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*The impacts of R&D investment and stock markets on clean energy consumption
and CO₂ emissions in OECD economies*

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ABSTRACT

The goal of this paper is to examine to what extent R&D investment and stock market development promote clean energy consumption and environmental protection across a panel of 30 OECD economies. Based on the theoretical approach, study employs robust panel econometric models which account for cross-sectional dependence in the analysis and uses annual data, spanning the period 1996 to 2013. The empirical results illustrate that R&D and stock market have a significant long-run equilibrium relationship with clean energy and CO₂ emissions. The long-run elasticities display that R&D and stock market growth have a significant positive impact on clean energy consumption, while they have a negative effect on the growth of CO₂ emissions. Given these findings, the paper suggests that the policy makers in the OECD economies should realize that it is worth investing in R&D activities as it is promoting the use of clean energy and ensuring low carbon economies. Therefore, the policymakers have to initiate effective policies to promote R&D activities and also encourage the firms that are listed in the stock market to adopt environmental friendly policies.

JEL Classification: F21, O16, O32, P28, Q42

Keywords: R&D investments; stock markets; clean energy consumption; CO₂ emissions; FDI; OECD economies

1. Introduction

Climate change related to carbon dioxide (CO₂) emissions is now considered one of the greatest environmental challenges with the traditional energy system being largely responsible for this. All fossil energy sources have a profound influence on environment during their life cycle. The fossil energy sources including coal, oil and natural gas accounted for 60 percent of worldwide CO₂ emissions in 2013. Among the total CO₂ emissions released from fossil fuels in 2013, coal accounted for 46 percent, while oil and natural gas represented 33 percent and 20 percent, respectively (IEA, 2014). Therefore, increasing the demand for energy from fossil fuels makes a significant contribution to global CO₂ emissions. Since the industrial revolution, total carbon emissions particularly from fossil fuel burning have risen rapidly from almost zero to 32 Giga tons (Gt) CO₂ in 2013 (IEA, 2014). Thus, historically, there has been a great need for clean energy sources within the energy system in order to minimize atmospheric CO₂ emission levels.

Fostering the improvement and development of modern clean and renewable energy know-how and technologies plays a fundamental role to the shift towards renewable and clean energy system. Likewise, new know-how and technologies allow shifting the pathway of the energy sector by increasing energy efficiency through improving the service delivery system. Thus, the investment in energy related R&D could be an important part in order to develop a sustainable and clean energy system. However, the development of new and improved clean energy technologies is not straight-forward. Nevertheless, channelling limited resources to energy R&D may imply fewer resources available for other factors of production, which may crowd out R&D investment in other sectors. Given that the social benefits of R&D investments are high, such crowding out may have negative impact on macro economy and limits the potential development of the economy (Goulder and Schneider; 1999; Marin, 2014).

While R&D is likely to cause a considerable positive effect on the development of new and improved clean energy technologies (Wiesenthal et al., 2012), government investments in clean-energy technology research and development have not been impressive in the last four decades. According to the International Energy Agency (IEA), the budget for overall public energy R&D investment in the world was nearly US\$ 17 billion in 2014, which is still below of its \$20 billion in the 1980s. In 2014, the U.S. allocated the highest public energy R&D investment of US\$ 6 billion. At the same time, Japan was among the top which had highest proportion of public energy R&D compared to overall R&D, though the portion of energy R&D has been shrinking constantly since 1990. Japan's portion of energy R&D was 23 percent in 1990, which decreased to 12 percent in 2014. The same scenario also exists across most of developed countries (IEA, 2015). One of the reasons for the reduction in energy R&D spending could be the lack of understanding of the potential positive return of energy R&D investment by both governments and policymakers. This might be due to the fact that there is very little empirical evidence on the nexus between R&D investment and energy-environmental outcomes. Therefore, the empirical studies on the relationships among R&D spending, clean energy use and carbon emissions may provide better understanding regarding the potential benefits of R&D.

Like R&D, stock market development also have significant impact on energy consumption in general, clean energy use and carbon emissions in various ways. The stock markets may expand the business activities by providing access to additional capital for the listed firms. As a result of that, the stock markets increase demand for energy (Sadorsky, 2010) and may contribute for higher carbon emissions. For instance, the empirical findings of Paramati, Alam and Apergis (2018) document that the stock markets have significant positive impact on carbon emissions in emerging market economies. On the contrary, the evidence also show that

the stock market have reducing impact on carbon emissions in developed market economies. The varying impacts of stock markets on carbon emissions may be due to the differences in implementation of environmental rules and regulations. Further, a number of recent studies (e.g. Kutan et al., 2018; Paramati, Ummalla and Apergis, 2016; Paramati, Apergis and Ummalla, 2017b) document that the stock markets play an important role in promoting clean/renewable energy consumption. The stock markets can promote clean/renewable energy consumption by providing additional funding sources for the clean/renewable energy projects. Further, the stock markets, through the regulatory authorities, may insist the listed firms to adopt environmental friendly activities, which may then have positive impact on clean energy consumption and reducing impact on carbon emissions.

However, according to our best knowledge, no empirical study is available that has empirically examined the influence of R&D in promoting clean energy consumption and minimizing CO₂ emissions. Similarly, only a few studies (Paramati et al., 2016, Paramati et al., 2017b) examine the impact of stock markets on clean energy consumption and CO₂ emissions. Thus, the goal of this paper is to meet this existing gap in the literature by considering the Organisation for Economic Cooperation and Development (OECD) countries as a sample. To achieve this objective, the study attempts to answer a number of important questions. First, is there any long-run equilibrium relationship between R&D spending, stock market development, clean energy consumption and CO₂ emissions? Second, how much clean energy consumption can be promoted for each unit of R&D spent? Does the development of stock market foster clean energy consumption? Finally, do the growths of R&D spending and stock market development significantly decrease CO₂ emissions?

