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Innovation, foreign direct investment (FDI), and the energy–pollution–growth nexus in OECD region: a simultaneous equation modeling approach

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Abstract

The paper proposes a new perspective in the environmental and resource economics literature by examining innovation (measured by R&D expenditures), FDI (measured by country–country technology transfer), and energy–environment–growth nexus. Using simultaneous equation modelling (SEMs), three econometric functions were formulated for production, energy consumption, and environmental pollution with GDP per capita, energy consumption, and CO_2 emissions (CO_2e) as dependent variables for twenty-four OECD economies for the period 1993 to 2014, respectively. The results failed to support the Environmental Kuznets Curve (EKC) hypothesis in the OECD economies. At the same time, a two-way causality was observed between GDP per capita and energy consumption per capita, indicating that the pollution has not yet reached the maximum threshold. Moreover, the results unveiled that fossil-fuel consumption, innovation, and FDI were the primary sources of CO_2e. The paper offers important implications for academics, policymakers, and identifies avenues for future research.

Keywords Energy consumption · FDI · Innovation · OECD · Pollution · Simultaneous equation modelling

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1 Introduction

Over the past few decades, there has been surging research in energy and environmental economics due to ever-increasing climate change, pollution, and carbon emissions. Climate change has become one of the most pressing concerns that the entire humanity faces today (cf. Bengochea-Morancho et al. 2001; Dar and Asif 2017; Sehid and Aydin 2019; Valadkhani et al. 2019). Recent reports have also warned that climate change may cause the global mean temperatures to rise between 4.8 and 7.4 °C by 2100 (Friedrich et al. 2016). CO_2e, as one of the primary determinant of rising global temperatures, is commonly associated with an escalating energy demand and consumption for economic activities and domestic use, e.g., cooking and heating (cf. Ahmad et al. 2018b; Inekwe et al. 2019; Rahman et al. 2019a). A significant decline in the global CO_2e from 2014 to 2016, however, indicates that green initiatives (i.e., green technology and energy efficiency improvements) have had positive environmental implications in term of reducing the long-standing overdependence on coal energy, a primary source of CO_2e. That said, a proportionate increase in CO_2e (0.5%) and overall production (1%) from 2017 to 2018 signals alarming climate change trends (IEA 2019). Thus, the complex interplay of innovation and FDI in the energy–pollution–growth nexus must be well-understood to design effective policies for a green future.

Theoretically, numerous studies have investigated the income–pollution nexus using various environmental indicators, e.g., degree of forestation, level of pollution, and air/environmental quality. Most of these studies have adopted the EKC hypothesis to investigate the link among economic growth and environmental pollution (cf. Ben et al. 2016; Mrabet et al. 2017; Rahman et al. 2019b; Wawrzyniak and Doryń 2020). Despite the novelty of economic techniques and the robustness of constructs (e.g., energy consumption, climate change, and globalization), there are apparent limitations in the previous models, i.e. use of single equations or reduced forms of the model (cf. Acaravci and Ozturk 2010; Ahmad et al. 2018a, b; Ahmed and Long 2012; Grossman and Krueger 1991; Javid and Sharif 2016; Lau et al. 2014; Nasir and Rehman 2011; Nassani et al. 2017; Obradović and Lojanica 2017; Saboori and Sulaiman 2013; Sehid and Aydin 2019; Shahbaz et al. 2012). Second, the use of pollution as an outcome of economic growth and energy is another methodological problem (cf. Ben et al. 2016; Chandia et al. 2018; Tamazian et al. 2009). Pollution also elicits an indirect impact on economic growth, given the cost associated with increased emissions (Ben et al. 2016), which partially explains significant differences in reported estimates conducted across different contexts and time horizons. Third, with several studies showing that innovation activities and FDI affect CO_2e (Atun et al. 2007), "estimating single equation relationships by ordinary least squares (where simultaneity exists) can produce biased and inconsistent estimates (Stern 1996, p. 6)." Therefore, Arminen and Menegaki (2019) proposed that a simultaneous equation model, under the EKC framework, is more appropriate for understanding energy–pollution–growth nexus.

Based on the above discussion, the main objective of this study is to assess the innovation, FDI, and energy–pollution–growth nexus using the much-asserted simultaneous equation modeling (SEM) technique for fresh insight. Secondly, the novelty of this study is the inclusion of new explanatory constructs (i.e. innovation and FDI) in the framework of energy–pollution–growth. Third, the paper entails a unique perspective, comprehensive insight, and a broader scope than most prior studies. Such that, the current study combines three strands of research using three equations presented hereafter. First, the *innovation-based production technology equation* investigates the link between energy consumption and per capita income. Second, the *energy consumption equation* examines the factors causing a change in energy demand. Third, *environmental pollution (EKC) equation* scrutinizes potential links between income and environmental pollution.

The structure of the remaining paper is as follows. Section 2 presents a review of theoretical and empirical works on the topic. Section 3 explains the simultaneous equation modeling procedures for three functions: production, energy consumption, and pollution. Section 4 exhibits details about Materials and methods including, data structures and econometric techniques. Section 5 includes the results and discussion. Section 6 constitutes the conclusion, policy implications, limitations, and future directions.

2 Literature review and conceptual framework

2.1 Innovation and economic growth

The classical *endogenous-growth theory* postulates that endogenous technological change is a key economic factor, which regulates the patterns of growth in the global economies. In the *new endogenous growth theory*, Romer (1986) views the research-sector as a production house for creating new ideas/innovation through effective use of existing stocks of knowledge and human capital. The new stock of knowledge facilitates the production of goods through permanent expansion in the final output (Ulku 2004). Many academics have explored the relationship between innovation and economic growth in different countries and regions. For instance, Kotabe (1992) found a positive correlation between innovation and economic growth in Germany, Britain, Japan, and the United States. Crosby (2000) examined the patents–economic growth nexus and found that innovation activities have significantly contributed to the economic growth in Australia. For Taiwan, Yang (2006) studied the impact of innovation activities (domestic and abroad) on economic growth and observed that an increase in patents increased economic growth. Using the GMM technique, Ulku (2004) tested [and found support for] the innovation-based growth model, which follows the assumption that innovations by the research-sector enable an economy to achieve sustainable economic growth. For China, Wu (2011) also observed the positive effects of innovation on economic growth. Bernier and Plouffe (2019) validated the positive impact of financial sector's innovation on economic growth in a sample of twenty-three nations. Hasan and Tucci's (2010) compared fifty-eight economies and concluded that economies with more patents demonstrated higher economic growth than those with fewer patents. Kacprzyk and Doryń (2017), however, found an insignificant effect of innovation on economic growth in the EU-15 and EU-13 economies. Table 1 depicts a summary of selected works on the innovation–growth nexus.

