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RESEARCH ARTICLE

Insights from Poland on the long-run effect of energy productivity on environmental degradation: a Fourier ARDL-based approach

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Abstract

The globally increasing trend of fossil fuel consumption has culminated in a historical degradation of the environment and the rising threat of global warming. Researchers and policymakers aim at examining critical relationships between energy productivity and environmental degradation to make recommendations for global policy action. This paper aims to capture the effect of energy productivity on environmental degradation in Poland from 1990Q1 to 2019Q4, using novel Fourier-bases ADF unit root and Fourier-based ARDL approaches. First, outcomes of the Fourier ARDL bounds test indicate that variables are integrated; second, outcomes of the Fourier ARDL long-run estimates indicate that (i) energy productivity has long-run negative effects on CO_2 emissions; and (ii) economic growth, globalization, and primary energy consumption have positive effects on CO_2 emissions. Among the options available to Polish policymakers are (i) liberalizing domestic energy markets to offer an opportunity for electricity consumers to switch companies and (ii) continuing to pursue a policy of decarbonizing energy supply by investing heavily in renewable energy, nuclear power, e-mobility, and energy productivity.

Keywords Environmental degradation · Asymmetric modeling · Environmental innovation · CO_2 emissions · Energy productivity · Poland

Introduction

Globally, it has been established that climate change, rising temperatures, and greenhouse gas emissions are linked. Carbon dioxide (CO_2) emissions have been found to account for over 80% of GHG emissions and are observed to be rising exponentially (Tvinnereim and Mehling, 2018; Kanat et al., 2022). The increased global temperature has been recognized to limit global agricultural production, causing increased flooding and threatening coastal communities, generating human health problems mainly due to pollution of air and water quality, growing wildfires, and worsening biodiversity losses. Available records indicate that temperatures across the world have increased by about 1.4° Fahrenheit since 1800, causing approximately 75% of the world's species to disappear (Addai et al., 2022). These have been found to pose existential threats to humanity, leading to rising calls by sustainability experts and the United Nations on the need for rethinking the current global growth trajectory and urgently reversing environmentally threatening human actions.

Fossil-based energy consumption has been blamed for this global problem, driven by transportation and ever-increasing industrialization drives for growth (Gurtu & Goswami, 2020; Umar et al., 2020; Umar et al., 2021). Global attempts to reverse this increasing existential threat to humanity have culminated in several policy proposals. For example, the proposal to raise public awareness culminated in the first US environmental policy in the 1960s, inspiring several world economies to develop regulations and relevant policy mechanisms to control environmental degradation. While in some economies, proposals focused on reducing fossil energy use and developing renewable base-energy

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sourcing; other economies have established policy focus on economic measures to limit growth and reduce GHG emissions. Some of those policy measures include cap-and-trade, carbon tax, and several carbon abatement policies. In recent times, however, several studies have cited energy productivity as playing a critical role in reducing the rate of carbon dioxide emissions. Supporting Schumpeter's economic theory, several studies claim that energy productivity investments remain the most globally viable energy alternative tool, which requires serious energy policy focus (Ike, et al., 2020; Omri & Belaïd, 2021; Sun et al., 2022). Several other experts equally claim energy productivity can drastically reduce GDP per unit of fossil energy used; hence, it should receive policy attention (Huaman & Jun, 2014; Hwang et al., 2017; Bazbauers, 2022). In economic terms, energy productivity is a measure of the economic benefit we receive from each unit of energy we consume. Total economic output is calculated by dividing output by the energy consumed (e.g., barrels of oil equivalent or kilowatt hours of electricity). Besides reducing greenhouse gas (GHG) emissions and other pollutants, energy productivity also reduces water use and other environmental footprints. From an economic standpoint, energy productivity can assist in reducing utility bills, creating jobs, and stabilizing electricity prices. Notwithstanding, while some studies claim that energy productivity has a limited role in reducing carbon emissions, studies have produced wide-ranging and inconclusive outcomes (Dong et al. 2018). For several years, experts have questioned whether energy productivity can be proven to play a role in reducing rates of carbon dioxide emissions in an economy.

