowatt-hours)

2. LITERATURE REVIEW

The pioneering study of Kraft and Kraft (1978) is the first search for energy consumption and economic growth nexus in an empirical base. Since then, other empirical studies have used different energy types (such as oil, natural gas, electricity, renewable energy, etc.) for different countries by using different methods and time periods[1]. However, there is a lack of unanimity about the direction of causality between energy consumption and economic growth in the literature. Though many empirical studies analyze the aggregate energy consumption–economic growth nexus, there are few studies on the nuclear energy consumption–economic growth nexus. However, because of the importance of nuclear energy as a potential source of energy security and a virtually carbon-free source of energy, the number of studies using alternative testing methodologies to examine the causality chain between nuclear energy consumption and economic growth has increased (Naser, 2013; Wolde-Rufael and Menyah, 2010). We can classify empirical studies based on their methodologies as time series and panel data studies.

[1] See. Ozturk (2010) and Payne (2010) for the literature review on energy consumption–economic growth relationship.

The first research strand includes time series studies that examine the nuclear energy consumption–GDP nexus directly. Some of them handle the issue in a bivariate case, while others also include additional variables such as labor force and capital. They generally apply causality tests (such as Granger, 1969 or Toda and Yamamato, 1995; TY hereafter), generalized impulse-response and variance-decomposition methods in a single or multi-country base. For instance, Wolde-Rufael and Menyah (2010), Yoo and Ku (2009) and Naser (2015) are the multi-country studies which supported a different hypothesis for each country in their samples. Among single-country studies, Wolde-Rufael (2012) for Taiwan and Payne and Taylor (2010) for the US found evidence to support the neutrality hypothesis. However, Wolde-Rufael (2010) for India, and Yoo and Jung (2005) for Korea supported the growth hypothesis. Last, Lin et al. (2015) supported the neutrality hypothesis and the growth hypothesis in the case of linear and nonlinear causality tests for Taiwan, respectively. Additionally, as a recent study, Aslan and Cam (2013), using a different bootstrap based causality test developed by the Hacker and Hatemi-J (2006) for Israel, substantiated the growth hypothesis.

In this line, there are also time series studies that analyze the causality between nuclear energy consumption and economic growth in an indirect way by including oil consumption, oil price, renewable energy consumption and CO2 emissions variables. Some of them want to expose the substitute or complementary effects between oil, renewable energy and nuclear energy (see Lee and Chiu, 2011b; Tsou and Huang, 2012; Naser, 2013, 2014), while the others' aim is to search the impact of each energy type on economic growth and CO2 emissions (see Menyah and Wolde-Rufael, 2010 for the US). The second strand consists of studies applying panel data models such as panel cointegration tests and panel error correction models. Many of them test the relationship between nuclear energy consumption and economic growth including CO2 emissions and energy types such as renewable energy and fossil fuel energy (see Apergis et al., 2010; Alam, 2013; Al-Mulali, 2014).

The prior aim is to search the impact of each energy type on CO2 emissions and economic growth. For instance, Apergis et al. (2010) examined the issue for a group of 19 developed and developing countries and supported the feedback hypothesis in the short-run. However, Alam (2013) for the panel consisting of 25 countries and Al-Mulali (2014) for 30 developed and developing countries (in the case of growth model and in the short-run) obtained convincing evidence on the neutrality hypothesis. There are also panel studies including oil price and oil consumption as control variables to define the substitute or complementary effects between oil and nuclear energy (see Lee and Chiu, 2011a). Lee and Chiu (2011a) obtained evidence of the conservation hypothesis in the long-run and the neutrality hypothesis in the short-run in 6 developed countries.

In the second research line, there are also panel studies employing different causality tests such as the bootstrap based causality tests developed by Konya (2006) (see Nazlioglu et al., 2014; Chu and Chang, 2012; Akhmat and Zaman, 2013; Chang et al., 2014) and Emirmahmutoglu and Kose (2011) (see Chang et al., 2014). Nazlioglu et al. (2011) analyzed the issue in 14 OECD countries and obtained results favorable to the neutrality hypothesis in 11 out of 14 cases. Furthermore, the growth hypothesis appeared to be valid in the UK and Spain, whereas the conservation hypothesis was supported in Hungary. In the same vein, Chu and Chang (2012) found evidence of the growth hypothesis in Japan, UK, and the US; the conservation hypothesis in the US; and the neutrality hypothesis in Canada, France, and Germany. In addition, Akhmat and Zaman (2013), employing the same test for South Asian countries, supported the conservation hypothesis in India, Nepal, and Srilanka and the growth hypothesis in Bangladesh, Nepal, and Pakistan. Besides, by using a different panel test, Chang et al. (2014) confirmed the feedback hypothesis for the UK, the growth hypothesis for the Germany, and the neutrality hypothesis for the rest of the countries.