Table 1 Summary of selective works on the innovation–growth nexus

Authors	Period Country	Method	Innovation proxy	Main findings
Atun et al. (2007)	1901–1997 Australia	Multiple Regression	Patents	• Patents increased labor productivity • Patents increased economic growth
Yang (2006)	1951–2001 Taiwan	VARs	Patents	• Patents increased economic growth in both the long-term and short-term
Ulku (2004)	1981–1997 OECD and non-OECD	Fixed-effects and Arellano–Bond GMM	R&D	• Findings validated the endogenous growth theory • Innovation activities did not lead to permanent expansions in economic growth
Wu (2011)	1998–2007 China	2SLS	R&D	• Innovation contributed to economic growth
Adak (2015)	1981–2013 Turkey	Multiple regression	Patents	• New technology investments brought high productivity, which boosted economic growth rate
Bernier and Plouffe (2019)	1996–2014 23 countries	GEE	R&D	• Innovation increased economic growth
Hasan and Tucci (2010)	1980–2003 58 countries	Arellano–Bond GMM	Patents	• Patents increased economic growth
Kacprzyk and Doryń (2017)	1993–2011 EU-15 and EU-13	Fixed effects	R&D	• Innovation and economic growth were unrelated
Kotabe (1992)	1989–1963 Germany, Britain, Japan, and the United States	Lag estimation method	Patents	• Innovation and economic growth were related

VARs vector autoregression, *GMM* generalized method of moments, *2SLS* two-stage least squares, *GEE* generalized estimating equation, *R&D* research and development, *OECD* Organization for Economic Co-operation and Development, *EU* European Union

2.2 Innovation and energy consumption

Generally, the factor-demand equation is derived from the production-function or a flexible form-cost. As a distinct paradigm, research on energy consumption can be traced back to the seminal works of David Wood, Ernst Berndt, and Dale Jorgenson, who published a series of articles in the 1970s. These authors used the translog-cost function to investigate energy demand in the United States of America (cf. Berndt and

Wood 1975; Griffin et al. 1976). Among them, Jorgenson was the first to introduce technological innovation in the production-technology models. Fraumeni and Jorgenson (1981), using ‘time-trends’ as a factor, observed that energy output increased with an increase in technological innovation over time. Mountain et al. (1989) found that technological innovation contributed to savings in the consumption of natural gas, oil, and electricity in the manufacturing industries of Ontario (Canada), which led to an increase in the demand for natural gas. Sterner (1990) concluded that technological progress has led to fuel-savings in the cement industry of Mexico. Berndt et al. (1993), using a translog cost equation, confirmed that technological change leads to savings in both electricity and different types of fuels in the manufacturing sectors of France, Canada, and the United States. Popp (2001a, b) stated that the two energy crises (during the 1970s) paved the way for innovation activities that focused on energy-savings (see also, David 1998).

Nonetheless, the use of ‘time-trend’ as a proxy for technological change in most prior models entails two critical limitations. First, these models are time-responsive, to the extent that, any improvement in energy-saving technology is dependent on energy prices. Second, the ‘time-trend’ approach greatly underestimates the overall influence of technological innovation (David 1998). As a feasible alternative to the noted approach, Du and Yan (2009) tested the link between the innovation of technology and energy consumption for China. The data supported that technological innovations facilitated energy efficiency and led to a significant reduction in energy consumption. Tang and Tan (2013) studied the relationship between innovation, energy prices, electricity consumption, and energy prices. As per results, innovation affected electricity consumption negatively while innovation-Granger led to electricity consumption. Sam et al. (2016) tested the role of endogenous drivers of innovation, demand-pull, and technology push vis-a-viz renewable energy across fifteen countries in Europe. The authors concluded that innovation positively influences the diffusion of renewable energy. Fei and Rasiah (2014) explored the relationship between innovation, growth, energy prices, and electricity consumption for Ecuador, Norway, Canada, and South Africa. Even though the results of this study failed to support a significant and positive impact of innovation on fossil-fuel consumption in the long-run, there is parallel evidence that innovation reduces fossil-fuel consumption (e.g., Jin and Zhang 2014). In another study, Sohag et al. (2015) conducted a study to investigate the link between trade openness, energy consumption, innovation, and economic growth for Malaysia, which revealed a negative relationship between innovation and energy use. Irandoust (2016) observed that innovation-Granger predicted renewable energy consumption among Nordic nations while examining the relationship between renewable energy consumption, CO_2e, and innovation. Jin et al. (2018) validated prior evidence concerning the positive impact of innovation on energy-use in the short-term.

2.3 Innovation and environmental pollution

There is considerable theoretical and empirical evidence to propose that innovation is a proximal tool to reduce the harmful effects of greenhouse gases (GHG) emissions on the environment. In an attempt to use eco-innovation to mitigate CO_2e, industries and governments around the world have been promoting R&D investments through budget allocations for R&D for product and process improvement (Gu and Wang 2018). Academics and researchers, on the other hand, have focused on unwrapping the complicated relationship between environmental pollution and innovation. For instance, Mensah et al. (2018) studied the innovation–CO$_2$e nexus for the OECD economies using a three equations STIRPAT model. The estimations indicated that innovation hindered CO$_2$e in some of the sampled OECD economies. Ali et al. (2016) examined the association between technological innovation, financial development, energy consumption, and economic growth for Malaysia. The results showed a negative but insignificant link between innovation and CO$_2$e. Santra (2017) found that innovation increased energy consumption and CO$_2$e in the BRICS economies. For Malaysia, Yii and Geetha (2017) used the VECM-based estimates to support that innovation helps to restrict CO$_2$e in the short run, but the long-run impact was found to be insignificant. Lee and Min (2015) explored the interaction between green R&D, financial development, and CO$_2$e for the manufacturing industry in Japan. The results showed that an increase in firm-level R&D investment led to reduced CO$_2$e, whereas green innovation positively affected financial performance. Su and Moaniba (2017) adopted the GMM method to investigate the nexus between innovation and climate change. The authors found that innovations in liquid-fuels (e.g., petroleum) and natural gas had a significant role in reducing CO$_2$e. Álvarez-Herránz et al. (2017) validated that energy-centric innovation played a major role in reducing GHG emissions in OECD members countries. In contrast, Shahbaz et al. (2018) found that energy-innovation and CO$_2$e are negatively interrelated, but FDI and financial development have mitigated CO$_2$e. Long et al. (2017) observed the impact of eco-friendly innovation on the environment and economic performance among Korean-owned firms in China. The results suggested that production-led innovation mitigated toxic emanations of gases. Apart from the studies discussed above, the inverse relationship between innovation and pollution has been documented for the EU, US, and China (Fernández et al. 2018), China (Zhang et al. 2017), OECD economies (Ahmad et al. 2019), BRICS (Khattak et al. 2020), selected provinces in China (Khan et al. 2019), and the USA (Dinda 2018). Table 2 provides a summary of selected works on the innovation–pollution nexus.