OECD is considered as a case study for this study because of its remarkable record in R&D investment and stock market development, with speedy developments in the energy efficient and clean energy infrastructures and technologies spending required for clean energy consumption. Since 1980s, OECD has been one of the pioneers in R&D investment in the energy sector. Likewise, the stock markets in the OECD countries have experienced rapid development in terms of volume and efficiency. The R&D spending and stock market growth have brought technological innovation and development for energy efficiency improvement and renewable energy production which might have a significant impact on decreasing CO₂ emissions. Hence, it is substantially vital to examine the relationship across R&D investment, stock market, clean energy consumption and CO₂ emissions in the case of OECD countries.

The contributions as well as the novelties of this study are three-fold. First, to the best of our knowledge, this is the first empirical study that analyses the nexus across R&D spending, clean energy consumption and carbon emissions. Second, our study is one of the pioneer studies that investigate the impact of stock market on clean energy consumption and carbon emissions. Third, the analysis follows a widely used theoretical model to choose variables in the empirical setting. The analysis employs I=P.A.T (Impact=Population x Affluence x Technology) model to investigate the factors that cause environmental degradation. Finally, this paper uses various panel econometric methodologies which provide robust and reliable findings. For example, the Pesaran (2004) cross-sectional dependence (CD) test is employed to detect the cross-sectional dependence among the selected variables. We also apply cross-sectionally augmented panel unit root test (CIPS) by Pesaran (2007) and bootstrap panel unit root test by Smith et al. (2004) which consider the presence cross-sectional dependence among the variables. Westerlund (2008) cointegration test is employed to investigate the long-run equilibrium relationship. Pesaran's

(2006) Common Correlated Effects (CCE) methodology is used to estimate long-run elasticities while the heterogeneous non-causality test (Dumitrescu & Hurlin, 2012) is used to examine the causal relationships among the variables.

The remainder of the paper is structured as follows. Section 2 presents a review of the relevant literature. Section 3 highlights the nature of data, their measurement and the empirical methodology, while Section 4 focuses on the empirical results and their discussion. Finally, Section 5 concludes the paper, while offering certain policy implications.

2. Literature review

2.1. R&D, energy efficiency and clean energy consumption

Energy R&D investment has been largely involved to the advancement of new technologies for sustainable energy systems. Margolis and Kammen (1999) claim that energy R&D spending and patents for innovative technology are strongly correlated in the U.S. for the period of 1976 to 1996. In the U.S., the Energy R&D spending was \$7.6 billion in 1976 which increased to \$11.9 billion in 1979, however, since then the amount has decreased dramatically and reached to only \$4.3 billion in 1996. Likewise, patents number linked to energy technology followed the same pattern; increased from 102 patents in 1976 to 228 in 1981, but since then dropped to only 54 in 1994. Thus, these measurements show that R&D funding and advancement of modern energy technologies have high positive correlation. The technological advancement increases energy supplies through innovating new sources of renewable energy and improves the efficiency of conversion of raw energy to required final-use forms. Therefore, it lowers the economic costs as well as adverse environmental impacts (Sagar and Holdren, 2002).

There are some analytical studies which claim that technological innovation is crucial for improving energy efficiency and lowering energy intensity. Fisher-Vanden et al. (2004) identify the factors that influence energy intensity in China. By using panel data for around 2,500 medium and large energy related industrial enterprises for the period between 1997 and 1999, the paper highlights that technological development is a crucial factor to decrease energy intensity in China. From theoretical point of view, Yongping (2011) argues that the magnitude of technological development impact on energy intensity since it has a direct relationship with the energy efficiency. Moreover, technological innovation creates prospects for the highly energy dependent countries to shift from non-renewable to renewable energy sources (Sohag et al., 2015). However, if technological advancement decreases energy use marginally, it might not reduce a significant portion of the energy consumed. Sagar and Zwaan (2006) fail to find any clear correlation among government R&D investment, energy intensity at national level (i.e., the amount of energy use to produce per unit of GDP) and carbon emissions intensity (i.e., the amount of carbon emitted from per unit of energy used). Nonetheless, Greening et al. (2000) point out that if the energy price decreases due to better energy efficiency, the decreased price may inspire economic agents to consume more energy, which ultimately increases energy use and CO₂ emissions.

While there is no published empirical research on the relationship across R&D spending, clean energy consumption and CO₂ emissions, a few studies, such as Ang (2009), Tang and Tan (2013), Fei and Rasiah (2014), Fei et al. (2014), Sohag et al. (2015), and Ahmed et al. (2016), which include technological innovation in their econometric model to investigate its impact on both energy consumption and CO₂ emissions. Ang (2009) explores the relationship among technology transfer, research intensity and CO₂ emissions in the case of China. Using a long time

series data during the period of 1953 to 2003, the study reveals that technology transfer and research intensity are negatively correlated with CO₂ emissions. Tang and Tan (2013) examine how technological innovation influences electricity consumption in the case of Malaysia during the period 1970–2009. The study uses patent as a proxy for technical innovation. The results, based on the autoregressive distributed lag (ARDL) methodological approach; show that technological innovation has significantly mitigated electricity consumption. Moreover, Granger causality results reveal that technology advancement Granger-causes electricity use in the case of Malaysia. Hence, the policymakers should encourage technological development to reduce the use of pollutant energy which may improve the quality of environment without affecting economic growth. Fei et al. (2014) also investigate the association among technological advancement, clean energy consumption and CO₂ emissions in New Zealand and Norway during 1971—2010. The ARDL model indicates that an equilibrium relationship exists across the selected variables in the long-run in both countries. The findings also suggest that technological advancement plays a significant role in promoting clean energy use and minimizing CO₂ emissions in both New Zealand and Norway. Thus, the authors recommend that Norway and New Zealand should give more focus on R&D spending in both public and private sectors to ensure the maximum advantages of clean energy use.