To our knowledge, there is only one panel study, developed by Apergis and Payne (2010), similar to ours, i.e. using the same model. Apergis and Payne (2010), including labor and capital as control variables in the framework of panel cointegration and panel error correction model, found evidence favorable to the feedback hypothesis in the short-run and the growth hypothesis in the long-run in 16 countries. However, we differ from them by taking cross-sectional dependence into account in our testing procedure and using different unit root and cointegration tests. To conserve space, a detailed explanation on literature review could not be provided. However, the findings, methods, samples, and periods of studies in the literature were summarized in Table 1.

Table 1. The Summary of Empirical Studies in the Literature

Study	Period	Sample	Additional variables	Method	Causality
Yoo and Jung (2005)	1977–2002	Korea	No	Cointegration and Granger causality	NE→Y
Yoo and Ku (2009)	1965–2005	6 countries	No	Cointegration and Granger noncausality	Y→NE: France, Pakistan NE→Y: Korea NE↔Y: Switzerland NE≠Y: Argentina, Germany
Apergis and Payne (2010)	1980–2005	16 countries	Capital and labor	Panel cointegration and panel VEC	In short-run: NE↔Y In long-run: NE→Y
Apergis et al. (2010)	1984–2007	19 developed and developing countries	CO_2 emissions, renewable energy	Panel cointegration and panel VEC model	NE↔Y
Payne and Taylor (2010)	1957–2006	US	Capital and labor	TY procedure	NE≠ Y
Menyah and Wolde-Rufael (2010).	1960–2007	US	CO_2 emissions, renewable energy	TY procedure	NE≠ Y
Wolde-Rufael and Menyah (2010)	1971–2005	9 developed countries	Capital and labor	TY causality test, GIR, GVD	NE→Y: Japan, Netherlands and Switzerland Y→NE: Sweden, Canada NE↔Y: France, Spain, UK, and the US.
Wolde-Rufael (2010)	1969–2006	India	Capital and labor	Bounds cointegration test and TY causality test	NE→Y
Lee and Chiu (2011a)	1971–2006	6 developed countries	Oil price, oil consumption	Panel cointegration, panel VEC	In the short run: NE≠ Y In the long-run: Y→ NE
Lee and Chiu (2011b)	1965–2008	6 highly industrialized countries	Oil price, oil consumption	TY causality test, GIR and GVD	Y→ NE: Japan NE↔Y: Canada, Germany, U.K NE≠ Y: France and the U.S.
Aslan and Cam (2013)	1985–2009	Israel	Capital and labor	Hacker and Hatemi-J (2006) causality test	NE→Y

Table 1. Continued

Chu and Chang (2012)	1971–2010	G-6 countries	Oil consumption per capita	Konya (2006) causality test	NE→Y: Japan, UK Y→NE: US NE≠ Y: Canada, France, Germany
Nazlioglu et al. (2011)	1980–2007	14 OECD countries	Capital and labor	Konya (2006) causality test	NE→Y:UK, Spain Y→ NE: Hungary NE≠Y: other countries
Tsou and Huang (2012)	1984–2008	13 OECD countries	Real oil price, renewable energy consumption	TY procedure	NE→Y: Finland, Germany, UK Y→NE: Spain
Wolde-Rufael (2012)	1977–2007	Taiwan	Capital and labor	TY causality test, GIR, GVD	NE≠ Y
Akhmat and Zaman (2013)	1975–2010	8 South Asian Countries	commercial energy consumption	Konya (2006) causality test	Y→NE: India, Nepal, and Srilanka NE→Y: Bangladesh, Nepal, and Pakistan
Naser (2013)	1965–2010	4 industrialized and 4 emerging countries	Oil price, oil consumption	TY procedure	NE→Y: India, Korea, Japan Y→NE: China, France NE≠ Y: Russia
Alam (2013)	1993-2010	25 developed and developing countries	CO_2 emissions	Panel cointegration and panel VEC	NE≠ Y: in both the short-run and the long-run
Al-mulali (2014)	1990-2010	30 developed and developing countries	CO_2 emissions, fossil fuel energy consumption, domestic investment, labor force and urbanization	Panel cointegration and panel VEC	NE→Y for the CO_2 model and NE≠Y for the GDP model in the short-run.
Chang et al. (2014)	1971-2011	Six developed countries (G6)	No	Emirmahmutoglu and Kose (2011) panel test	NE↔Y: UK NE→Y Germany NE≠Y Others
Naser (2014)	1965-2010	Four emerging markets	Oil consumption and oil price	TY procedure	NE≠Y: Russia NE→Y: South Korea and India Y→NE: China