2.4 FDI, energy consumption, and environmental pollution

Prior studies offer insight into the relationship between energy consumption, environmental pollution, and economic growth using the SEM approach. Nation–nation transfer of technologies can significantly boost energy demand and GHG emissions, yet in effect, the role of FDI, energy consumption, and environmental degradation in the energy–pollution–growth nexus remains unexplored (cf. Li and Qi 2016; Rahman et al. 2019b, c). As per the *pollution-haven hypothesis* (PHH), investments (FDIs) or trade liberalization (direct or indirect) triggers a shift in the production of pollution-intensive goods to economies with relatively weak environmental policies and regulations (Aklin 2016). As per Gallagher (2008), although FDI damage the environment in countries with weak environmental policies due to pollution-intensive production, it simultaneously generates trade advantages. In the first PHH study, Pethig (1976) used a simple

Table 2 Summary of selected works on the innovation–pollution nexus

Authors	Period Country	Method	Main findings
Mensah et al. (2018)	1990–2014 OECD	ARDL	• The effects of innovation on CO_2 varied across OECD countries, i.e. positive and negative
Ali et al. (2016)	1995–2012 Malaysia	ARDL	• There was a negative and insignificant relationship between innovation and CO_2e
Santra (2017)	2005–2012 BRICS	Pooled Regression	• Innovation increased CO_2e
Yii and Geetha (2017)	1971–2015 Malaysia	VECM	• Innovation decreased CO_2e in the short run
Lee and Min (2015)	2001–2010 Japan	Least square linear predictor	• Green R&D decreased in CO_2e
Su and Moaniba (2017)	1976–2014 70 countries	GMM	• Innovation increased CO_2e originating from liquid fuels and gases • Innovation reduced CO_2e from solid-fuel
Álvarez-Herránz et al. (2017)	1990–2014 OECD	Lag distribution model	• Energy-based innovation reduced GHG emissions
Shahbaz et al. (2018)	1955–2016 France	ARDL	• Energy-focused innovation decreased CO_2e
Innes and Carrio (2010)	1989–2004 US	GMM	• Environment-focused innovation mitigated toxic gas emissions
Long et al. (2017)	June 2015 to March 2016 China	Correlation; factor analysis	• Innovation activities have improved environmental quality
Fernández et al. (2018)	1990–2013 EU, US, and China	OLS	• R&D spending have positively contributed to reduce CO_2e
Zhang et al. (2017)	2000–2013 China	SGMM	• Environmental innovation reduced CO_2e
Yu and Du (2019)	1997–2015 China	Multiple Regression	• Innovation reduced CO_2e

ARDL autoregressive-distributed Lag, *VECM* vector error correction model, *GMM* generalized method of moments, *OLS* ordinary least square, *SGMM* system generalized method of moments, *R&D* research & development, *OECD* Organization for Economic Co-operation and Development, *BRICS* Brazil, Russia, India, China, South Africa, *EU* European Union, *US* United States two-Ricardian trade model and compared two similar economies (North vs. South), where the northern economy had a higher pollution tax than the southern economy. The results of this study suggested that both economies had distinct advantages, i.e. the former excelled in clean production and the latter thrived on pollution-intensive production (Rahman et al. 2019c). Several studies have attempted to validate the PHH for different regions through different methods. Some of the selected works are given below in Table 3.

3 Simultaneous equation modeling: integrating innovation and FDI into the energy–environment–growth framework

In the present context, the SEM (with a system of three equation) proves to be a superior choice for econometric analysis in many ways. First, this approach allows for the simultaneous estimation of relationships and causality among variables. Second, this method can help to calculate the reverse causality between the study variables (Arminen and Menegaki 2019; Tiba and Omri 2017). The current SEM framework comprises of three equations: (i) *production function*; (ii) *energy consumption function*; (iii) *environmental pollution function*. The afore-mentioned functions are discussed below.

3.1 Function 1: production

After 1973, the supply of energy resources experienced drastic changes in the US, Western Europe, and the rest of the world due to shocks in oil prices. As a possible explanation, theorists have argued that changes in capital stock have proven to be an inappropriate measure to predict changes in energy supply (Gabisch and Lorenz 2013). Rasche and Tatom (1977) were the first to introduce the energy-based production function. The authors incorporated energy resources as a factor of production in the Cobb–Douglas production function, as shown below in Eq. (1):

$$Y = AK^{\psi}L^{\chi}E^{\xi} \tag{1}$$

where Y is the aggregate output; A is the technology efficiency; K is the capital resources; L is the labor force; and E is the flow of energy resources. Alternatively, some authors have also used human capital as a factor of production in the endogenous growth model (cf. Fang and Chen 2017). Based on such a concept, the Eq. (1) was extended by including human capital in the neoclassical production function, an approach used in previous studies (e.g., Arminen and Menegaki 2019):

$$Y = AK^{\psi}(HL)^{\chi}E^{\xi} \tag{2}$$

where H is the human capital/per person. Assuming $\psi + \chi + \zeta = 1$ and dividing Eq. (2) by labor force, the following equation was obtained:

Table 3 Summary of selected studies on the FDI–pollution nexus

Authors	Period Country	Method	Main findings
Rahman et al. (2019b)	1975–2016 Pakistan	NARDL	• Environmental pollution increased with an increase in FDI
Rahman et al. (2019a)	1982–2014 6 Asian economies	ARDL	• A positive relationship existed between FDI and CO_2e
Haug and Ucal (2019)	1974–2014 Turkey	ARDL	• FDI had an insignificant effect on CO_2e per capita in the long run
Rana and Sharma (2019)	1982–2013 India	Toda-Yamamoto	• Environmental pollution increased with an increase in FDI
Seker et al. (2015)	1974–2010 Turkey	ARDL	• There exists a positive linkage between FDI and CO_2e
Kearsley and Riddel (2010)	1980–2004 OECD	Multiple Regression	• Environmental pollution increased with an increase in FDI
Neequaye and Oladi (2015)	2002–2008 Developing countries	Fixed effects	• Environmental pollution increased with an increase in FDI
Sapkota and Bastola (2017)	1980–2010 Latin America	Fixed and random effects	• The results validate the PHH
Wang et al. (2019)	2007–2010 China	OLS and PPML	• No relationship was observed between FDI and pollution
Dou and Han (2019)	2000–2015 China	Mediation model	• The results validate the PHH
Sun et al. (2017)	1980–2012 China	ARDL	• The results validate the PHH.
Solarin et al. (2017)	1980–2012 Ghana	ARDL	• The results validate the PHH
Al-Mulali and Tang (2013)	1980–2009 GCC	Fully modifies OLS	• FDI improved environmental quality
Rasit (2017)	2000–2010 ASEAN and OECD	Random effects	• No relation was found between FDI and pollution