Fei and Rasiah (2014) investigate the traditional electricity-growth nexus by incorporating new variables, namely, technological development and energy prices in Canada, Ecuador, Norway and South Africa. Applying the methodology of ARDL and vector error correction model (VECM), their study provides supportive evidence that technological development does not reduce fossil fuel electricity consumption. Sohag et al. (2015) apply the extended Marshallian demand theoretical framework to examine the influence of technological

innovation on energy use in Malaysia over the period 1985 to 2012. The extended Marshallian demand framework assumes that technological advancement, an important component in the energy demand function, improves energy efficiency, which eventually decreases energy use for a particular amount of economic output. Employing the ARDL bounds testing methodological approach, their study supports the theoretical predictions both in the short- and long-run. Thus, their findings recommend that the government of Malaysia should promote R&D spending to promote energy savings and clean energy technologies through both government and non-government initiatives. Ahmed et al. (2016) investigate the causal relationship across technological development, biomass energy energy use and CO₂ emissions 24 European countries during 1980—2010. Using pooled mean group estimations in a dynamic heterogeneous panel setting, their study illustrates that technological development is found to have a substantial effect on decreasing CO₂ emissions in the investigated countries. Their results imply that economic progress and environmental improvement can be attained concurrently, which provides new guidelines for policymakers for sustainable economic growth via the clean energy use through technological development. Finally, a recent study by Paramati et al. (2016) provides evidence in support of the argument that clean energy consumption significantly reduces CO₂ emissions in emerging market economies. Furthermore, the authors report that both inward FDI and stock market growth play an important role in increasing clean energy consumption in the same economies. Given that the authors make an important suggestion to policymakers to introduce effective policy guidelines to encourage clean energy investments through the public-private-partnerships (PPP), they argue that these additional investments not only increase clean energy consumption, but also significantly reduce CO₂ emissions in those countries.

2.2. Stock market development and environment

A few studies examine the link between stock market development and environment. For example, the study by Lanoie et al. (1998) is one of the pioneer studies that undertake an attempt to examine the role of capital markets on pollution control. Evidence drawn from American and Canadian markets, the study points out that effective capital markets enhances environmental performance by executing strong enforcement actions to their listed companies. Moreover, stock markets offer incentives to improve environmental performance. While, Lanoie et al. (1998) investigate the role of stock market in controlling pollution in the context of developed countries, Dasgupta et al. (2001) inspect the same issue in the context of developing countries. Considering Argentina, Chile, Mexico and the Philippines as a sample, the study shows that stock market development promotes environmental performance by improving public disclosure mechanisms. Gupta and Goldar (2005) examine whether stock markets punish those firms which pollute environment. The findings of the study demonstrate that efficient stock markets normally punish the polluting firms and therefore, stock markets play a crucial role in improving environmental management. The above studies provide enormous impetus on the theoretical development of the relationship between stock market and environment.

The study of Tamazian et al. (2009) is probably the first empirical study examines the impact of stock market on environmental degradation in Brazil, Russia, India and China (BRIC). The study uses 'stock market value added' as proxy for stock market development. From the panel data over the period of 1992 to 2004, the study finds that stock market reduces CO₂ emissions significantly in the selected countries. Sadorsky (2010) investigates the effect of stock market on energy consumption. The study considers a sample of 22 emerging countries during

1990 —2006. Considering stock market capitalization to GDP, stock market value traded to GDP and stock market turnover as proxies for stock market, the author provides evidence that stock market has a positive and statistically significant relationship with energy consumption. Subsequently, Zhang et al. (2011) examine the influence of stock market on energy consumption in China for the period of 1992-2009. The study explores that scale of the Chinese stock market has relatively higher influence on carbon emissions while the efficiency of stock market impact on emissions is found to be weaker.

Recently, Abbasi and Riaz (2016) investigate the relationship between stock markets and carbon emissions in Pakistan. The findings of the study conclude that the development of stock market significantly increase the intensity of carbon emissions. In the same vein, Paramati et al. (2016) examine the role of stock market in promoting clean energy consumption in 20 emerging market economies. Using the data from 1991–2012, the authors claim that stock market developments have a substantial positive influence on clean energy consumption. Paramati et al. (2017c) compare the influence of stock market on CO₂ emissions between developed and developing economies in G20 nations. Their findings indicate that the stock markets have significant negative impact on the CO₂ emissions in developed countries but positive effect on developing economies. Similarly, Paramati et al. (2017b) find that stock market developments play a significant role in promoting clean energy uses across the EU, the G20 and OECD countries.

2.3. Clean energy consumption and CO₂ emissions

A good number of studies have investigated the causal link between clean energy consumption and CO₂ emissions. In general, existing studies suggest that a rise in the consumption of clean

energy decreases carbon emissions across various countries. Sadorsky (2009) examines the link among renewable energy use, CO₂ emissions and energy prices for the G-7 nations during 1980-2005. Employing the VECM approach, his study shows that economic growth and emissions are the two most important factors that significantly increase renewable and clean energy growth in the long run. The author supports his findings by arguing that people from rich nations are more likely to finance in and purchase renewable energy. Governments in the high-income nations are expected to invest in new technologies that may raise production and the use of renewable energy. Employing various time series techniques during 1960–2007 for the U.S., Menyah and Wolde-Rufael (2010) investigate the causality between nuclear and renewable energy use and CO₂ emissions. Employing Granger causality testing, their study concludes that there is a one-way causal relationship that runs from nuclear energy use to carbon emissions, but no causality is detected between renewable energy and carbon emissions. The policy recommendations derived support that the use of nuclear energy consumption helps to considerably reduce CO₂ emissions, while renewable energy use has not reached that level where it can significantly mitigate CO₂ emissions.

Apergis et al. (2010) analyse the dynamics of causality between renewable energy and nuclear energy use and CO₂ emissions in a panel of 19 developing and developed economies during 1984–2007. The econometric evidence appears to suggest that a substantial and negative link exists between nuclear energy consumption and emissions, but a positive relationship between renewable energy consumption and CO₂ emissions. Therefore, the findings imply that while nuclear energy consumption makes a crucial role in mitigating CO₂ emissions, renewable energy use has no considerable role in reducing emissions in the sample countries. Silva et al. (2011) investigate the causality between economic growth, CO₂ emissions and electricity

generation from renewable energy sources in Denmark, Portugal, Spain, and the U.S. for the period between 1960 and 2004. The study report that across all countries, except the U.S., the growing portion of electricity from renewable energy sources have adverse effect on economic growth, however, a positive influence on decreasing CO₂ emissions.

