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RESEARCH ARTICLE

# A quantile analysis of energy efficiency, green investment, and energy innovation in most industrialized nations

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## Abstract

The continuous use of fossil fuels to meet the energy demands of the industrialized nations has led to environmental degradation. As such, there has been a call for research, exploration, and the usage of alternative energy which is believed to improve the depleting quality of the environment. This study investigates the relationship between energy efficiency, green energy investment, and energy innovation in a panel of nine highly industrialized countries, namely Canada, Japan, France, Spain, Germany, Switzerland, Italy, the USA, and the UK. Relying on the environmental Kuznets' hypothesis (EKC), we employ the quantile-on-quantile regression approach to the data obtained between 1980 and 2018. The empirical estimates validate the EKC hypothesis in most of these industrialized nations considered. The findings also reveal that the continuous use of non-renewable energy consumption escalates emissions, while the use of renewable energy reduces the level of emissions "in" the environment. Therefore, energy efficiency leads to an increase in emissions in the first 3 quantiles and reduces emissions in the remaining quantiles. Also, energy innovation leads to a high amount of emissions. Finally, the study calls for increased investments in renewable energy as well as energy efficiency to ensure continuous improvement in the quality of the environment.

**Keywords** Energy efficiency · Green energy investment · Energy innovation · Quantile Approach

## Introduction

There has been a monumental increase in the amount of pressure mounted on the environment alongside a high level of income, and this trend continues until a peak level of income is attained after which the environmental pressure drops. These behavioural patterns of income level and environmental degradation are captured in the environmental Kuznets curve (EKC) hypothesis. The pressure on the environment is majorly caused by the emissions of greenhouse gases such as carbon emissions which propel environmental degradation and climate change. Meanwhile, most industries are energy-intensive that requires most industries to be efficient enough in terms of their energy consumption with the sole aim of curtailing the impact of energy consumption on environmental quality in the global economy. In support of the EKC model, there is a significant positive relationship between carbon emissions and per capita income in most developed countries with a high level of technological advancement (Baek et al. 2009). These countries are found to be emitters of carbon as a result of their over-reliance on unclean energy sources that further the degradation of the environment.

Unlike previous studies, this study provides an argument for the need to overhaul the energy sources of the countries and industries with support for production techniques that are more energy efficient. However, the literature is scanty on the nexus between green energy investment, innovation, and environmental quality. To fill this gap in the literature, this study finds it noteworthy to introduce green energy alongside energy efficiency and innovation as determinants of

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environmental quality in selected samples of industrialized countries. More so, the investments channelled towards the adoption of green technology by most industrialized nations are on highs and lows. The level of credit facilities available to ease the transition from the conventional energy sources to greener energy sources has been found to encourage more adoption of the conventional energy sources that lead to more environmental degradation (Zhou et al. 2019). The conventional carbon-emitting energy sources have to be replaced with cleaner energy sources to promote efficiency in terms of energy consumption, as increased consumption of carbon-emitting energy sources has a significant degenerating effect on the investment likelihood (Fadly 2019). Also, renewable energy policy and energy security concerns play key roles as regard incentivizing the private sector to invest more in renewable energy technologies (Fadly 2019).

Therefore, as part of ensuring environmental sustainability outside the energy efficiency efforts, there is a need to ensure sustainable development is promoted through coexistence instead of tradeoffs among economic growth, energy consumption, and environmental degradation levels of countries (Ozcan et al. 2020). About 19% marginal effect of investments in green energy is experienced only by countries with high energy costs (Stucki 2019). Therefore, firms are likely to increase their productivity when they invest more in green energy (Stucki 2019). With 28.8% in total energy consumption, the energy intensity effect was retardant while the investment effect was accelerating. Similarly, Chinese energy consumption keeps rising between 2010 and 2015. Whether or not the energy conservation or intensity decline will be profitable depends greatly on the energy intensity effect (Yan and Su 2020). However, it should be noted that when the investment deadline is approaching, the impact of the green certificate subsidy is greatest, thereby investing in green energy optimal for investors compared to when there is no deadline to meet (Finjord et al. 2018). There is a possibility of a collapse in the price of the green certificate reducing the value of the investment options (Finjord et al. 2018).

The aim of this current study, therefore, is to assess the nexus between energy efficiency, innovation, and green energy investment within the context of industrialized nations. The contribution of this study to the literature is two-fold. The first is to fill the gap in the literature with regard to the relationship among the variables of interest and, the second is to explore the impact of the variables on environmental quality all within the context of major industrialized nations. The section that follows this introduction presents a review of the literature with an emphasis on energy efficiency, renewable, and non-renewable energy consumption. The "Methods" section explains the methodology and models while the description of variables, data, and their sources, as well as the discussion of results and implications of research findings, are all captured in the "Significant findings and result" section. The study concludes in the "Conclusion" section with vital recommendations for energy policy.

## Literature review

### Energy efficiency and non-renewable and renewable energy consumption

Energy consumption is the process by which energy is utilized for industrial and domestic purposes. Meanwhile, non-renewable energy consumption may lead to increased emission of $CO_2$, thereby contributing to environmental degradation. It is therefore imperative to pay considerable attention to renewable energy sources such as wind, solar, biomass, and so forth. Increased renewable energy consumption contributes to mitigating environmental degradation while non-renewable energy consumption contributes to $CO_2$ emissions (Dogan and Aslan 2017; Inglesi-Lotz and Dogan 2018; Su et al. 2019b; Dogan et al. 2020).