To asnwer this questions and bring closure to the debates, Poland's economy presents an intriguing case for studying the relationship between energy productivity and environmental degradation. Poland's economy is among the fastest-growing economies across the Euro Zone, with construction expected to account for 5.4% in 2021. The country's fossil energy consumption rate is higher in the transport sector, followed by industry, housing, and heat generation. The economy has a modernized oil infrastructure with a maritime oil terminal in Gdańsk, refineries with oil storage systems, and widespread pipeline infrastructure (see Fig. 1). According to IEA's energy policy review in May 2022, Poland's energy policy aims at cutting down emissions through investments in renewables, natural gas, and nuclear energy, increasing electric use and encouraging productivity energy use. Beginning from 2016, Poland has significantly diversified its gas supply and hugely invested in renewable energy technologies and offshore wind projects. Poland has successfully reduced its gas imports from 90% in 2010 to 55% in 2020 by investing heavily in LNG terminals and pipeline linkages to other EU neighboring countries such as Norway. However, fossil fuels still account for 85% of the total energy supply, with coal holding the largest share. In 2021, by generating electricity from coal during their 2021 economic rebound, this wiped out in just 1 year almost a decade of policy-driven steady reductions and placing coal at 80% of their total generation. This has compromised air quality, polluted drinking water, and increased health risks (Attia et al., 2022). Poland plans to construct a nuclear reactor as part of its energy strategy by 2033. But budgetary commitment is low. In IEA's 2021 energy policy review, Poland has not yet liberalized domestic energy markets, and the state-controlled corporations continue to regulate a huge part of the markets and impose electricity price hikes. Furthermore, investments in educating consumers on switching electricity suppliers are below the EU average.

By promoting greater energy productivity and modifying fuel consumption patterns, significant environmental and economic gains could be achieved, including reducing the domestic use of coal and electricity. Unfortunately, these important statistical events in Poland are least highlighted in the literature of environmental economics. Based on these facts, this paper aims to capture the effect of energy

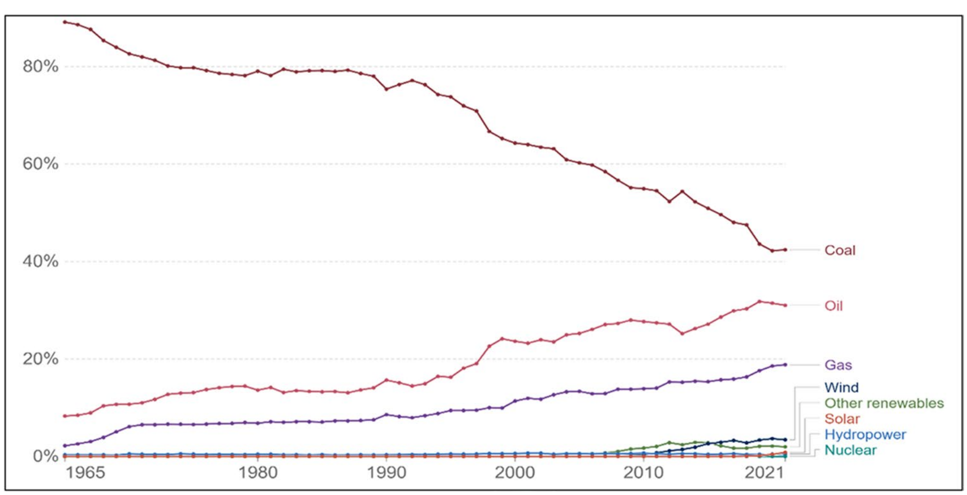

Fig. 1 Poland's energy consumption by source

productivity on environmental degradation in Poland while controlling economic growth, primary energy consumption, and globalization from 1990Q1 to 2019Q4. The study progresses as follows: the next section focuses on a relevant literature review, followed by methodology, results, and discussions, and the final section is dedicated to a conclusion with suggested policy recommendations.

Literature review

Globally, one of the biggest threats of the twenty-first century is climate change. The effects have been reducing agricultural production, serious flooding, rising global temperatures of varied intensity, worsening human health caused by polluted air and water quality, biodiversity loss, and threatening coastal communities. Experts have called for urgent global policy action to avert the growing dangers to humanity. Contributing to climate action, environmental economists have, for many years, made strenuous efforts to theoretically explain climate-causative factors and how they could be dealt with through articles and publications (Smulders et al. 2014). For example, Smulders et al. (2014) highlighted the significance of technological innovation in generating growth, market failures, and investing in natural capital to mitigate CO_2 emissions. Initial studies which offered a theoretical basis for such happenings for increasing CO2 emissions was the famous environmental Kuznets curve (EKC hypothesis) of Grossman and Krueger (1991). This theory sets the pace for environmental degradation studies and scientifically explained the U-shaped relationship between economic growth and environmental degradation.