Table 1. Contiuned

Naser (2015)	1965-2010	US, Canada, Japan and France	Oil consumption, oil price	TY procedure	NE→Y: Japan Y→NE: France NE≠Y: US and Canada
Lin et al. (2015)	1980-2010	Taiwan	Non-nuclear energy consumption	Granger causality test and Hiemstra and Jones (1994) causality test	NE≠Y: Granger test NE→Y: Hiemstra and Jones (1994) test

Notes: →, ↔, and ≠ represent unidirectional, bidirectional, and no causality relationship, respectively. NE: nuclear energy consumption. Y: real GDP. TY: Toda-Yamamoto causality test. VEC: vector error correction. GIR: generalized impulse-response function. GVD: generalized forecast error variance decomposition.

3. DATA AND MODEL

In this study, we use annual data from 1980 to 2012 and measure all variables in their natural logarithms to reduce the heterogeneity of data. Our sample of countries consists of the following 13 OECD countries: Belgium, Canada, France, Germany, Netherlands, Spain, Sweden, UK, US, Japan, Switzerland, Finland, and South Korea. The selection of time period and country sample was dictated by data availability. We use real gross fixed capital formation and labor force as control variables since nuclear energy alone might not be strong enough to spur economic growth and to avoid omitted variable bias (Wolde-Rufael and Menyah, 2010). Also, in an empirical analysis, exclusion of relevant variables could cause biased and inconsistent estimations and no-causality results in a bivariate system (Lutkepohl, 1982). In other words, “the bivariate models with energy consumption and real income may be biased and “unfortunately blurry” due to the omission of other variables . . .” (Lee and Chiu, 2011b, p.237). Regarding the capital variable, we are in line with many researchers (see Apergis and Payne, 2010; Lee et al., 2008; Narayan and Smyth, 2008; Soytas et al., 2007; Soytas and Sari, 2007, 2009; Wolde-Rufael, 2010, 2012) and use real gross fixed capital formation (2005 US dollar) as a proxy for the stock of physical capital due to the absence of capital stock. In addition, we use real GDP (2005 US dollar) instead of GNP as a proxy for economic growth given that nuclear energy consumption depends upon goods and services produced within the country, not outside the country (Yoo and Ku, 2009). Nuclear energy consumption is measured in terms of tera-Watt hours (TWh), while total labor force is measured in thousands. The real GDP and real gross fixed capital formation data are from the World Bank Development Indicators (2014), while nuclear energy consumption is from the British Petroleum Statistical Review of World Energy (2013) and the labor force is from the Conference Board and Groningen Growth and Development Centre (2013).

Besides, we utilized a panel data model given that panel data has many advantages over time series data. First, panel data produces more reliable and powerful results than time series by combining information from both cross-section and time dimensions. In addition, contrary to time series and cross-section data, panel data controlling individual heterogeneity allows for more informative data, more variability, less collinearity among the variables, more degrees of freedom, and more efficiency (Baltagi, 2005). The panel unit root test, panel cointegration test, and panel causality test based on a panel vector error correction model are the stages of this study. We empirically test the following model based on variables in their natural logarithms:

$$Y_{it} = \alpha_{it} + \beta_{1i} NE_{it} + \beta_{2i} L_{it} + \beta_{3i} C_{it} + \varepsilon_{it} \qquad (1)$$

Where $i = 1,2,....,N$ denotes the number of individual members in the panel, $t = 1,2,.....,T$ refers to the time period. NE_{it} is the nuclear energy consumption; L_{it} stands for labor force, while C_{it} represents real gross fixed capital formation. Given that all variables are expressed in their natural logarithms, the β_{1i}, β_{2i}, and β_{3i} parameters can be interpreted as elasticities. The signs of β_{1i}, β_{2i}, and β_{3i} are expected to be positive, as increases in nuclear energy consumption, labor force, and real gross fixed capital formation generally result in increases in real GDP.