However, to ensure environmental sustainability, there is a need to take cognizance of energy efficiency which is the most cost-effective way to ensure there is a reduction in energy consumption. This ensures that economic activities are still at their best "while electricity conservation measures are a viable option" (Corner et al. 2011). However, for an energy-dependent country, energy conservative policies will harm the country's economic growth (Narayan et al. 2007). Increased renewable energy consumption contributes to reducing $CO_2$ emission while non-renewable energy consumption contributes to $CO_2$ emissions (Tugcu et al. 2012). More relevance should, therefore, be placed on sources of renewable energy in the energy mix. This will help support and encourage the use of green energy (renewable energy), green technology, and more public awareness on green energy consumption, and clean technology will help to lower levels of emission (Paramati et al. 2017; Santra 2017).

However, the financial development of countries can help ensure a reduction in air pollution without having to consider the energy source. This is because they can afford to put in place appropriate measures to control greenhouse emissions from industrial activities. It should be noted that this is only obtainable in the long run (Al-Mulali and Ozturk 2016; Umar et al. 2020). Likewise, industrial activities require energy consumption to carry out their activities. This means that the energy source may not matter as far as the production is concerned but the effect of emissions from non-renewable energy consumption in industries is detrimental to the environment. Thus, there is a need to adopt renewable energy. The industrial production index (IPI) has a unidirectional effect on renewable energy production and consumption. Also, the direction of the causality between renewable energy and economic growth depends on the market conditions (Wadström et al. 2019).

Interestingly, a decrease in the energy intensity, i.e. the units of energy consumed per unit of GDP, is a major factor behind the decline in the emission of $CO_2$ (Li et al. 2016). To reduce $CO_2$ emissions, there is a need for measures to increase energy efficiency (Li et al. 2016; Onat et al. 2019; Retallack et al. 2018). The industrial sector contributes a high percentage of $CO_2$ emissions (Alvarez-Herranz et al. 2017; Zhang et al. 2019). Equally, a shift in the population, activity effects, and GDP are important to the increase of $CO_2$ emissions (Lin and Raza 2019). This means that the population increase, the rises in GDP, and the increase in energy consumption result in an increased $CO_2$ emission. Importantly, energy consumption occupies one-third of foreign green commercial buildings (Huang et al. 2019). While trade reduces emissions (Dogan and Turkekul 2016; Su et al. 2019a; Su et al 2020; Khan et al. 2020), there is a bidirectional relationship running from the level of trade to $CO_2$ emissions as well as between outputs and renewable energy (Ben Jebli et al. 2016).

Meanwhile, studies testing the validity of the EKC hypotheses differ in conclusion. This may be due to the method adopted or countries chosen for the study; the inverted U-shaped environmental Kuznets curve is verified (Ben Jebli et al. 2016). A U-shaped association EKC relationship runs from economic growth to carbon emissions, i.e. the EKC hypotheses are valid (Shahbaz et al. 2020). The EKC hypothesis was established, i.e. a U-shaped correlation between carbon dioxide emission and per capita income exists in the region (Zaman et al. 2016). The EKC hypothesis does not exist (Al-Mulali et al. 2015). EKC hypotheses are not valid for low- and lower-middle-income countries while the EKC hypothesis is validated in upper-middle- and high-income countries. As well, environmental damage increases as countries witness economic growth (Al-Mulali et al. 2015). The level of exports drives positive emission of greenhouse gases and foreign direct investments disrupt environmental quality by increasing $CO_2$ emissions (Shahbaz et al. 2020).

## Research and development and emissions in industrialized nations

Innovative activities directed towards developing new services or products, or modifying existing ones, are known as research and development. The emission of $CO_2$ due to energy consumption or other activities in society requires research and developmental activities to ensure an emission reduction. Research and development investments are important in ensuring that there is technological development by adopting human capital and existing knowledge. Moreover, endogenous growth models present a framework that allows a link between the stock of capital, labour, and human capital (research and development expenditures) and output (Romer 1986). Likewise, Inekwe (2014) confirms that “research and development” (hereafter referred to as R&D) are essential drivers of economic growth in the long run. R&D expenditures strengthen the effect of FDI on economic growth (Freimane and Bāliņa 2016). Expenditures on R&D contribute to the enhancement of economic growth indirectly through the enhancement of economic activities (Tsaurai 2017). This is because economic growth is a major determinant of countries’ success and things that may lead to economic growth requires adequate research and development to ensure resources are committed to the right places. Furthermore, investing in R&D expenditures is imperative for increased output. The R&D investments are highly imperative for sustainable economic growth; this is considered as a form of competitive advantage for firms and the economy as a whole (Grossman and Helpman 1994).

Firms or countries that embark or invest in inadequate research and development can foresee opportunities or threats which give them an edge over others. Apart from research and development, there are other 14 sustainable high-tech progress important for economic growth (Solow 1956). Moreover, many studies have used endogenous growth in recent times and concluded that R&D expenditure is the main factor for economic growth (Guloglu and Tekin 2012).