NARDL nonlinear autoregressive-distributed lag, *ARDL* autoregressive-distributed lag, *OLS* ordinary least square, *PPML* Poisson pseudo maximum likelihood, *OECD* Organization for Economic Co-operation and Development, *GCC* Gulf Cooperation Council, *ASEAN* Association of Southeast Asian Nations

$$\frac{Y}{L} = A\left(\frac{K}{L}\right)^{\psi} H^{\chi}\left(\frac{E}{L}\right)^{\xi}. \tag{3}$$

Next, logarithms were incorporated on both sides of the Eq. (3) to extract the growth equation, as shown in Eq. (4):

$$y_{it} = \eta_{it} + \psi k_{it} + \chi h_{it} + \xi e_{it} \tag{4}$$

where $y_{it} = \log(Y)$; $k_{it} = \log\left(\frac{K}{L}\right)$; $h_{it} = \log(H)$; $e_{it} = \log\left(\frac{E}{L}\right)$. Following prior concepts (cf. Karafillis et al. 2011; Kim and Park 2018; Wong et al. 2016), it was assumed that total factor productivity (η_{it}) is dependent on technological innovation, as depicted through Eq. (5) below:

$$\eta_{it} = \delta_0 + \theta Z_{it} + \varepsilon_{1.it}. \tag{5}$$

By combining Eqs. (4) and (5), Eq. (6) was obtained:

$$y_{it} = \delta_0 + \psi k_{it} + \chi h_{it} + \xi e_{it} + \theta Z_{it} + \varepsilon_{1.it}, \tag{6}$$

where Z_{it} is the innovation and $\varepsilon_{1.it}$ is the error-term. Assuming that human and physical capital, innovation, and energy consumption are important factors of production, these variables were expected to increase the final output. This implied that ψ, χ, ξ and θ should be higher than zero. Even though some academics have used pollution as a variable in production function (Hung and Shaw 2014), it was excluded from the equation due to its inconsistency with the original *production theory*. This theory posits that pollution variable is not a factor of production.

3.2 Function 2: energy consumption

Based on the literature discussed above, innovation and FDI were incorporated in the energy consumption function as depicted in Eq. (7):

$$EC_{it} = \gamma_o + \gamma_1 y_{it} + \gamma_2 ind_{it} + \gamma_3 z_{it} + \gamma_4 fdi_{it} + \varepsilon_{2.it}, \tag{7}$$

where EC_{it} is the energy consumption; y_{it} is the per capita income; ind_{it} is the industrialization; z_{it} is the innovation; fdi_{it} is the foreign direct investment; $\varepsilon_{2.it}$ is the error-term. With Apergis and Payne's (2009) study validating a two-way causality between energy consumption and CO_2e. CO_2e could be incorporated in the energy consumption function as an explanatory factor. That said, this conceptual support was considered insufficient in line with recent studies (cf. Arminen and Menegaki 2019). As energy consumption increases due to a rise in national income (cf. Zhang et al. 2011), γ_1 was expected to be higher than zero. Following Arminen and Menegaki's (2019) approach, γ_2 should be higher than zero as an increase in industrial production causes a massive surge in energy consumption, which enhances economic growth. Fraumeni and Jorgenson (1981) argue that technologies resulting from innovation have multiple benefits. For example, technologies increases the efficiency of capital goods and introduce new energy sources for public use. As energy-savings from innovation may vary across different industries and countries (Sterner 1990), it is estimated that z_{it} can have alternate signs (positive/negative), depending on the efficiency of energy capital. Previous research suggest that higher FDI translate into higher energy demand, which happens due to an increase in manufacturing, transportation, and industrial sectors (Salim et al. 2017). Mielnik and Goldemberg (2002), however, found an inverse association exists between FDI and energy consumption in twenty developing economies. Considering such, γ_4 was also estimated to have either a positive or negative sign, depending on the efficiency level of technology.

3.3 Function 3: environmental pollution

The environmental pollution function was drawn from past research in the EKC literature. This equation estimated the impact of innovation on the environment pollution and influence of FDI on energy consumption. Equation (8) below depicts the functional form of these relationships:

$$EP_{it} = \Phi_0 + \Phi_1 y_{it} + \Phi_2 y_{it}^2 + \Phi_3 e_{it} + \Phi_4 z_{it} + \Phi_5 fdi_{it} + \Phi_6 urb_{it} + \varepsilon_{3.it}, \qquad (8)$$

where EP_{it} is the environmental pollution (measured by CO_2e); y_{it} is the income per capita; y_{it}^2 is the income per capita (squared); e_{it} is the energy consumption[1]; z_{it} is the innovation (measured by R&D expenditures); fdi_{it} is the inflow of foreign direct investment; urb_{it} is the urbanization (measured by total urban population); and $\varepsilon_{2.it}$ is the error-term. In Eq. (8), all variables were transformed into logarithmic forms. The signs of Φ_1 and Φ_2 were predicted be positive and negative, respectively, given that y_{it} and y_{it}^2 capture the EKC's inverted U-shape. As previous findings indicate that increased use of energy causes high CO_2e (cf. Ahmad et al. 2018a), the sign of Φ_3 was predicted to be higher than zero ($\Phi_3 > 0$). Φ_4 was expected to be negative. Reason being, some studies have shown that continuous R&D investment generates new technology that not only increases productivity but also improves environmental quality (cf. Ali et al. 2016).

Congruent with above, past PHH studies reflect mixed results and inconsistent findings. Some studies have reported that transfer of less eco-friendly technologies contributes to CO_2e (cf. Dou and Han 2019), while others have found either a positive or insignificant impact of FDI on CO_2e (Wang et al. 2019). Thus, Φ_5 was assumed to be either positive or negative. In the same way, there is conflicting empirical evidence on the relationship between urbanization and CO_2e (cf. Arminen and Menegaki 2019). Due to this reason, the total impact of urbanization on CO_2e was assumed to be either positive or negative (Sharma 2011). Past studies have used different energy sources (rather than total energy consumption) to avoid the omitted variable biases (cf. Ahmad

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[1] Past literature (e.g., Burnett et al. 2013; Itkonen 2012; Jaforullah and King 2017) suggests that the inclusion of energy consumption in the EKC equation causes systematic volatility in the coefficients of all variables. But there is recent evidence for the use of energy consumption as a factor in the energy–environment–growth nexus (Ahmad et al. 2018a, b; Arminen and Menegaki 2019).