Climate change remains one of the greatest threats of the twenty-first century, and mitigating its effects has been found to require policy actions, technological advancement, and behavioral change. Energy productivity has been found to pivot around behavior change perspectives, enhanced by technology. At the Egyptian Conference on climate change (COP-27), productivity energy use was highlighted as world leaders sought pathways to save the planet from global warming. The European Union (EU) has set binding targets to reduce greenhouse gas emissions by at least 40% by 2030 (Salvia et al. 2021). The vital point here is to understand how energy productivity and efficient use of energy resources affect carbon emissions and it consequential effect on sustainable economic development. Several empirical studies have been conducted on the impact of energy productivity on environmental degradation (Alola & Joshua, (2020); Atalla & Bean, (2017); Cheng, et al., (2021); Lin & Sai, (2022); Yu et al., (2022); Kirikkaleli et al., (2022); Madžar, (2022); Arafat, et al., (2022); Liu et al., 2022; Raza & Lin, (2022)); Anjanappa & Jongwanich, (2022); Taušová et al., (2022); Yuan, et al., (2022). For further comprehensive review towards achieving the objectives of the study, the paper controls globalization, economic growth, and primary energy consumption since they have been validated to contribute to carbon emissions and environmental degradation debates. To assess the effect of these factors on environmental degradation, the study makes these four hypotheses in the literature review process:

Hypothesis 1(H_{o1}): globalization increases CO_2 emissions.

In their investigation of the effects of globalization and economic complexity on CO_2 emissions for 111 countries from 1983 to 2017, Nan et al. (2022) find positive spatial spillovers of CO_2 emissions from neighboring countries. More strikingly, several other scholars investigated the relationship between globalization and CO_2 emissions and had inconclusive outcomes (Saud et al. 2020; Akadiri et al., 2019; Adebayo and Kirikkaleli, 2021; Le and Ozturk, 2020; Chishti et al., 2020). However, several recent scholars have found that globalization can generate economic growth noted for creating a rise in CO_2 emissions (Gurgul and Lach, 2014; suki et al., 2020; Atil et al., 2020; Wang et al., 2020; and You & Lv, 2018). Based on these, we assume that a steady increase in globalization significantly increases CO_2 emissions in Poland, i.e., $\vartheta_1 = \frac{\vartheta LCO_2}{\vartheta LGLO} > 0$; where ϑ refers to a parameter of interest; LGLO refers to the natural log of globalization; and LCO_2 is the natural log of carbon dioxide emissions (as a proxy for environmental degradation). This hypothesis supports a study by Umar et al. (2020).

Hypothesis 2(H_{o2}): economic growth is associated with a steady increase in CO_2 emissions.

Economic growth is crucial for the economic prosperity of nations; however, the critical pathway to reduce carbon dioxide emissions remains a huge global policy concern due to rising carbon emissions from fossil fuels used to propel such growth. Several studies have confirmed that continuous economic growth is associated with a steady increase in fossil fuel use (Sun et al., 2022). Poland is much over-reliant on trade sales to power their GDP growth; and this has for several years remained a policy and academic problem. The recent attempt by Marek et al. (2022) to investigate the possible distributional effects of a carbon-intensive Poland indicated that any distributional policy action would directly affect economic growth, increase unemployment, and reduce well-being. To sustain growth, Poland imports an annual average 35% of its fossil energy from Russia, which amounts to 8bilion EUR for the continuous growth of its GDP (Eurostat 2022; Maćkowiak-Pandera and Gawlikowska-Fyk 2022). Hence, this paper hypothesizes that economic growth has steadily increased CO_2 emissions in Poland, i.e., $\vartheta_2 = \frac{\vartheta LCO_2}{\partial LGDP} > 0$; where ϑ refers to the parameter of interest; LGDP refers to the natural log of GDP per capita (constant 2015 US$) as a proxy for economic growth; and LCO_2 is the natural log of carbon dioxide emissions (as a proxy for environmental degradation). This hypothesis supports Sun et al. (2022) empirical study.

Hypothesis 3(H_{o3}): primary energy consumption has positive effects on CO_2 emissions.