4. METHODOLOGY

4.1 Cross-Sectional Dependency, Unit Root and Cointegration Tests

As a first step of analysis, we tested for cross-sectional dependency for each variable and model as OECD countries under scrutiny are highly integrated. For this purpose, we utilized the Lagrange multiplier test ($CDLM_1$) proposed by Breusch and Pagan (1980). As stated by Haggar (2012), this test is favorable to the other cross-sectional dependency (CD) tests, i.e. CD tests of Frees (1995) and Pesaran (2004) in case that T is larger than N. The $CDLM_1$ test is based on the sum of squared coefficients of correlation among cross-sectional residuals obtained through OLS and the test statistic can be calculated as $CD_{LM1} = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}$, herein $\hat{\rho}_{ij}$ denotes the sample estimate of the cross-sectional correlation among residuals. Under the null hypothesis of no-cross sectional dependency, the $CDLM_1$ statistic is distributed as chi-squared with N (N-1)/2 degrees of freedom. The presence of cross-sectional dependency led us to implement a second generation panel unit root test developed by Pesaran (2007). Pesaran's (2007) test is a cross-sectionally augmented version of the unit root test of Im et al. (2003) and is favored over all other tests due to its simplicity and clarity (Haggar, 2012). The procedure of the Pesaran (2007) test is formulated as in Eq. (2).

$$\Delta y_{it} = c_i + \alpha_i y_{i,t-1} + \beta_i \bar{y}_{t-1} + \sum_{j=0}^{p}\gamma_{ij}\Delta\bar{y}_{t-j} + \sum_{j=1}^{p}\delta_{ij}\Delta y_{i,t-j} + \varepsilon_{it} \quad (2)$$

Where $i = 1,2,.....,N$, c_i is a deterministic term, $\bar{y}_{t-1} = N^{-1}\sum_{i=1}^{N} y_{it-1}$ cross-section mean of y_{it-1} and p is the lag order. The test of unit root is based on the t-ratio of the OLS estimate of α_i ($\hat{\alpha}_i$). Taking the simple arithmetic averages of each series, Pesaran (2007) computed the CIPS statistic as $CIPS(N,T) = t - bar = N^{-1}\sum_{i=1}^{N} t_i(N,T)$, where $t_i(N,T)$ is the CADF (cross- sectionally augmented Dickey-Fuller) statistic for the ith cross-section unit given by the t-ratio of α_i. The CIPS statistic does not show standard normal distribution; thus, Pesaran (2007) calculated the critical values by means of simulation.

We implemented the panel bootstrap cointegration test developed by Westerlund and Edgerton (2007, WE hereafter). The WE cointegration test is based upon the popular Lagrange multiplier test of McCoskey and Kao (1998) and has the null hypothesis of cointegration. It utilizes bootstrap property to allow for correlation both within and between the individual cross-section units. It is based on the sieve-sampling scheme and simulation results indicated that it reduces the distortions of the asymptotic test. In addition, it is shown that it has good performance in small samples. The scalar variant y_{it} is given by:

$$y_{it} = \alpha_i + x'_{it}\beta_i + z_{it} \quad (3)$$

Where $t = 1,2,.........,T$ and $i = 1,2,......,N$ represent the time series and cross-sectional units, respectively. The vector x_{it} contains the regressors, i.e. NE_{it}, L_{it}, and C_{it} while y_{it} represents Y_{it} in this study. The regressors are assumed to follow pure random walk process. The error term z_{it} has the data components representation as $z_{it} = u_{it} + v_{it}$ with $v_{it} = \sum_{j=1}^{t}\eta_{ij}$, where η_{ij} is an independent and identically (i.i.d) process with zero mean and variance $(\eta_{it}) = \sigma_i^2$.

4.2 Estimation of Long-Run Parameters

Based on the presence of cointegration, we computed the long-run parameters in the cointegrating vector. To this aim, we utilized Pedroni's (2000) heterogeneous FMOLS estimator. However, first, to solve cross-sectional dependency problem, we demeaned the data with respect to common time effects since the FMOLS estimator does not take cross-sectional dependency into account. The FMOLS estimator has a great advantage because it corrects both the endogeneity bias and the serial correlation, and therefore a consistent and an efficient estimation of the long-run relationship is obtained. There are three versions of the panel FMOLS estimator: The estimators of the residual-FM and adjusted-FM pool the data along the within-dimensions, while the estimator of the group-FM pools the data along the between-dimension (Pedroni, 2001). In this study, we obtained the results from the group-FM. It has a special advantage because it allows for greater flexibility in the existence of heterogeneity in the cointegrating vectors. Furthermore, Pedroni (2000) asserted that the group-FM has relatively minor size distortions in small sample in comparison to the other estimators. In addition, test statistics computed from the within-dimension estimators test the null hypothesis $H_0 : \beta_i = \beta_0$ for all i against the alternative hypothesis $H_A : \beta_i = \beta_A \neq \beta_0$. However, test statistics constructed from the between-dimension estimators test the null hypothesis $H_0 : \beta_i = \beta_0$ for all i against the alternative hypothesis $H_A : \beta_i \neq \beta_0$, where the parameters of β_i in Eq. (1) do not need to be same under the H_A. The group-FM estimator can be computed as $\hat{\beta}^*_{GFM} = N^{-1}\sum_{i=1}^{N}\hat{\beta}^*_{FM,i}$, where $\beta^*_{FM_i}$ represents the time series FMOLS estimation of Eq. (1) for each country.