and Khattak 2020; Arminen and Menegaki 2019; Behera and Dash 2017; Burnett et al. 2013; Itkonen 2012; Jaforullah and King 2017; Zhou et al. 2018). Following Arminen and Menegaki's (2019) approach, fossil-fuel consumption per capita (ffc_{it}) was taken as an independent variable in the final environmental pollution equation (see Eq. (9):

$$EP_{it} = \varPhi_0 + \varPhi_1 y_{it} + \varPhi_2 y_{it}^2 + \varPhi_3 ffc_{it} + \varPhi_4 z_{it} + \varPhi_5 fdi_{it} + \varPhi_6 urb_{it} + \varepsilon_{3.it}. \quad (9)$$

The summarized form of three structural equations was estimated as follows:

$$y_{it} = \delta_0 + \psi k_{it} + \chi h_{it} + \xi e_{it} + \theta Z_{it} + \varepsilon_{1.it}$$

$$EU_{it} = \gamma_o + \gamma_1 y_{it} + \gamma_2 ind_{it} + \gamma_3 z_{it} + \gamma_4 fdi_{it} + \varepsilon_{2.it}$$

$$EP_{it} = \varPhi_0 + \varPhi_1 y_{it} + \varPhi_2 y_{it}^2 + \varPhi_3 ffc_{it} + \varPhi_4 z_{it} + \varPhi_5 fdi_{it} + \varPhi_6 urb_{it} + \varepsilon_{3.it}. \quad (10)$$

4 Materials and methods

4.1 Data sources and variables

A panel data of twenty-four OECD countries was selected data analysis. This data type was more appropriate to address common problems associated with the short panel series. It not only allows for controlling for country-specific effects, but also helped us to address cross-section heterogeneity across the panels. Data for different variables were extracted from the World Bank Indicators (2016). This comprehensive database enabled us to compile data for a longer time frame. Based on the work of Arminen and Menegaki (2019), the data for 2 years were averaged to avoid business-cycle and measurement errors and discrepancies. The final dataset included data for eleven periods between 1993–1994 and 2013–2014. For detailed information about data, see Appendices 1, 2, and 3. Appendix 1 provides the details of variables, descriptions, data sources, and estimation methods. Appendix 2 provides a list of sample countries. Appendix 3 shows the descriptive statistics for the study variables. All the variables were transformed into the logarithmic form (2-years average). The time-frame was considered too short for estimating stationarity, and thus, all variables were differenced. With first differences holding high probability of stationarity, computing the model in 1st difference proves to be an effective measure to avoid issues related to high persistence and trends. According to Stern et al. (2017), there is a high possibility that GDP and CO_2e might be stationarity in the first difference due to probable I(1) order of integration.

4.2 Econometric techniques

The SEM approach offers two options for data analysis. The first option involves estimation through a single equation and the second entails analysing a system of equations. Arminen (2018) and Wooldridge (2010) offers some advantages and disadvantages to this method. Arminen (2018) strongly recommends its use for analysing energy–environment–economic growth nexus. Model specification is regarded as the most critical step to avoid miscalculations, underestimation, and overestimation. With correct model specifications, the SEM provides better results than single equation models and techniques. If one of the system equation is not specified correctly, the reported estimates hold the risk of misleading outcomes and contaminated parameters. In previous studies, researchers have often relied on the dynamic generalized method of moment (both differenced and system GMM) to reduce the risk associated with model specifications (cf. Arellano and Bond 1991; Arellano and Bover 1995; Blundell and Bond 1998). Roodman (2009) also provides some properties of the SEM approach. Apart from estimating single dependent variables at a given time, this technique allows for categorizing unknown parameters through several equations (cf. Carrión-Flores and Innes 2010).

Nonetheless, scholars have used both the applied difference GMM estimator (Arminen and Menegaki 2019) and the system GMM approach (Tiba et al. 2016). With the SEM on internal instrumental variables, both the methods offer an added benefit of extracting statistically reliable external instrumental variables. Since it is challenging to find valid exogenous instruments that show variance over time and across units, external instruments have great potential to address estimation issues, e.g., potential reverse causality. Farhadi et al. (2015) advocated the use of difference and system GMM as the best alternatives for internal instruments. The functional forms of the SEM used in this study are given below;

$$\gamma_{it} = x_{it}\beta + \vartheta\gamma_{i,t-1} + \varepsilon_i + \mu_{it}. \tag{11}$$

Arminen and Menegaki (2019, p. 628) stated that, “the subscript i denotes cross-sectional units (here: countries) and t time (here: 3-year periods). In the current context, it was assumed that the error-term as composed of the fixed individual-effects ci, while the idiosyncratic shocks ‘ε’ would hold the following properties: $\mathrm{E}[c_i] = \mathrm{E}[\varepsilon_{it}] = [c_i\varepsilon_{it}] = 0$. By taking the difference of Eq. (11), an attempt was made to eliminate the individual fixed-effects. This condition is expressed as follows;

$$\Delta\gamma_{it} = \Delta x_{it}\beta + \vartheta\Delta\gamma_{i,t-1} + \mu_{it}, \tag{12}$$

where the sign “Δ” is the differenced operator in Eq. (12).

For the first difference, the predetermined variables were assumed to transform into endogenous variables. The explanatory variables’ deeper lags were taken as practical instruments. The differenced GMM estimators used the lagged endogenous and predetermined variables as similar constructs in the first difference. The original equations in levels were incorporated into the system of first-differenced equations by the system GMM estimator. Unlike the differenced GMM, the system GMM uses the first differences of the lagged endogenous and predetermined variables as instruments. Assuming that the individual effects are not correlated with the error terms, the autocorrelation and second-order autoregression were tested (with the Hansen test) to restrict the over-identification of instruments in the model (cf. Arellano and Bond). Roodman (2009), however, has highlighted a limitation that remains underestimated in most GMM-based studies. The results of the system and difference GMM would be consistent only if the cross-sections are greater than the periods (N > T). If the cross-sections are smaller with large T, the Arellano Bond test of autocorrelation and robust standard-error will prove to be unreliable. Therefore, Roodman (2009) offers a rule of thumb for the instrument selection: the number of instruments must be smaller than the number of studied cross-sections.

5 Results and discussion

As per accepted standards, the Xtabond2 command was employed for empirical estimation of multiple models (cf. Roodman 2009). As the one-step GMM requires efficiency of uncorrelated error and homoskedasticity, the two-step estimator was used given its asymptotical effectiveness. The finite sample correction approach was adopted to address potential downward-biased standard-errors, a method commonly used to treat asymptotic variance for the two-step GMM estimator (cf. Arellano and Bond 1991; Blundell and Bond 1998; Windmeijer 2005). In the transformed equation, the lag length of the instrumental variables was confined to 1–3 and 2–4 for the predetermined and endogenous variables, respectively. The small-sample statistics were assumed to make up for the small sample size. The period dummies were also included in all the models. This procedure was conducted to ensure that the assumption of no-autocorrelation across the cross-sections (countries) in the idiosyncratic error-term stands valid. Below, Tables 4, 5, 6 summarizes the results of the difference and system dynamic GMM approach for each model. As seen below, the results for A, C, E, and G were estimated with the two-step difference GMM method, whereas the outputs for B, D, F, and H were computed with the two-step system GMM.