However, little empirical evidence varies amongst countries. In the case of the USA, research and development expenditure increases GDP growth in the long run (Goel et al. 2008; Romano et al. 2017). Research and development have a positive effect on real GDP for 72 countries (Horvath 2011). Also, expenditures on R&D help to increase GDP (Bayarçelik and Taşel 2012) and no causal association exists between R&D expenditures and output for Turkey (Tuna et al. 2015). Research and development expenditures have a positive effect on real GDP (Akcali and Sismanoglu 2015). R&D expenditures contribute to the stimulation of real GDP output activity in 52 developed and developing countries (Gumus and Celikay 2015). A re-investigation of the OECD countries shows that R&D expenditures lead to output increase by improving the total factor productivity (Murad et al. 2019; Yilanci et al. 2019).

Therefore, the environmental sustainability and economic growth goal of countries can be achievable with adequate research and development. This is because it will help to know at what stage the economic growth contributes to a reduction in the environmental pressure as a state by the EKC hypotheses.

Having reviewed the literature on green energy investment, research and development, renewable and non-renewable energy, this study is aimed at analyzing energy efficiency, green energy investment, and eco-innovation in an industrialized nation. Table 1 presents the summary of the mixed empirical evidence on energy efficiency and gas emission; and green energy investment and gas emission; and eco-innovation and gas emission nexus.

**Table 1** Literature for energy efficiency, green energy investment, eco-innovation, and environmental sustainability

| S/N | Authors and year | Country/territory(ies) | Scope | Variables | Methodology | Conclusion |
|---|---|---|---|---|---|---|
| Energy efficiency and non-renewable and renewable energy consumption | | | | | | |
| 1 | Dogan and Aslan 2017 | EU | 1995–2011 | Renewable energy, non-renewable energy, $CO_2$ | OLS, FMOLS, DOLS | Renewable energy reduces $CO_2$, non-renewable energy increases $CO_2$ |
| 2 | Corner et al. 2011 | UK | 2005–2010 | Electricity, energy efficiency | Linear regression | Electricity ensures energy efficiency |
| 3 | Narayan et al. 2007 | G7 | 1960–2002 | Energy conservation, economic growth | DOLS | Energy conservation harms economic growth |
| 4 | Tugcu et al. 2012 | G7 | 1980–2009 | Renewable energy, non-renewable energy, $CO_2$ | ARDL | Renewable energy reduces $CO_2$, non-renewable energy increases $CO_2$ |
| 5 | Paramati et al. 2017 | 11 developing countries | 1990–2012 | Green technology, public awareness on green energy consumption, emissions | FMOLS | Public awareness of energy consumption reduces emissions |
| 6 | Ben Jebli et al. 2016 | OECD | 1980–2010 | Exports, renewable energy | FMOLS, DOLS | Bidirectional causality between exports and renewable energy |
| 7 | Al-Mulali and Ozturk 2016 | 27 advanced countries | 1990–2012 | Financial development, air pollution | FMOLS | Financial development reduces air pollution |
| 8 | Wadström et al. 2019 | Canada | 1996–2015 | Industrial production, energy consumption, energy production | Quantile causality | A unidirectional effect from Industrial production to energy consumption and energy production |
| 9 | Li et al. 2016 | EU | 1995–2009 | Energy intensity, C02 | Shapley/Sun index | Energy intensity has a negative impact on $CO_2$ |
| 10 | Zhang et al. 2019 | China | | Industrial activities, $CO_2$ | Back propagation model | Industrial activities increase $CO_2$ |
| 11 | Lin and Raza 2019 | Pakistan | 1978–2017 | Population, GDP, $CO_2$ | Logarithmic mean Divisia index | Population and GDP increase $CO_2$ |
| 12 | Huang et al. 2019 | China | 2014–2016 | Energy consumption, green buildings | Energy analysis | The green retrofit building decreases energy consumption |
| 13 | Shahbaz et al. 2020 | China | 1984–2018 | GDP, $CO_2$ | Bootstrapping autoregressive-distributed lag (BARDL) | The presence of U-shaped EKC |
| 14 | Zaman et al. 2016 | East Asia and Pacific, European Union and high-income OECD and non-OECD countries | 2005–2013 | GDP, $CO_2$ | Panel two-stage least square | The presence of U-shaped EKC |
| 15 | Al-Mulali et al. 2015 | 93 countries | 1980–2008 | GDP, $CO_2$ | GMM | GDP has a positive impact on $CO_2$ |
| 16 | Baek et al. 2009 | 50 countries | 1960–2000 | GDP, $CO_2$ | Cointegrated vector autoregression (CVAR) | GDP has a positive impact on $CO_2$ |
| 1 7 | Alvarez-Herranz et al. 2017 | OECD | 1990–2012 | GDP, $CO_2$ | Two-stage least square | Presence of an N-shaped EKC |
| 18 | Su et al. 2020 | USA | 1990–2017 | Exports, $CO_2$ | ARDL | Exports have a negative impact on $CO_2$ |
| 19 | Su et al. 2020 | USA | 1990–2017 | Exports, $CO_2$ | ARDL | Exports have a negative impact on $CO_2$ |
| 20 | Dogan and Turkekul 2016 | USA | 1960–2010 | Trade, $CO_2$ | ARDL | Trade has a negative impact on $CO_2$ |
| 21 | Umar et al. 2020 | China | 1971–2018 | Financial development, $CO_2$ | Bayer-Hanck co-integration test | Financial development has a negative impact on $CO_2$ |
| 22 | Inglesi-Lotz and Dogan 2018 | 10 sub-Saharan countries | 1980–2011 | Renewable energy, non-renewable energy, $CO_2$ | DOLS | Renewable energy reduces $CO_2$, non-renewable energy increases $CO_2$ |
| 23 | Dogan et al. 2020 | 17 African countries | 1971–2014 | Energy consumption and $CO_2$ | Non-parametric quantile causality approach | Energy consumption causes $CO_2$ |