4.3 Panel Causality Analysis

We utilized a panel based error correction model by following the two steps of Engle and Granger (1987) to expose Granger causality among the variables in both the long-run and the short-run. To this aim, we estimated Eq. (1) via the FMOLS estimator and obtained the residuals to define the first-lagged residuals as the error correction term. Besides, we used the time demeaned data to solve the cross-sectional dependency problem in causality test. Then, we estimated the following dynamic error correction model (4a–4d):

$$\Delta Y_{it} = \alpha_{1i} + \sum_{k=1}^{m}\theta_{11ik}\Delta Y_{it-k} + \sum_{k=1}^{m}\theta_{12ik}\Delta NE_{it-k} + \sum_{k=1}^{m}\theta_{13ik}\Delta L_{it-k} + \sum_{k=1}^{m}\theta_{14ik}\Delta C_{it-k} + \gamma_{1i}ECT_{it-1} + u_{1it} \quad \text{(4a)}$$

$$\Delta NE_{it} = \alpha_{2i} + \sum_{k=1}^{m}\theta_{21ik}\Delta NE_{it-k} + \sum_{k=1}^{m}\theta_{22ik}\Delta Y_{it-k} + \sum_{k=1}^{m}\theta_{23ik}\Delta L_{it-k} + \sum_{k=1}^{m}\theta_{24ik}\Delta C_{it-k} + \gamma_{2i}ECT_{it-1} + u_{2it} \quad \text{(4b)}$$

$$\Delta L_{it} = \alpha_{3i} + \sum_{k=1}^{m}\theta_{31ik}\Delta L_{it-k} + \sum_{k=1}^{m}\theta_{32ik}\Delta Y_{it-k} + \sum_{k=1}^{m}\theta_{33ik}\Delta NE_{it-k} + \sum_{k=1}^{m}\theta_{34ik}\Delta C_{it-k} + \gamma_{3i}ECT_{it-1} + u_{3it} \quad \text{(4c)}$$

$$\Delta C_{it} = \alpha_{4i} + \sum_{k=1}^{m}\theta_{41ik}\Delta C_{it-k} + \sum_{k=1}^{m}\theta_{42ik}\Delta Y_{it-k} + \sum_{k=1}^{m}\theta_{43ik}\Delta NE_{it-k} + \sum_{k=1}^{m}\theta_{44ik}\Delta L_{it-k} + \gamma_{4i}ECT_{it-1} + u_{4it} \quad \text{(4d)}$$

Where the term Δ indicates the first differences, m is the lag length set at three, which is based on the Akaike information criterion. The variables in logarithmic differences refer to the growth rates of variables of interest. ECT stands for error-correction term, γ_{ji} $(j = 1,2,3,4)$ is the adjustment coefficient, and u_{jit} is the disturbance term assumed as uncorrelated with zero means. In respect to Eqs. (4a)– (4d), the short-run causality is defined by the statistical significance of the chi-square (χ^2) statistics of the related independent variables, while the log-run causality is determined by using a t-test for the statistical significance of the respective error correction terms.

5. RESULTS AND DISCUSSION

5.1 Results of Cross-Sectional Dependency, Unit Root and Cointegration Tests

The results of cross-sectional dependency test are tabulated in Table 2. As seen in Table 2, the null hypothesis of cross-sectional independency could be rejected for the model and each variable at different significance levels. Therefore, we decided to implement Pesaran (2007) unit root test, which allows for cross-sectional dependency.

As shown in Table 3, the unit root null hypothesis could not be rejected in level variables in both only intercept and intercept and trend cases. However, the variables of interest turn out to be stationary after taking their first-differences. Therefore, we can conclude that all variables are integrated of order one[2]. Having established that all variables are I (1), as a next step, we proceeded to search for the long-run relationship among variables. As tabulated in Table 4, the asymptotic probability values indicate the absence of cointegration under the assumption of cross-sectional independency, which is not the case in this study. Thus, we need to depend on bootstrap probability values indicating that there is a long-run equilibrium relationship among variables. In other words, nuclear energy consumption, economic growth, total labor force, and real gross fixed capital formation move together in the long run.