Table 4 presents the empirical results of the production function. The table showed that energy consumption, innovations, and physical capital are important factors of production in OECD countries. The estimated model supported the significant role of energy consumption, physical capital, and technological innovation in the production process, while human capital was found to be an insignificant factor in all the estimated models. As noted earlier, the Hansen test was used to assess the over-identification of the instruments. The results of this test showed that all the instruments were valid. The insignificant values supported that no second-order autocorrelation existed in the first difference error-terms. Also, the model estimators were consistent and free from autocorrelation. Roodman's (2009) rule of thumb was validated as the number of groups were greater than the instruments used.

Table 5 shows the results of the energy consumption function. The estimated model revealed a direct relationship between the GDP per capita and energy consumption, where an increase in income caused a rise in energy consumption. From both the production and energy consumption function, the existence of a two-way causality was observed between energy consumption and the GDP per capita. More so, the data suggest that industrialization positively contributed to energy consumption for some models. Compared to the FDI and innovations, industrialization proved to be a better predictor of energy consumption for the OECD region. Beyond that, the results indicated that all the instruments were valid. The second-order Arellano–Bond test

Table 4 Production function

Output function	A	B	C	D
Y_{t-1}	0.2817**	0.2818***	0.2795***	0.2651***
	(0.0695)	(0.0582)	(0.0631)	(0.0557)
K	0.2492***	0.2637***	0.2456***	0.2585***
	(0.0344)	(0.0229)	(0.0364)	(0.0239)
H	0.4815	0.2006	0.4531	0.7003
	(0.5254)	(0.2546)	(0.5216)	(1.2641)
EU	0.0905**	0.0751**	0.1024**	0.0830**
	(0.0424)	(0.0431)	(0.0386)	(0.041)
Z			0.186***	1.44E−01***
			(0.0152)	(0.0164)
Observations	240	264	240	264
Groups	24	24	24	24
Instruments	23	18	21	19
Arellano–Bond AR (1)	P = 0.003	P = 0.002	P = 0.002	P = 0.004
Arellano–Bond AR (2)	P = 0.811	P = 0.772	P = 0.699	P = 0.783
Hansen test	P = 0.081	P = 0.224	P = 0.245	P = 0.271

Year dummies are not reported here, the values in (), are standard errors, The Arellano–Bond and Hansen test's P values are given for; H0 = no autocorrelation and instruments are valid respectively. ** and *** represents level of significance at 5% and 1%, correspondingly

Table 5 Energy consumption function

Output function	A	B	C	D	E	F
EU_{t-1}	0.118	0.1429**	0.1069	0.1327	0.115	0.1118**
	(0.111)	(0.0842)	(0.1028)	(0.5011)	(0.0918)	(0.035)
Y	0.3414***	0.3247***	0.3480***	0.3227***	0.3468***	0.3758***
	(0.0997)	(0.080)	(0.0992)	(0.0535)	(0.095)	(0.054)
IND	0.1081*	0.0527*	0.1074**	0.0585	0.1118**	0.0081
	(0.0722)	(0.043)	(0.068)	(0.4178)	(0.0668)	(0.1446)
Z			0.0159	0.0225	0.0128	0.0198
			(0.0216)	(0.0165)	(0.0201)	(0.0169)
FDI					− 0.0062	− 0.0448*
					(0.0046)	(0.026)
Observations	240	264	240	264	240	264
Groups	24	24	24	24	24	24
Instruments	21	22	23	23	23	21
Arellano–Bond AR (1)	P = 0.007	P = 0.003	P = 0.007	P = 0.002	P = 0.006	P = 0.005
Arellano–Bond AR (2)	P = 0.894	P = 0.96	P = 0.834	P = 0.931	P = 0.838	P = 0.406
Hansen test	P = 0.283	P = 0.49	P = 0.337	P = 0.487	P = 0.437	P = 0.382

Year dummies are not reported here, the values in (), are standard errors, The Arellano–Bond and Hansen test's P values are given for; H0 = no autocorrelation and instruments are valid respectively. *, **, and *** represents level of significance at 10%, 5% and 1%, correspondingly

Table 6 Environmental pollution function

Output function	A	B	C	D	E	F	G	H
EP_{t-1}	0.0742	0.07902***	0.0782	0.0933***	0.0776	0.0818**	0.1007**	0.0859**
	(0.0748)	(0.0247)	(0.0825)	(0.0274)	(0.0666)	(0.033)	(0.0517)	(0.0326)
Y	0.0632	− 0.1113	0.0718*	0.0328**	0.0905	0.0378	4.4957	0.00074
	(0.0612)	(0.0434)	(0.0648)	(0.1154)	(0.0648)	(0.1162)	(3.9101)	(0.118)
Y^2	− 2.6197***	1.1353**	− 2.584***	− 2.4369***	− 2.308***	− 0.2908	− 0.5397	− 1.0129
	(0.7365)	(0.5312)	(− 0.7886)	(0.1491)	(0.8924)	(2.5218)	(0.4612)	(2.5779)
FFC	0.9180***	0.9222***	0.9129***	0.8995***	0.9135***	0.9027***	0.9623***	0.8995***
	(0.0790)	(0.0262)	(0.0798)	(0.0295)	(0.0791)	(0.0298)	(0.08817)	(0.0294)
Z			0.0248*	0.0441***	0.0355*	0.0417***	0.0453*	0.0488***
			(0.0215)	(0.0118)	(0.0202)	(0.0123)	(0.0246)	(0.0137)
FDI							0.0065**	0.0061**
							(0.0032)	(0.0023)
URB					0.0226	0.0226	0.1487	− 0.0614
					(0.1687)	(0.1687)	(0.8712)	(0.1753)
Observations	240	264	240	264	240	264	264	264
Groups	24	24	24	24	24	24	24	24
Instruments	23	23	17	21	19	22	17	23
Arellano–Bond AR (1)	P = 0.041	P = 0.045	P = 0.007	P = 0.007	P = 0.002	P = 0.049	P = 0.054	P = 0.001
Arellano–Bond AR (2)	P = 0.126	P = 0.068	P = 0.415	P = 0.415	P = 0.551	P = 0.51	P = 0.156	P = 0.44
Hansen test	P = 0.100	P = 0.065	P = 0.100	P = 0.100	P = 0.351	P = 0.119	P = 0.129	P = 0.186

Year dummies are not reported here, the values in (), are standard errors, The Arellano–Bond and Hansen test's P-values are given for; H0 = no autocorrelation and instruments are valid respectively. *, **, and *** represents level of significance at 10%, 5% and 1%, correspondingly suggested that the models were free from autocorrelation in differenced residuals. Roodman's (2009) rule of thumb was validated.