**Table 1** (continued)

| S/N | Authors and year | Country/territory(ies) | Scope | Variables | Methodology | Conclusion |
|---|---|---|---|---|---|---|
| 24 | Santra 2017 | BRICS | 2005–2012 | Green technology innovation, $CO_2$ | Least square dummy variable regression | Green technology innovation has a negative impact on $CO_2$ |
| 25 | Khan et al. 2020 | G7 | 1990–2017 | Export, eco-innovation, and renewable energy $CO_2$ | Augmented Mean Group (AMG) and Common Correlated Effect Mean Group (CCEMG) | Export, eco-innovation, and renewable energy reduce $CO_2$ |
| 26 | Su et al. 2019 | Saudi Arabia | | Geopolitical risk, oil prices | Wavelet coherence | Geopolitical risk is correlated with oil prices |
| 27 | Dogan and Inglesi-Lotz 2020 | EU | 1980–2014 | GDP, $CO_2$ | OLS, FMOLS | The presence of U-shaped EKC |
| 28 | Azhgaliyeva et al. 2018 | 13 countries | 2004–2016 | Renewable energy policy, renewable energy production | Fixed effects and random effects model | Renewable energy policies have a positive impact on renewable energy production |
| 29 | Su et al. 2020 | USA | 1990–2018 | Partisan crisis, oil price | Time-varying parameter-stochastic volatility-vector autoregression (TVP-SV-VAR) mode | The partisan crisis causes an impact on oil prices |
| 30 | Retallack et al. 2020 | 10 countries and regions | 2020 | Energy efficiency, awareness of energy efficiency | Desk review | Energy efficiency improves through awareness of energy efficiency |
| 31 | Onat et al. 2019 | USA | 2004–2013 | Solar charging scenario, carbon footprints | ANOVA | Solar charging scenario improves carbon footprints |
| 33 | Romano et al. 2017 | EU | 2004–2011 | Government regulation, investment in renewable energy | OLS, FMOLS | Government regulation has a positive impact on investment in renewable energy |
| 34 | Su et al. 2019b | The World | 1990–2018 | Geopolitical risk, oil prices | Granger causality | No causality between geopolitical risk and oil prices |
| 35 | Del Moretto et al 2018 in a protected area | Tuscany and in other Italian regions. | 2012–2015 | Energy consumptions, energy efficiency, and $CO_2$ emission | The threshold | Energy efficiency reduces $CO_2$ emission |
| Research and development and emissions in industrialized nations | | | | | | |
| 35 | Inekwe 2014 | 66 countries | 2000–2009 | R&D, GDP | System GMM | R&D has a positive impact on GDP |
| 36 | Freimane and Bāliņa 2016 | EU | 2000–2013 | R&D, FDI, GDP | Difference GMM | R&D has a positive impact on FDI and GDP |
| 37 | Tsaurai 2017 | Hungary | 1963–2013 | R&D, GDP | Granger causality | R&D has a positive impact on GDP |
| 38 | Guloglu and Tekin 2012 | OECD | 1991–2007 | R&D, GDP | Panel vector autoregressive (VAR) model | R&D has a positive impact on GDP |
| 39 | Goel et al. 2008 | USA | 1953–2000 | R&D, GDP | ARDL | R&D has a positive impact on GDP in the long run |
| 40 | Horvath 2011 | 72 countries | 1960–1992 | R&D, GDP | Bayesian Model Averaging | R&D has a positive impact on GDP |
| 41 | Bayarçelik and Taşel 2012 | Turkey | 1998–2010 | R&D, GDP | Two-stage least square | R&D has a positive impact on GDP |
| 42 | Tuna et al. 2015 | Turkey | 1990–2013 | R&D, GDP | Co-integration analysis | R&D has no impact on GDP |
| 43 | Akcali and Sismanoglu 2015 | | | R&D, GDP | | R&D has no impact on GDP |
| 44 | Gumus and Celikay 2015 | 52 developing countries | 1996–2010 | R&D, GDP | Mean group, pooled mean group estimators | R&D has a positive impact on GDP |
| 45 | Yilanci et al. 2019 | OECD | 1961–2013 | R&D, GDP, factor productivity | Panel stationarity test | R&D has a positive impact on factor productivity and GDP |
| 46 | Murad et al. 2019 | Denmark | 1970–2012 | Technological innovation, energy consumption | ARDL, Granger causality | -Technological innovation has a negative impact on energy consumption<br>-Bidirectional causality between Technological innovation and energy consumption |

## Methods

### Empirical methodology

To investigate the relationship between energy efficiency, green energy investment, eco-innovation, and $CO_2$ emission in most industrialized nations, this study follows the environmental Kuznets of 1956. We set up our regression equation as follows:

$$CO2_{it} = \beta_0 \ + \beta_1 GDPpc_{it} + \beta_2 GDPpc^2{}_{it} + \beta_3 engeff_{it} + \beta_4 rew_{it} + \beta_5 \ nrew_{itit} + \beta_6 enginv_{it} + \varepsilon_{it} \quad (1)$$

where $CO_2$: $CO_2$ emissions is $CO_2$ emissions (in metric tons per capita); engeff is energy efficiency (final energy consumption in million tons of oil equivalent (TOE)); GDPpc, GDP per capita, GDPpc is calculated as GDP/Pop; GDPpc^2, GDPpc square is calculated as GDP/Pop Square; NREN is non-renewable energy consumption, measured by fossil fuel energy consumption (% of total); REN is renewable energy consumption (renewable energy consumption (% of total final energy consumption)); enginv is green energy innovation (Energy Technology RD&D Budget). Also, "I" is the cross-section that represents the countries in the sample, and "t" is the error term.