For several decades, Poland's heating markets have been a subject of low energy production efficiency with increasing levels of CO_2 emissions. A recent study by Księżopolski et al. (2020) finds increasing calls for changing heating sources from coal to clean energy. Additionally, the study finds that without "governments" incentive support, people will not abandon coal usage, and the continuous use of primary energy (i.e., coal) by a large percentage of its population increases CO_2 emission, which is a steep policy challenge in Poland. Scholars report that Poland's plans to develop nuclear energy have either been postponed or canceled; and electricity generation and heavy industrialization continue demonstrating inefficient energy use; and with recent desulfurization equipment in power plants virtually unknown, this presents a dire environmental situation in Poland (Brauers & Oei, 2020). However, some scholars claim that renewable energy use could be helpful to Poland in reducing carbon dioxide (Akbar et al., 2022). Based on the review, the paper hypothesizes that primary energy consumption has positive effects on CO_2 emissions in Poland, i.e., $\vartheta_3 = \frac{\vartheta LCO_2}{\partial LPEC} > 0$; where ϑ refers to the parameter of interest; LPEC refers to the natural log of primary energy consumption; and LCO_2 is the natural log of carbon dioxide emissions (as a proxy for environmental degradation). This hypothesis corroborates the recent study by Sun et al. (2022).

Hypothesis 4(H_{o4}): energy productivity reduces CO_2 emissions.

Generally, the quality of the environment is directly related to meeting the unprecedented demands for energy consumption. According to IEA, Poland utilizes its own indigenous domestic renewable energy sources, such as water, wind, sun, and biofuels, to generate electricity at home. Also, Poland is an importer of nuclear fuels, biofuels, and fossil fuels such as oil and natural gas; thus, the Swedish government has always placed a high priority on energy security. Encouraging environmental innovation and behavioral change for productive energy use has been debated in academia and policy circles. Major advanced economies, including Norway, Germany, Japan, the USA, and the UK, were among the first countries to introduce energy productivity policies and launch green patent applications in 2009 for several environmental reasons. Energy productivity also provides strong economic incentives for innovators to develop more green technologies toward reducing human vulnerabilities arising out of fossil fuel emissions (Oyebanji et al., 2022). Several empirical studies have found a beneficial impact of energy productivity on environmental quality (Alola & Joshua, 2020; Atalla & Bean, 2017). Based on this, the study hypothesizes that energy productivity negatively affects CO_2 emissions in Poland, i.e, $\vartheta_4 = \frac{\vartheta LCO_2}{\partial LEPR} < 0$; where ϑ refers to the parameter of interest; LEPR refers to the natural log of energy producitivity; and LCO_2 is the natural log of carbon dioxide emissions (as a proxy for environmental degradation). This assumption supports a study by Oyebanji et al. (2022). The empirical applications of these hypotheses are presented in the empirical findings and discussions section

Based on the review of these theoretical and empirical studies, it is clear that literature estimating the effect of energy productivity on carbon emissions is scanty. To make contibutions to this emergy field of study, this paper aims to capture the effect of energy productivity on environmental degradation in Poland while controlling economic growth, primary energy consumption, and globalization from 1990Q1 to 2019Q4. Additonally, in the review process, the study detects no clarity in assessing the relative effects of renewable energy, economic growth, and financial development on environmental degradation. This study is intended to bring clarity to the debates for the case of Poland, using novel Fourier-based ARDL methods, Toda Yamamoto causality estimators, dynamic ordinary least squares (DOLS), and fully modified ordinary least squares (FMOLS) estimators (Addai et al., 2022).

Methodology

This paper aims to capture the effect of energy productivity on environmental degradation in Poland while controlling economic growth, primary energy consumption, and globalization in Poland from 1990Q1 to 2019Q4. Time-series data from Poland, beginning in 1990 and ending in 2018, are collected for use. Data was collected on (i) GDP per capita (constant 2015 US$) as a proxy for economic growth and sourced from the World Development Indicators; (ii) globalization (GLO) with data from the KOF globalization index; data on (iii) energy productivity (EPR); (iv) primary energy consumption (PEC) involving five sources as coal, crude oil, natural gas, hydroelectric, and other renewables (such as solar, wind, geo biomass, and biofuels); and (v) CO_2 emissions (as a proxy for environmental degradation) were sourced from UNFCC database, respectively. CO_2 emissions are regarded "the most emitting gas in greenhouse gas emissions, several scholars assert, using CO_2 emissions as an environmental quality indicator is appropriate" (Fei et al. 2011; Mohsin et al. 2022). To prevent scaling, all variables are analyzed in their natural logarithms to reduce the likelihood of heteroscedasticity in the estimation outcomes