Salim and Rafiq (2012) attempt to identify the factors that motivate renewable energy consumption in six developing countries, namely, Brazil, China, Indonesia, India, the Philippines and Turkey. Employing various panel econometric models, including fully modified ordinary least square (FMOLS) and dynamic ordinary least square (DOLS), their study reveals that income and pollution are the two important factors of renewable energy use in the long-run. Moreover, their study also finds bidirectional causal relationship between renewable energy use and pollutant emissions in the short-run. Thus, the findings of the study support the suitability of the undertaken efforts by the governments in emerging countries to decrease the carbon intensity by raising the proportion of renewable energy in their total energy mix. Using the STIRPAT as a theoretical model, Shafei and Salim (2014) examine the factors for CO₂ emissions for OECD countries during the period 1980 to 2011. The empirical evidence indicates that renewable energy use helps to significantly reduce CO₂ emissions in these countries. Hence, policymakers should concentrate on clean energy consumption to contribute climate change mitigation significantly.

Rafiq et al. (2014) inspect the dynamics among renewable energy generation, GDP per capita and CO₂ emissions in China and India during 1972 to 2011. Employing the multivariate vector error correction model (VECM), their study finds one-way causality running from CO₂ emissions to renewable energy generation in the short-run and a bidirectional causality between the variables in the long-run. The same findings are also revealed by Apergis and Payne (2015)

for a panel of 11 South American countries. Their study uses data for the period 1980 to 2010. The findings of the panel error correction model indicate a feedback relationship between renewable energy consumption and CO₂ emissions. Using the panel cointegration methodological approach, as well as Granger causality tests, Jebli and Youssef (2015) address the dynamic relationships across combustible renewables and waste (CRW) consumption, GDP and CO₂ emissions for five African countries during 1971—2008. The panel Granger causality test results indicate that there is a one-way causality running from CRW to CO₂ emissions in the short-run. Therefore, the policy recommendations support the economies to focus on using more CRW that may significantly decrease CO₂ emissions in these countries. Dogan and Seker (2016a) investigate the connection between renewable energy use and carbon emissions by employing a panel framework of top twenty-three renewable energy consuming countries between 1985 and 2011. The study suggests the negative relationship between renewable energy consumption and CO₂ emissions. The empirical findings by Bhattacharya et al. (2016) also confirm that renewable energy use makes a crucial contribution to sustainable economic growth.

Very recently, Jebli et al. (2016) employ panel cointegration methodologies to examine relationships between CO₂ emissions and renewable energy use in 24 sub-Saharan African countries during 1980—2010. The Granger causality test results indicate that an indirect short-run causality running from emissions to renewable energy. Tiba et al. (2016) explore the association between environmental performance, renewable energy consumption and economic growth for 24 medium- and high-income nations during 1990—2011. The study documents bidirectional causality exists between renewable energy and CO₂ emissions in the high-income nations. Finally, Dogan and Seker (2016b) empirically investigate the impact of renewable and non-renewable energy on CO₂ emissions in terms of the Environmental Kuznets Curve (EKC)

for the European Union over the period 1980 to 2012. By using the dynamic ordinary least squares estimator, their study shows that renewable energy significantly mitigates CO₂ emissions.

From the above literature review, it can be concluded that no empirical study is available that investigates the role of R&D in clean energy consumption and CO₂ emissions. A few studies are available on the connection between stock market development, clean energy consumption and CO₂ emissions; however, these studies have not followed any theoretical framework to construct their empirical models. Hence, our study is undertaken to meet this existing research gap and, by making contribution to the knowledge, also to provide fresh insights for policymakers.

3. Data and methodology

3.1. Data

This study uses yearly data, spanning the period 1996 to 2013 on 30 OECD countries. Using these annual data, we construct a balanced panel data set for the empirical analysis. The considered OECD countries are: Australia, Austria, Canada, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Israel, Italy, Japan, Korea, Mexico, the Netherlands, New Zealand, Norway, Poland, Portugal, Slovak Republic, Slovenia, Spain, Sweden, Switzerland, Turkey, the United Kingdom (UK) and the United States (US). The sample countries from the OECD economies and time period are selected based on the availability of data.

The considered variables of this study are measured as follows: clean energy consumption (CEC) is the alternative and nuclear energy as a percent of total energy use; CO₂ emissions per capita (CO₂) from energy consumption in MtCO₂ per million people; GDP per

capita (GDPPC) in constant 2005 US\$; research and development (R&D) expenditure as percentage of GDP; foreign direct investment (FDI), net inflows as a percent of GDP; market capitalization (SMC) of listed domestic firms as a percent of GDP and, finally, population density (PD) per square (Sq.) kilometre (km) of land area. The obtained annual data on CEC, GDPPC, R&D, FDI, SMC and PD are sourced from the World Development Indicator, while data on CO₂ emissions are sourced from the US Energy Information Administration (EIA) historical statistics. All of these variables are converted into natural logarithms for the easy interpretation and to avoid the issues that are associated with data measurement.

3.2. Empirical methodology

The first objective of this research is to examine the effect of R&D on clean energy consumption across a panel of OECD countries. The model in Equation (1) is developed by following Paramati et al. (2016) who argue that CO₂, GDPPC, FDI and SMC have considerable effect on clean energy uses. Therefore, we make use of the following model for the empirical analysis:

$$CEC_{it} = f(CO_{2it}, R\&D_{it}, SMC_{it}, FDI_{it}, GDPPC_{it}, v_i) \quad (1)$$

where, CEC, CO₂, R&D, SMC, FDI and GDPPC indicate clean energy consumption, CO₂ emissions, research and development, stock market capitalization, foreign direct investment and GDP per capita, respectively. v_i represents individual fixed country effects, while countries and time period are indicated by the subscripts i ($i = 1, \dots, N$) and t ($t = 1, \dots, T$), respectively.