### Econometric methodology: quantile-on-quantile regression approach

This study introduces energy efficiency, green energy investment, and eco-innovation into the existing literature on the environmental Kuznets model, using the new approach of quantile-on-quantile (QQ) regression method developed by Sim and Zhou (2015). The quantile model studies the effect of energy efficiency, green energy investment, and eco-innovation on the quantile carbon discharged in the most industrialized nations, which are all encompassing a single QQ method. This new method is a combination of non-parametric evaluation as well as quantile regression. The orthodox quantile regression model surveys the impact of energy efficiency, green energy consumption, and energy innovation on the variant quantiles of carbon discharge. Meanwhile, the usual linear regression model evaluates the effect of a specific quantile of energy efficiency, green energy consumption, and energy innovation on the $CO_2$ emission.

The quantile-on-quantile regression technique syndicates these two conventional processes to construct the relationship between quantiles of energy efficiency, green energy consumption, and energy innovation, and carbon discharge. A significant number of studies have embraced the orthodox OLS approach to discover the influencing factors for $CO_2$ emissions (Fan et al. 2006). However, this method solely establishes the conditional expectation (mean value) of $CO_2$ emission (the dependent variable) but fails to provide an appropriate and adequate description of the image of the conditional distribution (Pires et al. 2010).

Therefore, due to the remarkable heterogeneity among these countries (Arouri et al. 2012; Mensah et al. 2019; Ogundipe et al. 2014), the relationships among several technological development and $CO_2$ secretions are probable to carry out discriminately at different quantiles (i.e. to perform otherwise across emitters with distinct degrees of emissions). As such, the quantile regression (Khalifa et al. 2018) permits the coefficients to differ numerous quantiles and has unique benefits of detecting the difference within the impact of energy efficiency, green energy investment, and energy innovation on the distribution of $CO_2$ emissions (Wang et al. 2019).

Furthermore, the quantile regression technique is also beneficial for tackling issues that may significantly affect the accuracy of estimation, which includes heteroscedasticity, outliers, and unobserved heterogeneity (Alsayed et al. 2019; Distante et al. 2018). Consequently, this study uses quantile regression to broadly explore the associations amid a couple of energy efficiency, green energy investment, and energy innovation at several quantiles in $CO_2$ emissions. The econometric model indicated below is employed to tackle the conditional quantile function of the panel data:

$$Q_{y_{it}} = (\tau x_{it}) = x_{it}^{'} \varphi(\tau) + \vartheta_i + \mu_{it} \quad (2)$$

Note that $Q_{y_{it}}(\tau x_{it})$ is the dependent variable for $\tau th$ quantile; however, the vector explanatory variable vector is $x_{it}$; $\vartheta_i$ denoting the individual effect; $\tau$ is the quantiles, and the regression coefficient for $\tau th$ quantile is $\varphi(\tau)$. This is further simplified as follows:

$$\varphi(\tau) = min \sum\nolimits_{k=1}^{q} \sum\nolimits_{t=1}^{T} \sum\nolimits_{i=1}^{N} \left( y_{it} - \vartheta_i - x_{it}^{'} \varphi(\tau)/w_{it} \right) \quad (3)$$

where $q$ denotes the number of quantiles, $T$ represents the number of years, and $N$ is the population within the $\tau th$ year. The study emulates the operation of (Koenker and Bassett Jr 1978) our model, thereby allocating 0.25, 0.5, and 0.75 in turn to the quartiles of τ.

## Significant findings and result

### Variables, data, and variations

To investigate the effect of energy efficiency, green energy investment, energy innovation, and trade openness on $CO_2$ emission, the study employs an annual balanced panel data of 9 most industrial countries. The countries are Canada, Japan, France, Spain, Germany, Switzerland, Italy, the USA, and the UK. The data cover the period 1980–2018, giving 351 observations. To remedy the relative short-time series for variables usually utilized for nexus, the study utilized panel data. In the panel, GDP per capita at the current price was utilized as a measure for income level which is sourced from World Bank WDI (Kumar and Muhuri 2019), the energy innovation (Energy Technology RD&D Budget (in millions)) from IEA 2020 (Balsalobre et al. 2015), renewable energy (renewable energy consumption (% of total final energy consumption), non-renewable (fossil fuel energy consumption (% of total)), trade openness (exports and imports (% of GDP)), and $CO_2$ emission ($CO_2$ emissions (in metric tons per capita)) all from World Bank WDI (2020) (see Bhattacharya et al. 2017)). Also, Mutascu (2018) used trade openness as a control variable to examine environmental and growth nexus; see Tables 2 and 3.