Table 6 exhibits the results of the pollution function. The estimations showed an insignificant coefficient for GDP per capita for A, B, C, E, F, G, and H, except for D (after the inclusion of innovation in the model). The GDP per capita value became significant (with a positive effect), while the squared term displayed a negative sign with significant explanatory power. This supported the existence of an inverted-EKC in the OECD region. Some of the results are as follows. First, fossil-fuel consumption was found to be the most important determinant of environmental pollution (significant and positive). Second, FDI and innovations also exerted a substantial impact on CO_2e, given that the significant explanatory powers and positive direction of these variables. Third, the results showed that energy consumption, innovations, and FDI inflows also increase CO_2e in the OECD regions. In addition, the Hansen and Arellano–Bond test showed that the instruments were valid, and the second-order serial correlation among the first-differenced errors was non-existent. Roodman's (2009) rule of thumb was validated as all the models met the criterion stated earlier.

To summarize, although the empirical estimates supported a two-way causality between energy consumption and GDP per capita (feedback hypothesis), the existence of the EKC was unsupported. The EKC was excepted for the model (D) only when innovation was integrated into the model. Overall, the results identified energy consumption, innovation, and FDI as the key factors causing environmental pollution in the OECD region.

The following part presents a brief discussion on the results of the production, energy consumption, and environmental pollution function.

5.1 Production function

As stated above, the results of the production function highlighted the importance of physical capital for the OECD economies. The strong explanatory power (with a positive sign) depicted that a single unit increase in the physical capital caused an increase in the total economic output. The data also supported the energy consumption-led growth hypothesis, where an increase in energy consumption significantly contributed to economic growth. With the present results validating the feedback relationship between energy consumption and GDP growth, these findings are consistent with prior studies (cf. Omri and Kahouli 2014; Sinha 2016; Sunderasan 2013). Moreover, the present results supported the new growth theory as the inclusion of innovation in the production function had a significant positive effect on the output (Ulku 2004). This finding supports earlier evidence suggesting that R&D and innovation have positively affected GDP growth in Australia (Atun et al. 2007); Taiwan (Yang 2006); China (Wu 2011); Turkey (Adak 2015); GEE nations (Bernier and Plouffe 2019); 58 nations (Hasan and Tucci 2010); and Germany, Britain, Japan and the United States (Kotabe 1992). Beyond that, the present results also validated an insignificant/positive association between human capital and economic growth. A possible explanation is that most industries in the OECD economies have replaced labor with artificial intelligence/robots during the last few decades, thereby significantly reducing the industrial's labor force. This initiative, to some extent, undermed labors' contribution in the process of growth.

5.2 Energy consumption function

The inclusion of the income per capita term in the energy function led to a bidirectional feedback effect between energy consumption and GDP per capita. The positive explanatory power showed that per-unit energy consumption, coupled with an industrialization strategy, play an important role in the production process. This result not only the feedback effect of energy and GDP per capita, but also supported previous estimations for China (Yanqing and Mingsheng 2012); 24 selected economies (Tiba and Frikha 2018); India (Sinha 2016); 63 selected economies (Nasreen et al. 2018); 13 MENA countries (Sekrafi and Sghaier 2018); 72 selected economies (Amri 2017); 58 countries (Saidi and Hammami 2016); and 17 selected countries (Omri et al. 2015). Moreover, although academics have asserted that innovations in technology positively impact energy-savings (Berndt et al. 1993; David 1998; Mountain et al. 1989; Popp 2001a, b), current estimations reflected an insignificant effect. This finding suggested that industrialization and GDP per capita are more robust determinants of energy savings than innovation.

5.3 Environmental pollution function

CO_2 was included in the pollution function as a dependent variable for the reasons stated below, even though this method was not unique. Dinda (2004) argued that the integration of CO_2 in the model adds robustness to the EKC framework. Reason being, the costs associated with the CO_2e are more inclusive while air pollution entails short-term costs. This means that the CO_2e increase with an increase in real income and vice versa. Second, Arminen and Menegaki (2019) noted an important limitation in the EKC framework. Despite the results showing a feedback relationship between energy consumption and economic growth, the authors concluded that pollution has not yet reached the EKC threshold. Third, the EKC hypothesis is often recommended as an effective method to estimate better results in a single country analysis. Testing the EKC with panel data can also become problematic if country-specific heterogeneity exists in the data. In this study, the GDP per capita and its quadratic term were estimated with CO_2e. The present results, however, offered insufficient support to confirm the presence of the EKC in the OECD region, i.e. no U-shaped Kuznets curve found in our models, except for the model C and D. The inverted Kuznets curve was observed after including innovation in the model. As a possible explanation, this result suggests that technological innovation can help to reduce pollution only when R&D and innovations are targeted at CO_2e (cf. Gu and Wang 2018; Mensah et al. 2018). Santra (2017) also found that R&D expenditures focused on improving production (rather than environment) create environmental challenges due to their heterogeneous effects. By demonstrating the significant, positive, mitigating impact of technical innovation on environmental pollution in the sampled OECD economies, this finding supports the work of Santra (2017) for BRICS economies and Su and Moaniba (2017) for 70 economies.

Finally, the results also supported the PHH in the OECD regions. The results showed that environmental pollution has increased with an increase in the FDI, thereby confirming the need for more research and development in green innovation. Scholars have also reported similar evidence for Pakistan (Rahman et al. 2019c); 6 Asian economies (Rahman et al. 2019b); India (Rana and Sharma 2019); Turkey (Seker et al. 2015); OECD nations (Kearsley and Riddel 2010); developing economies (Neequaye and Oladi 2015); Latin America (Sapkota and Bastola 2017); Malaysia [21]; China (Dou and Han 2019; Sun et al. 2017); Ghana (Solarin et al. 2017); and GCC (Al-Mulali and Tang 2013).