The second objective of this study is to examine the impact of R&D on CO₂ emissions. To identify the potential determinants of CO₂ emissions, we employ the the environmental impact model or IPAT theoretical model which is widely used for empirical analysis of

environmental pollution (York et al., 2002 and Raskin, 1995). The approach indicates that environmental impact (I) is primarily caused by the level of population (P), per capita consumption or affluence (A) and technology (T). Therefore, by following the settings of the IPAT model, we account for population, per capita income, and technology is proxied with R&D, SMC and FDI indicators. Using the above approach, we derive the following equation for the empirical analysis:

$$CO_{2it} = f(CEC_{it}, R\&D_{it}, SMC_{it}, FDI_{it}, GDPPC_{it}, PD_{it}, v_i) \quad (2)$$

where, CO₂ emissions is a function of clean energy consumption, research and development, stock market capitalization, foreign direct investment, GDP per capita and population density, respectively. We incorporate clean energy consumption (CEC) in the CO₂ emission model because the clean energy consumption may have an important role on carbon emissions.

A number of previous studies (e.g. Alam et al. 2017; Chang, 2015) argue that there is a considerable cross-sectional dependence among the variables and across the countries. Therefore, it is important to examine whether the considered variables are cross-sectional dependent. To this end, we apply Pesaran's (2004) cross dependence (CD) test to examine whether the variables are cross-sectionally dependent. Based on the findings derived from the CD test, we apply both Pesaran (2007) CIPS and Smith et al. (2004) bootstrap panel unit root tests. Both of these panel unit root tests account for cross-sectional dependence in the analysis.¹

In the next step, the long-run equilibrium relationship among the variables in Equations (1) and (2) are explored using the approach suggested by Westerlund (2008). This is a preferred methodology as it accounts for cross-sectional dependence in the data series and makes use of

¹ A number of recent studies (Lee and Chiu, 2013; Paramati et al., 2016) apply CIPS unit root tests to explore the order of integration of the variables.

the Durbin-Hausman test in the analysis. The recent study by Paramati et al. (2016) documents the significance of Westerlund (2008) panel cointegration test for the analysis of long-run equilibrium relationship among the variables. In contrast, the previous literature (Alam and Paramati, 2015; Alam and Paramati, 2016; Paramati et al., 2017a) use the panel cointegration modelling approach which does not account for cross-sectional dependence in the analysis. Therefore, to overcome the issue of cross-sectional dependence, we apply the second generation panel cointegration model to examine the long-run association among the variables under study.

Furthermore, to examine the long-run association between clean energy and CO₂ emissions elasticities, we use the Pesaran's (2006) CCE methodology. This is a more suitable methodological approach compared to the conventional regression models, as the former accounts for cross-sectional dependence. Therefore, the evidence derived from this analysis will be more reliable than those of the conventional models. This study also makes use of Dumitrescu and Hurlin's (2012) approach to explore the causal relationship between the variables. This test is applied to explore the short-run dynamic causal relationship between the variables. This is a robust methodology as it allows coefficients to vary across the cross-sections. This test is applied on the first differences of the data series. Finally, for robustness purposes, the analysis applies the panel autoregressive distribution lag (ARDL) model, based on the framework suggested by Pesaran et al. (1999)². The purpose of applying ARDL model is to confirm whether the findings of long-run elasticities derived from the Pesaran's (2006) CCE methodology are consistent.³

The country-specific summary statistics for the period of 1996—2013 are provided in Table 1. The statistics show that Sweden (46.680), France (45.237), Switzerland (39.167) and

² The detailed discussion on the models is avoided to conserve the space in the paper, however the detailed methodology can be provided upon the request.

³ The detailed discussion on the empirical methodology is avoided to conserve the space in the paper.

Norway (38.588) have the highest average clean energy consumption across the OECD countries, while Estonia (0.213), Poland (0.303), Australia (1.458), Ireland (1.463) and the Netherlands (1.640) have the lowest. The mean per capita CO₂ emissions are higher for the U.S. (4.860), Australia (4.744) and Canada (4.431), whereas the lowest is for Turkey (0.855), Mexico (0.908) and Estonia (1.121). It is interesting to note that Israel, Sweden, Finland and Japan spend more money on R&D than any other country in the OECD; in contrast, Mexico, Greece, Turkey, Slovak Republic and Poland spend the least. The average stock market capitalization is higher for Switzerland, the UK, Canada and the US, while it is lower for Slovenia, Czech Republic, Estonia and Hungary. Countries like the Netherlands and Ireland receive the highest average FDI inflows, while Japan, Greece, Italy and Korea receive the lowest. The average per capita GDP is significantly higher for Norway and Switzerland, while Turkey, Mexico, Poland and Estonia have the lowest across all OECD countries. Finally, the average population density is higher in countries like Korea, the Netherlands, Japan and Israel, while the lowest values are observed in Australia, Canada and Norway. Overall, these country-specific summary statistics suggest that there is a significant difference among the variables and across the OECD countries.

[Insert Table 1 about here]

The panel descriptive statistics are displayed in Table 2. They show that the average clean energy consumption across the sample countries is 14.902 percent of total energy use, while per capita CO₂ emissions are 2.292 Mt per million people. Similarly, the average R&D, SMC, FDI, per capita GDP and PD are 1.784 percent of GDP, 66.892 percent of GDP, 4.154 percent of GDP, 28866.370 US\$ and 135.616 people per sq. km of land area, respectively. These panel summary statistics imply that the share of R&D expenditure in total GDP is less than 2

percent. Hence, we can argue that the R&D expenditure has to be further grown to realize the potential benefits of it.

[Insert Table 2 about here]

4. Results and discussion

We begin our empirical investigation by exploring the residual cross-sectional dependence (CD) for our selected variables in the model. This has become an important issue to be looked at before applying any panel unit root tests. Therefore, we apply CD test based on the approach suggested by Pesaran (2004). This test is based on a simple average of all pair-wise correlation coefficients of the OLS residuals obtained from the standard augmented Dickey-Fuller regressions for each variable in the panel. Under the null hypothesis of cross-sectional independence, the CD test statistic follows asymptotically a two-tailed standard normal distribution. The results, reported in Table 3, uniformly reject the null hypothesis of cross-section independence regardless of the number of lags (from 1 to 4) included in the ADF regressions. Hence, these results confirm that there is a significant cross-sectional dependence.