## Long-run results and discussions

The quantile results presented in Table 4 confirm a positive correlation between our linear and on carbon emissions in most industrialized nations, that is, $CO_2$ emission growth ($\beta_1$ greater 0) along with increasing per capita income (*GDPpcit*) in all quantiles. The indication is that *GDPpc* increases environmental degradation in the selected sample. After that, $CO_2$ emissions decrease ($\beta_2 < 0$). $\beta_2$ is negative and significantly related to $CO_2$ emissions. This shows that a 1% rise in real GDP per capita increases carbon emissions by 19.84%, 29.25%, 30.89%, and 33.78% at quantile 0.25, 0.50, 0.75, and 0.90, respectively, and the latter GDPpc square has a negative coefficient, therefore validating the EKC hypothesis in the most industrialized nations. It also indicated that most industrialized nations have a U-shaped EKC for $CO_2$ emissions. The findings concur with results obtained from the studies of Shahbaz et al. (2020) and Zaman et al. (2016).

In Table 4, again, the study found that $nonrew_{it}$ has a positive relationship and significant with $CO_2$ emission, $nonrew_{it}$ directly affected $CO_2$ emissions; meanwhile, the positive effect is seen in terms of *GDPpc*. This indicates that $nonrew_{it}$ increases $CO_2$ emissions ($\beta_3 > 0$) in the sample. This shows that a unit increase in non-renewable energy consumption increases $CO_2$ emission by 1018.3, 1290.5, 1210.2, and 1098 tons, respectively, in all the quantiles, and also our 2sls result confirmed a similar result. This finding is similar to Tugcu et al. (2012) and Dogan and Aslan (2017) that confirmed non-renewable energy consumption causes more $CO_2$ emissions and suggested that less consumption may help to reduce the amount of $CO_2$ emission in any society.

Renewable energy consumption and carbon emission nexus are negative ($\beta_4 < 0$) and significant, suggesting renewable energy consumption mitigates environmental degradation by improving the quality of carbon emissions in most developed countries. This shows that a unit increase in renewable energy consumption reduces $CO_2$ emission by 217.05, 360.3, 726.63, and 2550 tons, respectively, in all the quantiles. Also, our 2sls result confirmed a similar result. Moreover, governments should encourage the use of renewable energy consumption to mitigate environmental degradation in most industrialized economies. This conclusion is in line with the works of Inglesi-Lotz and Dogan (2018) in 10 sub-Saharan countries and Ozturk and Acaravci (2013) in the case of Turkey, and Dogan and Aslan (2017) in EU, and Paramati et al. (2017) showed that renewable energy has a significant contribution to reducing environmental degradation. They suggested that more relevance should be placed on renewable energy sources

**Table 2** Descriptive statistics

| Variable | Description | Unit of measurement | Mean | Std. dev. |
|---|---|---|---|---|
| CO2t | $CO_2$ emissions | $CO_2$ emissions (in metric tons per capita) | 1027746 | 1523819 |
| GDPpc | GDP per capita | GDPpc is calculated as GDP/Pop | 39206.18 | 12530.03 |
| GDPpc^2 | GDP per capita Square | GDPpc is calculated as GDP/Pop Square | 1.69e+09 | 1.18e+09 |
| Nrew | Renewable energy | Renewable energy consumption (% of total final energy consumption | 179.6691 | 324.7115 |
| Rew | Non-renewable energy | Fossil fuel energy consumption (% of total) | 165.4376 | 271.0216 |
| enginv | Energy innovation | Energy Technology RD&D Budget | 170.9969 | 281.1735 |
| engeff. | Energy efficiency | Final energy consumption in Million tons of oil equivalent (TOE) | 194.1161 | 502.714 |

Variable notations: $CO_2$, $CO_2$ emissions per capita; *NREN*, non-renewable energy consumption; *REN*, renewable energy consumption; *engeff.*, energy efficiency; *ecoinvo*, energy innovation; *GDPPC*, GDP per capita; all variables are in logarithmic form; robust standard errors in parentheses

*$p < 0.1$

**$p < 0.05$

***$p < 0.01$

**Table 3** The total investments in billion USD on green energy, innovation, and efficiency 2000–2018 in most industrialized nations

| Years | Energy efficiency | Non-renewable | Renewable | R&D on energy innovation |
|---|---|---|---|---|
| 2000 | 164.61 | 60.77 | 81.76 | 171.11 |
| 2001 | 176.98 | 82.95 | 87.91 | 211.36 |
| 2002 | 185.88 | 145.20 | 96.92 | 229.28 |
| 2003 | 139.52 | 135.75 | 92.69 | 240.47 |
| 2004 | 127.16 | 137.70 | 107.00 | 202.83 |
| 2005 | 144.33 | 134.30 | 110.71 | 159.64 |
| 2006 | 146.49 | 145.14 | 109.90 | 161.25 |
| 2007 | 163.99 | 145.64 | 157.93 | 183.59 |
| 2008 | 188.62 | 164.19 | 151.10 | 195.21 |
| 2009 | 406.04 | 532.83 | 407.20 | 14.01 |
| 2010 | 312.48 | 178.29 | 312.68 | 44.89 |
| 2011 | 259.92 | 178.30 | 375.82 | 299.80 |
| 2012 | 257.18 | 176.27 | 392.03 | 327.15 |
| 2013 | 298.47 | 198.59 | 316.35 | 317.57 |
| 2014 | 301.08 | 170.45 | 297.09 | 304.70 |
| 2015 | 289.89 | 153.67 | 273.48 | 317.83 |
| 2016 | 283.18 | 131.05 | 244.91 | 371.92 |
| 2017 | 298.67 | 118.90 | 229.94 | 393.67 |
| 2018 | 387.61 | 159.36 | 256.50 | 517.07 |

Source: Energy Technology RD&D Budgets (2020 edition)

in the energy mix to support. They also submitted that it is highly imperative to encourage the use of clean innovation (technologies) and renewable energy, and to create more public alertness of renewable energy consumption to lower the levels of emission in the most industrial nation.