Table 2. Cross-sectional Dependency Test Results

Variables	$CDLM_1$ Statistics
Y	215.927[a]
	(0.000)
L	152.831[a]
	(0.000)
C	147.856[a]
	(0.000)
NE	99.054[c]
	(0.054)
Model	353.789[a]
	(0.000)

Notes: Constant and trend terms were included as deterministic components. [a], [b], and [c] indicate significance at 1%, 5%, and 10% levels

Table 3. Results of the Pesaran (2007) Test

Variables	**p=1 Intercept- Trend Case**		**Intercept Case**		**p=2 Intercept- Trend Case**		**Intercept Case**	
Level	**Level**	**First-differences**	**Level**	**First-differences**	**Level**	**First-differences**	**Level**	**First-differences**
Y	-1.764	-2.920[b]	-1.909	-3.080[a]	-1.662	-2.82[b]	-1.696	-2.602[a]
L	-1.775	-2.796[b]	-1.787	-3.078[a]	-1.701	-2.996[a]	-1.794	-2.770[a]
C	-1.678	-2.968[a]	-1.788	-3.313[a]	-1.712	-3.192[a]	-1.625	-2.968[a]
NE	-2.622	-4.862[a]	-1.922	-4.783[a]	-2.584	-4.862[a]	-1.927	-4.783[a]

Notes: The critical values in intercept and trend case are -2.96, -2.76, and -2.66 at 1%, 5%, and 10% significance levels, respectively. In only intercept case, the critical values are -2.45, -2.25, and -2.14 at 1%, 5%, and 10% significance levels, respectively. See Table II (b, c) in Pesaran (2007). We select 1 and 2 lag as a maximum lag number to correct serial correlation. [a], [b], and [c] indicate significance at 1%, 5%, and 10% levels.

Table 4. Results of the Westerlund and Edgerton (2007) Test

Models	**LM-statistics**	**Asymptotic p-value**	**Bootstrap p-value**
Model with a constant term	3.240	0.001[a]	0.464
Model with constant and trend terms	3.891	0.000[a]	0.122

Notes: Bootstrap based on 2000 replications. The test is conducted under the null hypothesis of cointegration. [a] denotes significance at 1% level.

[2] We also implemented the IPS panel unit root test proposed by Im et al. (2003) and obtained the same results, indicating that all variables are stationary at their first differences. The results are available upon request from the author.

5.2 Estimation of Long-run Parameters

Employing the FMOLS estimator, we computed the long-run coefficients for each country and the whole panel set. As presented in Table 5, for the whole panel set, all coefficients are positive and significant at 1% level. The results indicate that a 1% increase in nuclear energy consumption increases real GDP by 0.02%, indicating that shortage in the infrastructure for nuclear energy consumption may restrain economic growth in OECD countries under study (Yoo and Ku, 2009); a 1% increase in real gross fixed capital formation increases real GDP by 0.23%; and a 1% increase in labor force increases real GDP by 0.46%. While the nuclear energy consumption has a positive but small impact on real GDP, the most effective variable on real GDP is the labor force, with a coefficient of 0.46. Regarding the country-based results, for Belgium, only the labor force has a positive effect on GDP, while the other variables do not have significant effects on real GDP. In Canada, the capital formation and labor force have positive and negative impacts on GDP, respectively. However, nuclear energy consumption is insignificant. The negative impact of the labor force could be attributed to the hidden unemployment case. An unexpected result was obtained for France: An increase in nuclear energy consumption contributes to a decrease in real GDP. However, France has the second highest nuclear capacity after the US. This case may be a result of inefficient use of nuclear energy concerned with relatively high capital costs and subsequent disposition of radioactive waste (Apergis et al., 2010).

Table 5. FMOLS Estimation Results

Country	NE	C	L
Belgium	0.00	-0.08	1.67[a]
	(0.01)	(-0.33)	(3.55)
Canada	-0.05	0.25[a]	-0.16[c]
	(-1.62)	(5.38)	(-1.66)
France	-0.28[b]	0.06	0.89
	(-2.54)	(0.36)	(1.57)
Germany	0.11[a]	0.35[a]	0.30
	(3.61)	(5.09)	(1.40)
Netherlands	0.06[a]	0.24[a]	0.16[a]
	(5.34)	(5.37)	(2.88)
Spain	-0.02[a]	0.13[a]	0.19[a]
	(-2.85)	(3.30)	(3.92)
Sweden	0.10[b]	0.24[a]	0.13
	(2.41)	(5.86)	(1.17)
UK	-0.01	0.25[a]	-0.03
	(-0.38)	(4.13)	(-0.12)
US	0.09[a]	0.21[a]	0.37[a]
	(2.87)	(4.96)	(3.44)
Japan	0.00	0.52[a]	-0.29[c]
	(0.44)	(8.74)	(-1.75)
Switzerland	0.08[c]	0.74[a]	-0.13
	(1.81)	(13.75)	(-0.84)
Finland	-0.02	0.39[a]	-0.19
	(-0.58)	(5.32)	(-1.43)
South Korea	0.17[a]	-0.31[b]	3.07[a]
	(4.92)	(-1.99)	(4.56)
Panel	0.02[a]	0.23[a]	0.46[a]
	(3.73)	(16.63)	(4.63)

Notes: [a], [b], [c] indicate significance at 1%, 5%, and 10% levels; t-statistics are reported in parentheses; intercept and linear trend are included in regressions.