[Insert Table 3 about here]

Given the evidence from the CD test, we employ two second-generation panel unit root tests to explore the degree of integration in the respective variables. More specifically, we apply Pesaran (2007) and Smith et al. (2004) panel unit root tests. Both of these tests account for cross-sectional dependence while investigating the order of integration of the variables. Further, both of these tests follow the null hypothesis as a unit root. The results of these tests are reported in Table 4. The results on level data show that the null hypothesis is not rejected for both of these

tests. However, the evidence from first difference data confirms that the null hypothesis is strongly rejected.

[Insert Table 4 about here]

Given the evidence from the panel unit root tests, we employ panel cointegration methodologies to examine the long-run association across the variables under study. Under cross-sectional dependence, the analysis makes use of the Durbin-Hausman test, recommended by Westerlund (2008). This significance of this approach is that it accounts for cross-sectional dependence, while exploring the long-run relationship among the selected variables in the model. The results of the DH_g and DH_p tests, across equations (1) and (2), are reported in Table 5. The empirical findings confirm the rejection of the null hypothesis of no-cointegration at the 1 percent significance level for both tests and across both modelling equations.

[Insert Table 5 about here]

The above results only confirm that the variables in equation (1) and (2) are cointegrated in the long-run, but do not imply whether R&D effects positively or negatively both clean energy consumption and CO₂ emissions. Therefore, we estimate two long-run elasticity models, equation (1) and (2), with clean energy consumption and CO₂ emissions being the dependent variables, respectively. To consider the presence of cross-sectional dependence, the analysis implements the methodology of the Common Correlated Effects suggested by Pesaran (2006). It allows individual specific errors to be serially correlated and heteroskedastic. The empirical findings of these results are displayed in Table 6 and the results go as follows:

- A 1 percent increase in R&D expenditure, stock market growth and FDI raises clean energy consumption by 0.259 percent, 0.047 percent, and 0.061 percent, respectively.

These results show that the R&D expenditure, stock market growth and FDI inflows have a significant positive impact on clean energy consumption in the case of the OECD economies. Furthermore, the results also confirm that per capita income significantly and positively contributes to clean energy consumption. Based on these findings, we argue that the policymakers should initiate effective policies to increase the funding towards R&D expenditure, which brings several innovations in the clean energy and energy efficiency technologies. These innovations will assist those countries to promote the clean energy generation and consumption, as well as energy saving. Moreover, the policymakers also should initiate the policies to make use of FDI inflows and stock market growth by shifting the investments into the clean and renewable energy industries. In years to come, both the FDI and stock market growth are expected to play a significant role in funding energy projects. However, it was surprise to find that the growth of CO₂ emissions reduces clean energy consumption. The overall findings recommend the OECD economies to increase the share of clean energy in total energy use to minimise CO₂ emissions, which eventually ensures sustainable economic growth.

- A 1 percent increase in clean energy consumption, R&D expenditure and stock market growth reduces CO₂ emissions by 0.106 percent, 0.248 percent and 0.037 percent, respectively, while a 1 percent raise in FDI increases CO₂ emissions by 0.052 percent.

Furthermore, our findings confirm that clean energy consumption, R&D expenditure and stock market growth play a dominant role in minimizing CO₂ emissions in the OECD economies, while FDI positively contributes to CO₂ emissions. These findings have important policy implications. More specifically, the growth of clean energy consumption, R&D expenditure and stock markets is the key factor for mitigating CO₂ emissions in OECD economies. Increasing the share of clean energy consumption in total energy not only meets the raising demand for energy,

but also it reduces CO₂ emissions. Similarly, R&D also brings new innovations in energy and emission controlling technologies, which will play a pivotal role in reducing CO₂ emissions. Finally, the growth of stock market also instructs the listed firms to adopt energy efficient and emission controlling technologies in the production of goods and services to ensure a low carbon economy. As a result of those initiatives, OECD economies were capable of minimizing the growth of CO₂ emissions in the recent past. However, the policymakers still need to implement effective policies to further decline CO₂ emissions in these countries.

[Insert Table 6 about here]

Further, we examine the short-run causalities between the variables using the method that is recommended by the Dumitrescu and Hurlin (2012). This is a robust technique to estimate the short-run causalities between the variables as it accounts for heterogeneity across the cross-sections.⁴ In addition to that, this test assumes that all coefficients are different across the cross-sections. Given that, this technique out performs the conventional Granger causality test and provides reliable results on the direction of causality between the variables, particularly in the short-run. Since this test is designed to apply on the stationary data so we apply this test on the first difference data series.

The findings of short-run causality are reported in Table 7. In terms of our primary interest of variables, the evidence shows bidirectional causality between R&D expenses and clean energy consumption, as well as of unidirectional causality running from CO₂ emissions to R&D expenses. In terms of the remaining variables, the findings document the presence of:

- i) Unidirectional causality running from clean energy consumption to FDI,

⁴ A number of recent empirical studies (Alam et al., 2017; Alam and Paramati, 2016; Bhattacharya et al., 2016; Paramati et al., 2016) argue that the heterogeneous panel non-causality test provides better results than those of the traditional Granger causality tests.

- ii) Bidirectional causality between clean energy consumption and per capita income,
- iii) Unidirectional causality running from stock market capitalization to carbon emissions.
- iv) Unidirectional causality running from per capita income to carbon emissions,
- v) Unidirectional causality running from population density to carbon emissions.

[Insert Table 7 about here]

Finally, for robustness purposes, the analysis also employs the panel ARDL model, suggested by Pesaran et al. (1999), to examine the long-run relationship between clean energy and CO₂ emissions. The robustness results are reported in Table 8. The new findings provide robust supportive evidence to those presented in Table 6. In particular, R&D expenses show a positive association with clean energy consumption, while they exert a negative impact on carbon emissions. In terms of the remaining variables, stock market capitalization, FDI and per capita income all have a positive effect on clean energy consumption, while clean energy consumption, stock market developments and per capita income reduce carbon emissions. Finally, both population density and FDI lead to higher CO₂ emissions.