All the estimation techniques show that both renewable energy and non-renewable energy contribute to the reduction of $CO_2$ emissions in most industrialized countries, indicating that the best option to reduce $CO_2$ emissions in these countries is to consider a mix of non-renewable and renewable energy consumption, i.e. green energy consumption should be encouraged by government and industries.

Energy efficiency and carbon emission nexus are positive ($\beta_5 > 0$) and significant in quartile 0.25 to 0.75. This indicates that a unit increase in energy efficiency increases $CO_2$ emission by 677.06, 660.80, and 804.66 tons, respectively, in the quantile 0.25, 0.50, and 0.75. In other words, energy efficiency causes environmental degradation in the first 3 quantiles in most industrialized countries. However, after the third quantile, energy efficiency turned negative and significant, meaning that the fourth quantile energy efficiency drives a reduction in environmental degradation in most industrialized countries. A unit increase in energy efficiency reduced $CO_2$ emission by − 103.4 tons. These findings support the consensus of scholars that energy efficiency could decrease environmental degradation by improving the quality of carbon emissions in any nation. Therefore, governments in the most industrialized nations are encouraged to put energy efficiency as a core policy to reduce environmental degradation (the rising energy-related carbon dioxide) in their countries. Our findings are similar to that of Del Moretto et al. (2018), and that of other Italian regions. Corner et al. (2011) in the UK stressed that energy efficiency is a viable option to minimize the increasing $CO_2$ emission in a country.

Finally, the impact of energy innovation (R&D spending has on $CO_2$ emissions), the parameter $\beta_6$, is positive ($\beta_6 > 0$). This indicates that energy innovation (spending on R&D) is positive and significant on $CO_2$ emission in most industrialized nations, leading to an increase in $CO_2$ emissions by 1610.3, 2682, 3003.48, and 3371 tons in all the quantiles forever 1 dollar increase in energy innovation (R&D spending has on CO2 emissions). The indication of this is that innovation drives economic growth and therefore economic activities increased the use of highly polluting energy resources in the 9 most industrialized nations used for this study. Our findings support Khan et al. (2020) in G7, Santra (2017) in BRICS, Murad et al. (2019) in Denmark, and Tuna et al. (2015) in Turkey that hinted that energy innovation (R&D expenditures) significantly contributes to economic growth and similar to the conclusion of Inekwe (2015). We suggest environmental policy targeted towards enhancing innovation in emission-reducing technology at both the public and private levels to mitigate environmental degradation problems in the 9 listed most industrialized nations.

**Table 4** Long-run estimation of full data

| | Variable | OLS | Quantile regression | | | | |
|---|---|---|---|---|---|---|---|
| Quantile regression | co2t | POLS | 2SLS | Q-req@ 0.25 | Q-req@ 0.50 | Q-req@ 0.75 | Q-req@ 0.90 |
| | GDPpc | 19.91** | 36.43** | 19.84 | 29.24** | 30.89* | 33.78** |
| | | 7.919 | 15.07 | 17.19 | 10.56 | 18.09 | 13.07 |
| | GDPpc^2 | − 0.00018** | − 0.00047** | − 0.00029 | − 0.00037** | − 0.00037** | − 0.0004** |
| | | 000092 | .00016 | .00018 | .00011 | .00019 | .00013 |
| | nrew | 211.9*** | 1560.3*** | 1018.3*** | 1290.5*** | 1210.2*** | 1098.*** |
| | | 78.90 | 150.43 | 171.61 | 105.38 | 180.58 | 130.4 |
| | Rew | − 428.08*** | − 727.15** | − 217.05 | 360.3** | 726.63** | 2550.*** |
| | | 105.18 | 237.51 | 270.94 | 166.38 | 285.11 | 205.94 |
| | engeff. | 584.13*** | 1101.89*** | 677.06** | 660.80** | 804.66** | − 103.4 |
| | | 118.4 | 268.74 | 306.57 | 188.25 | 322.602 | 233.02 |
| | enginv | 462.82** | 2297.2*** | 1610.3*** | 2682*** | 3003.48*** | 3371*** |
| | | 66.79 | 102.89 | 117.37 | 72.07 | 123.51 | 89.21 |
| | con | 402633.3** | − 346163.6 | − 113849 | − 292844 | − 309798.7 | − 208461 |
| | | 191628 | 321895.3 | 367201.8 | 225487.2 | 386400.7 | 279107.7 |
| Simultaneous quantile reg. | co2t | POLS | 2SLS | Q-req@ 0.25 | Q-req@ 0.50 | Q-req@ 0.75 | Q-req@ 0.90 |
| | GDPpc | 19.91** | 36.43** | 19.84 | 29.25*** | 30.89** | 33.78* |
| | | 7.919 | 15.07 | 12.43 | 4.610 | 9.507 | 18.30 |
| | GDPpc^2 | − 0.00018** | − 0.00047** | − 00029** | − 0038*** | − 0.00037*** | − 0.00044** |
| | | 000092 | .00016 | .00015 | 000054 | .000096 | .00017 |
| | nrew | 211.9*** | 1560.3*** | 1018.3** | 1290.5*** | 1210.*** | 1098** |
| | | 78.90 | 150.43 | 394.7 | 238.4 | 438.8 | 474.1 |
| | Rew | − 428.08*** | − 727.15** | − 217.1 | 360.31 | 726.6** | 2550.2** |
| | | 105.18 | 237.51 | 794.18 | 230.6 | 728.8 | 748.8 |
| | engeff. | 584.13*** | 1101.89*** 268.74 | 677.07 | 660.79 | 804.7** | 103.4*** |
| | | 118.4 | | 746.8 | 520.26 | 232.7 | 173.72 |
| | enginv | 462.82** | 2297.2*** | 1610.4** | 2682*** | 3003.*** | 3371 |
| | | 66.79 | 102.89 | 481.8 | 198.52 | 274.3 | 194.48 |
| | con | 402633.3** | − 346163.6 | − 113849 | − 29284** | − 309798 | − 208461 |
| | | 191628 | 321895.3 | 204120 | 82903.6 | 194689 | 398518 |
| | R-squared | 0.8567 | 0.4455 | 0.4874 | 0.6186 | 0.7597 | 0.8540 |
| | Breusch-Pagan | 37.71 | | | | | |