In addition, the other variables appear to be insignificant. As such, other factors such as human capital and total factor productivity may have essential roles in the economic growth process of France. Regarding Germany, Switzerland, and Sweden, nuclear energy consumption and gross fixed capital formation have positive and significant impacts on real GDP, while the labor force does not affect GDP. Regarding the Netherlands and the US, all variables have positive and significant effects on GDP. For Spain, nuclear energy consumption negatively affects the real GDP, whereas the other variables have positive effects. In the UK and Finland, only capital formation has a positive and significant effect on GDP; the other two variables have no significant influences on GDP. Concerning Japan, nuclear energy consumption is insignificant, while capital formation has positive and labor force has negative impacts on real GDP. The hidden unemployment case is confirmed in Japan as well. Japan is the country in which technology is used at the highest level. Therefore, technology may be effectively substituted for labor, and the increases in the labor force may lead to a hidden unemployment case that has a negative impact on the economic growth[3]. In the last country, South Korea, nuclear energy consumption and labor force have expected positive and significant influences, whereas capital formation appears to negatively affect the real GDP. This unexpected result may be attributed to the deficiency of talented employees and employers. In the case of inadequate human capital, making investments into physical capital is not efficient as there are not enough skillful people who will use the equipment and machines and manage the companies.

In summary, with respect to nuclear energy–economic growth nexus, in 6 out of 13 countries, namely Germany, Netherlands, Sweden, UK, Switzerland, and South Korea, an increase in nuclear energy consumption leads to increases in real GDP. In France and Spain, it appears that an increase in nuclear energy consumption causes decreases in real GDP due to inefficient usage of nuclear energy, while for the other five countries, namely Belgium, Canada, UK, Japan, and Finland, nuclear energy consumption has no significant influence on GDP. In these five countries, nuclear energy consumption is a neutral variable, and energy consumption may be a relatively small component of overall output, and therefore has little or no impact on economic growth (Apergis and Payne, 2010).

Table 6. Results of Panel Causality Test

Dependent variable	**Sources of Causation (independent variables)**				
	Short-run				**Long-run**
	ΔY	ΔNE	ΔL	ΔC	ECT
ΔY	----	12.523[a] [0.005] (0.045)	3.986 [0.262] (-0.255)	5.290 [0.151] (0.016)	0.072[a] [2.805]
ΔNE	9.603[b] [0.022] (1.264)	----	3.162 [0.367] (-0.279)	8.312[b] [0.040] (-0.711)	-0.690[a] [-3.767]
ΔL	5.372 [0.146] (0.040)	4.065 [0.254] (0.015)	----	12.695[a] [0.005] (0.068)	0.080[a] [5.093]
ΔC	7.659[c] [0.053] (0.516)	9.374[b] [0.024] (0.096)	1.555 [0.669] (-0.319)	----	0.204[a] [3.049]

Notes: χ^2 statistics were reported in respect to short-run changes in the independent variables. The sum of lagged coefficients for the respective short-run changes is given in parentheses. Probability values are in brackets and reported underneath the corresponding χ^2 statistic. However, t-statistics were reported in brackets underneath the ECT terms, while ECT represents the coefficient of the error correction term; [a], [b], and [c] denote significance at 1%, 5%, and 10% levels, respectively.

5.3 Panel Causality Test Results

The short and long-run panel causality test results are provided in Table 6. In respect to Eq. (4a), nuclear energy consumption has a significant and positive impact on economic growth in the short-run, while the labor force and gross fixed capital formation are statistically insignificant in the short-run. In terms of Eq. (4b), economic growth has a significant and positive influence on nuclear energy consumption, whereas gross fixed capital formation has a significant but negative impact on nuclear energy consumption. This result may be interpreted as the more investment in real gross fixed capital formation the less investment in the nuclear energy sector, which in turn leads to a decrease in nuclear energy consumption. Also, the labor force is statistically insignificant. In regard to

[3] The hidden unemployment case indicates the superfluous labor force. In this case, there is a negative relationship between the labor force and economic growth.