[Insert Table 8 about here]

5. Conclusion and policy implications

In the recent period, policymakers, government officials and stakeholders are really concerned for the increasing global warming, which is mainly caused by greenhouse gas emissions. As a result, policymakers are initiating various energy and emission policies to reduce increasing CO₂ emissions across countries. More specifically, policymakers are paying more attention to the

R&D spending by hoping that it will bring the innovations in energy and emission technologies which can assist them to fight against CO₂ emissions. Policymakers are also shifting significant amount of FDI inflows and stock market investments into clean energy projects to generate more clean energy so that the demand for non-clean energy can be significantly reduced. In this study we aimed to examine the effect of R&D expenditure on clean energy consumption and CO₂ emissions across a panel of 30 OECD economies. To this end, the analysis considered annual data from 1996 to 2013 and employed various robust panel econometric methodologies.

The empirical findings confirmed the significant long-run equilibrium relationship among the variables. Furthermore, the results established that R&D spending had a considerable positive and negative effect on clean energy consumption and CO₂ emissions in the long-run. The results showed that FDI and stock market growth also promoted clean energy consumption, while they are consistent with previous findings provided by Paramati et al. (2016). The evidence also revealed that stock market growth had a negative effect on CO₂ emissions, while FDI had a positive impact. Overall, the results showed that R&D played an important role in promoting clean energy consumption and reducing CO₂ emissions across the OECD economies under investigation.

Given these findings, we suggest that policymakers and government officials in these OECD economies have to initiate more effective policies to increase funding directed to R&D activities, which eventually are expected to bring more innovations in energy efficiency and emission controlling technologies. Furthermore, the growth of R&D activities is expected to lower the cost of energy related technologies and help the firms and individuals to adopt cleaner technologies in their daily activities. Hence, it is important for policymakers to strengthen R&D activities so as to make the path towards sustainable economic growth along with a low carbon

economy. Finally, policymakers also should initiate more effective policies to divert the significant amount of FDI inflows and stock market investments into the clean energy industry. All these factors are expected to play a considerable role in promoting the boost of clean energy generation and consumption, and also minimizing (or even deleting) CO₂ emissions.

Statement of availability of data: The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Table 1

Country-specific summary statistics

Countries	CEC	CO ₂	R&D	SMC	FDI	GDPPC	PD
Australia	1.458	4.744	1.966	104.607	2.846	33195.388	2.660
Austria	11.172	2.111	2.254	25.176	3.950	37767.521	99.205
Canada	21.161	4.431	1.846	126.187	3.211	34656.761	3.545
Czech Republic	13.869	2.327	1.249	22.084	5.086	12810.114	133.632
Denmark	2.826	2.547	2.494	60.092	3.027	46953.810	127.927
Estonia	0.213	1.121	1.090	22.873	8.787	9284.583	32.100
Finland	20.564	2.568	3.258	102.045	3.152	37012.159	17.280
France	45.237	1.584	2.128	71.119	2.280	34048.483	114.778
Germany	13.162	2.537	2.493	44.908	2.067	35227.081	235.337
Greece	2.496	2.219	0.580	48.264	0.762	20544.081	84.770
Hungary	15.083	1.379	0.956	23.296	9.494	10197.386	112.434
Ireland	1.463	2.432	1.299	54.862	14.134	45788.551	60.184
Israel	3.871	2.567	3.876	64.847	3.322	21106.113	317.669
Italy	5.230	1.866	1.099	35.858	0.836	30858.220	197.278
Japan	15.251	2.361	3.192	72.523	0.161	35224.527	349.369
Korea	15.774	2.604	2.815	62.189	0.969	18294.422	496.042
Mexico	6.468	0.908	0.379	28.906	2.676	7818.912	56.404
Netherlands	1.640	3.731	1.810	97.552	21.077	40987.422	480.999
New Zealand	26.217	2.280	1.140	36.495	2.114	26481.552	15.540
Norway	38.588	2.284	1.596	49.209	2.946	64092.755	12.763
Poland	0.303	1.958	0.653	24.953	3.458	8173.980	124.909
Portugal	5.917	1.392	0.981	38.613	3.510	18354.286	113.737
Slovak Republic	24.685	1.758	0.641	69.885	3.851	11761.808	111.960
Slovenia	25.147	2.045	1.639	21.006	1.648	17271.603	99.891
Spain	16.310	1.877	1.078	103.171	3.125	25085.124	86.625
Sweden	46.680	1.614	3.437	101.922	5.089	41225.374	22.191
Switzerland	39.167	1.503	2.635	211.473	3.863	54615.642	189.116
Turkey	5.844	0.855	0.631	28.456	1.402	6948.306	87.443
United Kingdom	10.216	2.293	1.685	130.411	4.111	37879.887	250.573
United States	11.057	4.860	2.621	123.791	1.659	42325.194	32.111

Notes: Variables are measured as follows: CEC: Alternative and nuclear energy (% of total energy use); CO₂: CO₂ emissions per capita from energy consumption (MtCO₂ per million people); R&D: Research and development expenditure (% of GDP); SMS: Market capitalization of listed domestic companies (% of GDP); FDI: Foreign direct investment, net inflows (% of GDP); GDPPC: GDP per capita (constant 2005 US\$); PD: Population density (people per sq. km of land area).

Table 2

Panel summary statistics

Variable	Mean	Std. Dev.	Min	Max
CEC	14.902	13.401	0.003	50.734
CO2	2.292	1.006	0.711	5.195
R&D	1.784	0.978	0.259	4.480
SMC	66.892	51.288	1.194	291.658
FDI	4.154	7.097	-16.091	87.443
GDPPC	28866.370	15025.680	5505.048	69094.740
PD	135.616	128.767	2.384	515.253

Note: The measurement of the variables is as Table 1.**Table 3**

Cross-section dependence (CD) tests

Variables	Lags			
	1	2	3	4
CEC	8.765*** [0.00]	8.529*** [0.00]	8.449*** [0.00]	8.109*** [0.00]
CO ₂	7.326*** [0.00]	7.195*** [0.00]	7.310*** [0.00]	7.003*** [0.00]
R&D	9.436*** [0.00]	8.934*** [0.00]	9.118*** [0.00]	8.894*** [0.00]
SMC	9.104*** [0.00]	8.864*** [0.00]	9.007*** [0.00]	8.745*** [0.00]
FDI	7.883*** [0.00]	7.572*** [0.00]	7.430*** [0.00]	7.125*** [0.00]
GDPPC	8.125*** [0.00]	7.944*** [0.00]	8.006*** [0.00]	7.751*** [0.00]
PD	7.239*** [0.00]	7.038*** [0.00]	6.911*** [0.00]	6.784*** [0.00]

Notes: Under the null hypothesis of cross-sectional independence the CD statistic is distributed as a two-tailed standard normal. Results are based on the test of Pesaran (2004). Figures in parentheses denote p-values. Significance level: *** (1%).