Table 1 Descriptive statistics

Variables	LCO2	LEPR	LGDP	LGLO	LPEC
Description	Production-based CO_2 emissions	Energy productivity	GDP (constant 2015 US$)	Globalization index	Primary energy consumption
Mean	5.496330	3.851951	11.50942	1.846001	3.047283
Median	5.491481	3.876071	11.50677	1.873980	3.050621
Maximum	5.552000	4.089917	11.76296	1.907625	3.084789
Minimum	5.454142	3.583037	11.25612	1.705869	2.998265
Std. Dev.	0.028814	0.149977	0.150400	0.059510	0.022802
Skewness	0.552868	−0.384317	−0.121308	−0.824212	−0.415231
Kurtosis	2.035459	1.892392	1.808050	2.542707	2.467450
Jarque-Bera	10.76496	9.087970	7.398036	14.63208	4.866379
Probability	0.004596	0.010631	0.024748	0.000665	0.087757

and to ensure that the normality assumptions in the error term in the model can be sustained (Rahman et al., 2022).

Theoretical foundation

Several forms of environmental sustainability hypotheses have been proposed. Oyebanji et al. (2022) find a relationship between GDP growth and degradation in Spain; Debref (2016) explains a special nexus between eco-friendly growth policies and improvements in environmental quality. The scientific argument is to weigh the pros and cons of the growth of the model. To open up the space for further academic inquiry, this study focuses on the relationship between energy productivity and environmental degradation in Poland. To realize robust and reliable outcomes, we control for economic growth, primary energy consumption, and globalization: (i) recent research findings indicate that primary energy consumption has significant effects on reducing demand for fossil-based energy fuels. For this cause, several experts call for a policy focus on primary energy consumption (Gyamfi et al., 2021; Sun et al., 2022); (ii) a number of studies in the literature have shown that economic growth rates are good indicators for measuring environmental degradation since energy is a requirement for increasing production which culminates in CO_2 emissions generation (Umar et al., 2020; Solarin et al., (2017); and (iii) in their studies on the study on the role of globalization and CO_2 emissions in China, Liu et al. (2020) find that between 970 and 2015, the relationship existing between globalization and CO_2 emissions displays an inverted U-shaped, a result hugely supporting environmental Kuznets curve theory (i.e., EKC hypothesis).

$$LCO_{2it} = \beta_1 LEPR_{it} + \beta_2 LGDP_{it} + \beta_3 LGLO_{it} + \beta_4 LPEC_{it} + \varepsilon_{it} \quad (1)$$

Where LCO2, LEPR, LGDP, LGLO, and LPEC stand for production-based CO_2 emissions, energy productivity, economic growth, globalization, and primary energy consumption, respectively.

The study begins the pre-estimation processes by first checking whether the time-serried variables are linearly dependent or behave differently in Poland using Broock–Dechert–Schinkman (BDS) test known to have advantages in detecting linearity, nonlinearity, misspecification, and judgmental errors in econometric analysis (Broock, Dechert, and Scheinkman test 1996).

Fourier ADF and ADF unit root tests

There is a general recognition in the literature that several time series data are random walks or are non-stationary and contain a unit root. Testing for unit roots is necessary since their presence leads to invalid econometric analytical inferences (Joseph and Perman, 2006). If the outcomes from the BDS test shows nonlinearity of seried variables, the next step involves checking the integration order of our times series variables using Fourier ADF and ADF unit root tests with structural brakes. In the past several unit with breaks have been used, such as Nelson and Plosser's (1982) ADF model (unit root with no break); Perron's (1989) exogenous breaks model (unit root with 1 breakpoint); Zivot and Andrews's (1992) endogenous breaks model (unit root with one breakpoint); and Lumsdaine and Papell's (1997) endogenous breaks model (unit root with 2 breaks) (Joseph and Perman, 2006). However, over the years in econometric analysis, it has been found that variables seen to be integrated at varying degrees are not testable for cointegration using traditional cointegration approaches. To deal with this problem, the study adopts both Fourier ADF and ADF unit root tests validated by Tiwari & Albulescu (2016) to produce reliable outcomes over traditional unit root tests. This is because it is a simple form of Gallant's (1981) Flexible Fourier Form specially employed to approximate obvious time series smooth breaks (Enders and Lee, 2012).