Eq. (4c), only gross fixed capital formation has a significant and positive impact on the labor force, while economic growth and nuclear energy consumption are statistically insignificant. In the case of Eq. (4d), economic growth and nuclear energy consumption have statistically significant and positive influences on real gross fixed capital formation, whereas the labor force does not have a significant impact on capital formation. It appears that the increasing level of nuclear energy consumption leads to more investment in physical capital because nuclear reactors and power plants need to be constructed to meet the demand for nuclear energy. As a result, regarding the nuclear energy–economic growth nexus, the short-run results confirm the feedback hypothesis, implying that nuclear energy consumption and economic growth complement and reinforce each other.

The long-run relationships represented by the error correction terms from Eqs. (4a)– (4d) display that all variables of interest respond to deviations from long-run equilibrium as their respective error correction terms are statistically significant. In the case of Eq. (4a), there is a long-run relationship from nuclear energy consumption, labor force and capital formation to economic growth, while the long-run causality is from the economic growth, labor force, and gross fixed capital formation to nuclear energy consumption in Eq. (4b). In Eq. (4c), there is a long-run relationship from the nuclear energy consumption, economic growth and capital formation to labor force, while the direction of long-run causality is from the economic growth, nuclear energy consumption and labor force to capital formation in Eq. (4d).

We can compare our panel causality results with those of Apergis and Payne (2010) since their variables are same as ours. Apergis and Payne (2010) found bidirectional positive causality results among nearly all variables in the short-run, except for the relationship between nuclear energy consumption and labor force. However, we attained a bidirectional positive causality result between nuclear energy consumption and economic growth, a one-way negative causality from gross fixed capital formation to nuclear energy consumption, a one-way positive causality from gross fixed capital formation to labor force, and a one-way positive causality from economic growth and nuclear energy consumption to gross fixed capital formation. In the long run, we found that all variables respond to deviations from the long-run equilibrium, whereas they found that nuclear energy consumption does not respond to deviations from the long-run equilibrium. Thus, Apergis and Payne (2010) confirmed the feedback hypothesis in the short-run and the growth hypothesis in the long-run; however, we provided evidence favorable to the feedback hypothesis in both the short-run and long-run. Also, the second panel study implemented by Lee and Chiu (2011a) obtained evidence of the conservation hypothesis in the long-run and the neutrality hypothesis in the short-run. Our result favorable to the feedback hypothesis was also confirmed by Wolde-Rufael and Menyah (2010) in France, Spain, UK, and US; Yoo and Ku (2009) in Switzerland; and Lee and Chiu (2011b) in Canada, Germany, and the UK.

6. CONCLUSION AND POLICY IMPLICATIONS

Nuclear energy is believed to provide major solutions to the problems related to energy security, environmental degradation, and pollution. Thus, supply security in energy, greenhouse gas emissions, rising fossil fuel prices, and environmental issues arising from the usage of fossil-based energy have led countries to focus on alternative energy sources (Chu and Chang, 2012) and therefore, the importance of nuclear energy has come to the forefront of the wider issue of the energy debate (Wolde-Rufael and Menyah, 2010). In addition, scholars have started to show an interest in uncovering the causal relationship between nuclear energy consumption and economic growth by using alternative testing methodologies. Their findings have shed light on this subject, which helps policy makers to design sectorial energy and environmental strategies and policies (Wolde-Rufael, 2010).

Based on the increasing importance of nuclear energy consumption, we examined the relationship between nuclear energy consumption and economic growth in a panel cointegration and causality framework for 13 OECD countries. The heterogeneous FMOLS results indicated that in 6 out of 13 countries, nuclear energy consumption makes positive and significant contribution to economic growth. Regarding the whole panel set, nuclear energy consumption has a positive and significant coefficient. Besides, the panel causality results indicated that there is a bidirectional positive causality between nuclear energy consumption and economic growth. In other words, the feedback hypothesis was confirmed in both the short-run and long-run, indicating that nuclear energy consumption and economic growth are interrelated and may very well complement each other. The complementarity between nuclear energy consumption and economic growth implies that nuclear energy consumption can boost economic growth, and in turn, economic growth may cause more nuclear energy demand. In this case, nuclear energy conservation policies may negatively affect the economic growth.

In a nutshell, this study confirms the importance of nuclear energy power in the development processes of countries. Though there is still some general public opposition with respect to the production and consumption of nuclear energy, countries must seriously think about nuclear energy as a substitute for oil and other non-renewable energy types. Therefore, improving public awareness about energy issues, providing factual information, and conducting comprehensive and efficient communication campaigns are the essential tools in this process (World Energy Council, 2007). Governments should take active roles by working with all stakeholders to overcome constraints on nuclear energy plans. However, some questions still await answers: First, do nonlinear panel estimation techniques change the causality results? Second, does including other energy types such as oil and renewable energy into the model change the impact of nuclear energy consumption on real GDP? Future studies could answer these questions.

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