Variable notations: *$CO_2$*, $CO_2$ emissions per capita; *nren*, non-renewable energy consumption; *ren*, renewable energy consumption; *engeff.*, energy efficiency; *ecoinvo*, energy innovation; *GDPpc*, GDP per capita; all variables are in logarithmic form; robust standard errors in parentheses

*$p < 0.1$

**$p < 0.05$

***$p < 0.01$

## Policy implications

Based on our findings, we suggest the promotion of environmental policies that are geared towards enhancing innovation in emission-reducing technology at both the public and private levels. This is to mitigate the challenge of environmental degradation in the nine most industrialized economies under study. Specifically, the governments of these countries are enjoined to double their investments in research and development programmes, to enhance innovativeness in energy production and efficiency in its use. Also, the policymakers in these countries are advised to promote programmes that will increase the rate of economic growth so that pollutants may be reduced over time. These include, among others, enhanced incentives—tax cuts and lower interest rates—to essential sectors for sustainable growth-driven industries. Our research further shows that renewable energy contributes to the reduction of $CO_2$ emissions in the 9 listed most industrialized nations, indicating that the best option to reduce $CO_2$ emissions in these countries is to consider an investment in renewable energy. This indicates the need for some vital policy directions;

First, regarding the role of renewable energy in reducing $CO_2$ emissions, governments must create an enabling policy environment that encourages industry and the private sector to produce and promote the consumption of renewable energy. Thanks to more efficient technologies, the government can target an increase in the energy efficiency of installations and limit losses during production, transport, and distribution. It will be essential for governments to incorporate general actions and measures that encourage the production of renewable energy, such as biodiesel blend mandate, developing human institutional capacity, setting up research and development infrastructure, and creating a favourable investment environment. These efforts can be enhanced by the active engagement of the private investors in the broad area of renewable energy activity through a public-private partnership (PPP) initiative and identifying barriers to increasing investments in renewable sources. Involving the private investors will boost confidence and address concerns on governance-related risks, which could intensify the pressure for change on governments. Second, regarding the role of energy efficiency, the findings support the claim that energy efficiency can be considered an important factor in long-term energy development and environmental strategies to meeting the growing demands for global energy. Especially as energy efficiency reduces greenhouse gas emissions, the demand for energy imports lowers the costs at household and economy-wide level.

## Conclusion

Given that environmental quality is an important element of development, the development process tends to be neglected as production takes place in the direct implementation of some macroeconomic policies. While several studies have examined this phenomenon through the EKC hypothesis across countries and (sub)regions, the findings from these research works have suggested conflicting results, leading to contradictory policy recommendations, thereby providing avenues for further research. In this regard, our study is the first to examine the nexus between energy efficiency, green energy investment, eco-innovation, and $CO_2$ emissions in a panel of nine most industrialized countries (Canada, Japan, France, Spain, Germany, Switzerland, Italy, the USA, and the UK). Employing the quantile-on-quantile regression estimates on the data obtained between 1980 and 2018, our empirical findings validate the EKC hypothesis in the countries under consideration. Moreover, the coefficient of non-renewable energy consumption is positive, while that of renewable energy consumption is negative. Energy efficiency and carbon emission nexus produce a positive estimate; energy efficiency causes environmental degradation in the first 3 quantiles in most industrialized countries, with the effect turning negative afterward. Finally, the impact of energy innovation is positive.

One limitation to this research is its concentration on a panel of industrialized economies, even though both the developed and developing economies are desirous of improved environmental quality. Also, the data coverage is only between 1980 and 2018, based on availability. Future research should, therefore, be targeted at extension beyond just the industrialized countries, while the timeframe is largely expanded to cover a more recent period.

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**Data availability** Available upon request

## Compliance with ethical standards

**Competing interest** The authors declare that they have no competing interests.

**Consent to participate** All authors have consented to participation in this research.

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We declare that this manuscript has not been published elsewhere or under consideration in any journal.