Table 4

Panel unit root tests

Variable	Pesaran	Pesaran	Smith et al. t-test	Smith et al. LM-test	Smith et al. max-test	Smith et al. min-test
	CIPS	CIPS*				
CEC	-1.24	-1.30	-1.33	3.64	-1.29	1.38
Δ CEC	-5.77***	-5.91***	-5.66***	21.54***	-5.95***	6.16***
CO ₂	-1.28	-1.36	-1.40	3.51	-1.38	1.30
Δ CO ₂	-5.53***	-5.74***	-6.13***	20.81***	-7.39***	7.85***
R&D	-1.15	-1.28	-1.27	2.81	-1.26	-1.34
Δ R&D	-7.31***	-7.85***	-7.11***	23.82***	-7.35***	-7.90***
SMC	-1.34	-1.41	-1.35	2.80	-1.25	-1.33
Δ SMC	-6.38***	-6.59***	-6.19***	20.05***	-6.26***	-6.49***
FDI	-1.32	-1.40	-1.30	2.94	-1.31	-1.39
Δ FDI	-6.52***	-6.83***	-6.20***	20.85***	-6.58***	-6.72***
GDPPC	-1.25	-1.32	-1.32	2.95	-1.29	-1.38
Δ GDPPC	-6.11***	-6.58***	-6.28***	20.52***	-6.85***	-7.23***
PD	-1.32	-1.42	-1.39	2.93	-1.29	-1.35
Δ PD	-6.27***	-6.61***	-5.94***	19.74***	-5.96***	-6.39***

Notes: Δ denotes first differences. A constant is included in the Pesaran (2007) tests. Rejection of the null hypothesis indicates stationarity in at least one country. CIPS* = truncated CIPS test. Critical values for the Pesaran (2007) test are -2.40 at 1%, -2.22 at 5%, and -2.14 at 10%, respectively. “***” denotes rejection of the null hypothesis at the 1% level. Both a constant and a time trend are included in the Smith et al. (2004) tests. Rejection of the null hypothesis indicates stationarity in at least one country. For both tests the results are reported at lag = 3. The null hypothesis is that of a unit root.

Table 5

Westerlund's (2008) cointegration tests

Equation (1)	
DH _g	9.742[0.00]***
DH _p	9.906[0.00]***
Equation (2)	
DH _g	8.784[0.00]***
DH _p	9.051[0.00]***

Notes: p-values are reported in brackets. The criterion used in this paper is IC₂(K) with the Maximum number of factors (K) set equal to 5. For the bandwidth selection, M was chosen to represent the largest integer less than $4(T/100)^{2/9}$, as suggested by Newey and West (1994). *** indicates the rejection of null hypothesis of no cointegration at the 1% level of significance.

Table 6Long-run estimates on clean energy and CO₂ emission elasticities

Variable	Coefficient	P-value
Equation (1)		
CO ₂	-1.247***	[0.00]
R&D	0.259***	[0.00]
SMC	0.047***	[0.00]
FDI	0.061***	[0.01]
GDPPC	0.328***	[0.01]
Equation (2)		
CEC	-0.106***	[0.00]
R&D	-0.248***	[0.00]
SMC	-0.037***	[0.00]
FDI	0.052***	[0.00]
GDPPC	-0.139***	[0.00]
PD	0.256***	[0.00]

Note: The results are based on Common Correlated Effects estimates. '***' denotes significance at 1%.

Table 7

Heterogeneous panel non-causality test results

Null Hypothesis	Zbar-statistic	P-value
<i>Equation (1)</i>		
CO ₂ does not cause CEC	0.974	0.341
CEC does not cause CO ₂	0.337	0.683
R&D does not cause CEC	4.096 ^{***}	0.000
CEC does not cause R&D	2.153 ^{**}	0.024
SMC does not cause CEC	0.716	0.501
CEC does not cause SMC	0.488	0.624
FDI does not cause CEC	0.659	0.538
CEC does not cause FDI	2.006 ^{**}	0.035
GDPPC does not cause CEC	3.219 ^{***}	0.002
CEC does not cause GDPPC	1.996 ^{**}	0.048
<i>Equation (2)</i>		
R&D does not cause CO ₂	0.736	0.368
CO ₂ does not cause R&D	2.338 ^{**}	0.138
SMC does not cause CO ₂	3.783 ^{***}	0.000
CO ₂ does not cause SMC	0.604	0.583
FDI does not cause CO ₂	0.751	0.349
CO ₂ does not cause FDI	0.895	0.284
GDPPC does not cause CO ₂	4.893 ^{***}	0.000
CO ₂ does not cause GDPPC	1.006	0.125
PD does not cause CO ₂	5.439 ^{***}	0.000
CO ₂ does not cause PD	0.830	0.259

Note: ‘***’ and ‘**’ denote rejection of the null hypothesis at 1% and 5%, respectively.

Table 8

Robustness checks: panel ARDL model estimates

Variable	Coefficient	P-value
Equation (1)		
CO ₂	-1.672***	[0.00]
R&D	0.281***	[0.00]
SMC	0.041***	[0.00]
FDI	0.057***	[0.01]
GDPPC	0.286***	[0.00]
Equation (2)		
CEC	-0.093***	[0.00]
R&D	-0.293***	[0.00]
SMC	-0.043***	[0.00]
FDI	0.046***	[0.00]
GDPPC	-0.126***	[0.00]
PD	0.228***	[0.00]

Note: *, **, *** indicates the significance at the 10%, 5%, 1% level, respectively.