Table 2 BDS test

LCO2			
Dimension	BDS statistic	Std. error	z-Statistic
2	0.191686	0.005844	32.79952
3	0.323752	0.009320	34.73713
4	0.413098	0.011134	37.10344
5	0.473033	0.011640	40.63862
6	0.513248	0.011259	45.58593
LEPR			
Dimension	BDS statistic	Std. error	z-Statistic
2	0.200850	0.004755	42.23892
3	0.341608	0.007582	45.05690
4	0.441446	0.009054	48.75955
5	0.513126	0.009461	54.23720
6	0.564483	0.009146	61.71698
LGDP			
Dimension	BDS statistic	Std. error	z-Statistic
2	0.202515	0.003791	53.42304
3	0.343083	0.006037	56.83338
4	0.441978	0.007198	61.39902
5	0.512476	0.007511	68.22775
6	0.563894	0.007251	77.77128
LGLO			
Dimension	BDS statistic	Std. error	z-Statistic
2	0.207618	0.005599	37.08335
3	0.352967	0.008895	39.68163
4	0.454736	0.010586	42.95830
5	0.525723	0.011025	47.68598
6	0.575179	0.010623	54.14471
LPEC			
Dimension	BDS statistic	Std. error	z-Statistic
2	0.176395	0.005670	31.10910
3	0.292925	0.009044	32.38727
4	0.365634	0.010806	33.83538
5	0.409492	0.011299	36.23997
6	0.434783	0.010931	39.77460

Table 3 Fourier ADF and ADF unit root tests

Variable	F-STAT	FADF	ADF with break point
LCO2	2.022332		−4.321* (1997Q1)
LEPR	5.333748**	−3.764805 [1] <9>	
LGDP	2.035628		−2.494 (1991Q4)
LGLO	2.865954		−7.132*** (1991Q1)
LPEC	2.448424		−3.364 (2009Q1)
DLCO2			−4.688 ** (1992Q1)
DLEPR		−5.135240**[1] <8>	
DLGDP			−6.186*** (2012Q1)
DLGLO			
DLPEC			−5.626*** (1992Q1)

*,**,*** indicate level of statistical significance at 1%, 5%, and 10%, respectively. 1% critical values for the F test and Fourier ADF test are 12.21 and 4.491, respectively. The values into [ ] and < > indicate frequency and lag lengths

Fourier-based ARDL long run cointegration test

For decades, several researchers have historically adopted Pesaran et al. (2001) autoregressive distributed lag (ARDL) cointegration approach. But later, studies have shown the existence of a long-run nexus among variables. McNon et al. (2018) and Yilanci et al. (2019) claim that Fourier-based ARDL method provides a more robust long-run cointegration estimation outcomes than the traditional ARDL approach. Additionally, Fourier functions can identify structural changes, although for the Fourier-based ARDL approach, further structural change test is not required. The Fourier function created by Yilanci et al. (2020) considers structural changes in the model, as seen in Eq. (2).

$$d(t) = \sum_{k=1}^{n} a k \sin\left(\frac{2\pi kt}{T}\right) + \sum_{k=1}^{n} b k \cos\left(\frac{2\pi kt}{T}\right) \tag{2}$$

"where 'n' indicates the number of frequencies, $\pi = 3.14$, 'k' is the number of special frequencies selected, 't' is the trend, and 'T' is the sample size." A single frequency value suggested by Ludlow and Enders (2000) is used in Eq. (2).

$$d(t) = \gamma 1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma 2 \cos\left(\frac{2\pi kt}{T}\right) \tag{3}$$

The FARDL model for this study is shown in Eq. (4).

$$\begin{aligned} \Delta LCO2t =& \beta 0 + \gamma 1 \sin\left(\frac{2\pi kt}{T}\right) + \gamma 2 \cos\left(\frac{2\pi kt}{T}\right) + \beta 1 LCO2t - 1 \\ &+ \beta 2 LEPRt - 1 + \beta 3 LGDPt - 1 \\ &+ \beta 4 LGLOt - 1 + \beta 4 LPECt - 1 + \sum_{i-1}^{\rho-1} \varphi i' \Delta LCO2t - i \\ &+ \sum_{i-1}^{\rho-1} \delta i' \Delta LEPRt - i \ + \sum_{i-1}^{\rho-1} \varnothing i' \Delta LGDPt - i \\ &+ \sum_{i-1}^{\rho-1} \vartheta i' \Delta LGLOt - i + \sum_{i=1}^{\rho-1} \vartheta i' \Delta LPECt - i + et \end{aligned} \tag{4}$$