6 Conclusion and policy recommendations

The motivation for this study lies at the heart of contrasting evidence in the energy–pollution–growth nexus literature. The novelty of this work is that the paper comprehensively integrates innovation and FDI with energy consumption, environmental pollution, and economic growth. This paper, with the latest SEM technique and robust constructs, is expected to develop for a fresh perspective on the topic. Through a unified framework of three functions (i.e. production, energy consumption, and environmental pollution), this paper has attempted to combine three different strands of research. Previous studies on the energy–pollution–growth nexus have examined these areas separately. The current framework offers an alternative to rectify potential biases, often associated with single-equation models. The main findings of this work are discussed hereafter. First, the results of the production function indicated that a positive association exists between physical capital, innovation, energy-use, and economic growth. This indicated that, except for human capital, energy consumption, technological innovation, and physical capital have contributed to the economic growth in the OECD economies. Second, the empirical consumption function model reflected that industrialization and per capita income play a more significant role in energy consumption than innovation and FDI. Third, the environmental pollution function revealed that fossil-fuels, innovation, and FDI are major determinants of CO_2e in the OECD economies.

The paper presents the following critical policy implications. First, the present findings call for formulating effective policies to encourage innovation and R&D activities across the OECD economies. Thus, governments are expected to promote strategic collaborations across regions and countries at different levels (i.e. industry–industry, industry–academia, industry–government), mainly focusing on the demand side. Besides, governments and policymakers can take various measures to increase green-innovation. For instance, they can: (i) introduce exclusive vouchers, bonus schemes, and public procurement as incentives for innovation; (ii) support internalization of research activities in the public domain through improvements in research quality and development of global information networks and platforms; (iii) ensure lifelong learning that people have enough opportunities to develop skills and engage actively in the digital revolution; (iv) play a central role in the enhancement of equity capital for innovation among SEMs; (v) introduce policies for financial institutions to legitimize intellectual property as collaterals.

Another important implication is the need to design environmental policies focused on green innovation. Being a highly attractive market, OECD members are encouraged to steer the global ‘green innovation drive’ using market-based policies and design standardization to meet country-specific needs. The market size of the OECD opens multiple opportunities. First, it provides incentives for technology developers to invest in tailored innovation. Second, the existing knowledge pool in these countries is rich enough to sponsor and harness eco-innovation at the state and regional level. Third, governments are encouraged to venture capital (VC) as another important tool for green technologies. Fourth, governments can effectively manage renewable and clean energy markets by designing and adopting market-based standards. This policy is less likely to cause economic disruption.

The chief limitation of this work pertains to the studied sample, which only included 24 OECD economies. Perhaps future research can reexamine the current model using different regions and countries, e.g., BRICS, G7. Second, another limitation is that the paper used R&D expenditures as a proxy to measure innovation. Researchers can overcome this limitation through alternate innovation proxies, e.g., patents. Third, this study estimated a linear relationship of innovation with economic growth, energy consumption, and CO_2e. Still, some economists contend that innovation is procyclical—innovation increases in the economic boom and diminishes during the recessions. This means that the positive and negative shocks of innovation may have a different impact on economic growth, energy consumption, and CO_2e. Future studies can use a non-linear technique to examine innovation shocks–energy–pollution–growth nexus, under the SEM framework. Finally, the EKC model can be replaced with the STIRPAT model to get new insight into the link among GDP per capita, innovation, fossils fuels, and CO_2e.

Appendices

Appendix 1

See Table 7.

Table 7 Description of the variables

Variables	Description	Source of data	Estimation method
Environmental pollution	CO_2 emissions (metric tons per capita)	World Bank (2016)	
Income level	Real GDP at constant 2005 national prices (in mil. 2005 USD)	World Bank (2016)	Divided by population
Energy consumption	Energy use (kilogram of oil equivalent per capita)	World Bank (2016)	Divided by population
Foreign direct investment	net inflows (BoP, current US$)	World Bank (2016)	
Innovation	R&D expenditures as a percentage of GDP	OECD (2019)	
Urbanization	Urban population (total)	World Bank (2016)	
Physical capital	Gross fixed capital at constant 2005 national prices (in mil. 2005 USD)	UNSTATS (2019)	Divided by population
Fossil fuel energy consumption	Fossil fuel energy consumption per capita	World Bank (2016)	Energy use multiplied by the share of fossil fuel energy consumption
Industrialization	Manufacturing value added at constant 2005 national prices (in mil. 2005 USD)	UNSTATS (2019)	Divided by population
Human capital	Index of human capital per person	Penn World Table[a]	

[a] See for details, Feenstra et al. (2015)

Appendix 2

See Table 8.

Table 8 List of the sampled OECD countries

Austria	France	Japan	Portugal
Canada	Germany	Mexico	Slovak
Czech Republic	Hungary	Netherland	Slovenia
Denmark	Ireland	New Zealand	Turkey
Estonia	Israel	Norway	UK
Finland	Italy	Poland	USA

Appendix 3

See Table 9.

Table 9 Descriptive statistics based on 2-year averages

Variable(s)	Mean	SD	Min.	Max.	Obs.
CO_2					
Overall	5.1387	0.6302	4.1222	6.7519	n = 264
Within		0.0475	4.967	5.2939	N = 24
Between		0.6409	4.1736	6.7316	T = 13
Y					
Overall	4.426928	0.2854	3.7763	4.9603	n = 264
Within		0.0709	4.1927	4.5928	N = 24
Between		0.2819	3.9427	4.5928	T = 13
EU					
Overall	− 3.6686	0.6621	− 4.9035	− 2.4558	n = 264
Within		0.0352	− 3.7833	− 3.579	N = 24
Between		0.6743	− 4.846	− 2.5454	T = 13
Z					
Overall	0.144	0.2561	− 0.6869	0.5725	n = 264
Within		0.0882	− 0.1056	0.3992	N = 24
Between		0.2452	− 0.4427	0.4801	T = 13
FDI					
Overall	10.5664	0.2823	10.0023	11.6871	n = 264
Within		0.1553	9.9909	11.2193	N = 24
Between		0.2405	10.347	11.2834	T = 13
UBN					
Overall	1.856	0.0686	1.7	1.9641	n = 264
Within		0.1553	9.9909	11.2193	N = 24
Between		0.0684	1.7127	1.961	T = 13
K					
Overall	3.7575	0.29	2.9006	4.3309	n = 264
Within		0.10054	3.3399	4.0604	N = 24
Between		0.2774	3.2422	4.2145	T = 13
IND					
Overall	3.572	0.2857	2.7277	4.0284	n = 264
Within		0.1042	3.1755	3.8758	N = 24
Between		0.2712	3.0692	3.9276	T = 13
H					
Overall	0.4958	0.0646	0.2644	0.5717	n = 264
Within		0.0185	0.4455	0.5478	N = 24
Between		0.0631	0.3147	0.5581	T = 13

CO_2 carbon dioxide emissions, *Y* GDP per capita, *EU* energy use, *Z* innovation, *FDI* Foreign direct investment, *UBN* urbanization, *K* physical capital, *IND* industrialization, *H* human capital, *SD* standard deviation, *Min.* minimum, *Max.* maximum, *Obs.* observations

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