As in Christopoulos and Leon-Ledesma (2011) and Omay (2015), Yilanci et al. (2020) use the frequency value at the minimum sum of squared residuals. Bootstrapping simulation is used to determine F_A, F_B, and t-test critical values. In addition, we used FMOLS and DOLS approaches to support the outcomes of the Fourier ARDL test.

Empirical findings

This paper aims to capture the effect of energy productivity on environmental degradation in Poland while controlling economic growth, primary energy consumption, and globalization in Poland from 1990Q1 to 2019Q4. As

Table 4 Fourier ARDL bounds test

F-bounds test	Value
F-statistic	10.79534***
K	4

Note: *, **, and *** denote statistically significant at the 10%, 5%, and 1% levels, respectively

Table 5 Fourier ARDL long run form

Variable	Coefficient	Std. error	t-Statistic	Prob.
LEPR	−0.635117	0.114109	−5.565892	0.0000
LGDP	0.372268	0.115074	3.235045	0.0017
LGLO	0.263879	0.055405	4.762709	0.0000
LPEC	0.375857	0.109216	3.441397	0.0009
C	2.025204	0.580205	3.490495	0.0007

Table 6 Robust test

FMOLS				
Variable	Coefficient	Std. error	t-Statistic	Prob.
LEPR	−0.745294	0.105087	−7.092150	0.0000
LGDP	0.470156	0.112351	4.184720	0.0001
LGLO	0.308328	0.043868	7.028575	0.0000
LPEC	0.325119	0.110672	2.937675	0.0040
C	1.396038	0.537909	2.595308	0.0107
DOLS				
Variable	Coefficient	Std. error	t-Statistic	Prob.
LEPR	−0.726135	0.184647	−3.932558	0.0002
LGDP	0.470769	0.182732	2.576283	0.0117
LGLO	0.234508	0.070364	3.332782	0.0013
LPEC	0.313611	0.171827	1.825152	0.0715
C	1.489182	0.913789	1.629678	0.1069

already indicated, all forms of power generation cause some varying degree of environmental impact on our air, water, and land. Efficient production of power has significant policy implications. This is precisely the reason for this empirical study on Poland. As reported in Table 1, the outcomes of this assessment show that the distribution of the data is not normally distributed.

Outcomes of the BDS, as illustrated in Table 2, suggest nonlinear patterns in the time series data and that values for all variables are higher than BDS "dimensional critical values"; and based on this, the paper rejects the null hypothesis at 1% level of significance to validly claim that variables are non-linearly dependent.

Next, the paper checks for unit roots using Fourier ADF and ADF with breaks unit root test (see Table 3). However, we first check the roles of the Fourier function if they are statistically significant before employing ADF with breaks unit root test. Otherwise, the ADF unit root test is simply used to assess the stationarity properties of the series.

The F-stat of the LEPR seems significant; therefore, the FADF test is used for making unit root decisions toward next estimation action. However, for the other time series variables, the ADF unit root test with a breakpoint test was used. The outcome of FADF reveals that LEPR is integrated at order one. The outcomes of the ADF unit root test with a break point suggest that besides LEPR, all other variables are integrated at order one — I(1). The observed breakpoint dates are critical periods of policy variations by the Polish government and other external shocks. Beginning from the 1990s, Poland undertook a series on radical economic and social policy changes toward quick growth. Again, the 2008 global financial crisis caused policy variations in Poland. Furthermore, the COVID-19 outbreak had a major impact on Poland's economy and energy system, when total final consumption (TFC) grew from 70 million tonnes of oil equivalent (Mtoe) to 75 Mtoe, driven between 2010 to 2019, mainly by increased energy demand from transport and industry. However, improvements in energy efficiency and the increasing role of the service sector driven by policy over the period have decoupled energy demand from economic growth.

With these outcomes, we can infer that there is a cointegration relationship between the selected variables. However, to estimate short-run and long-run coefficients, we first apply diagnostic tests on our empirical ARDL model to ensure that it is free from serial autocorrelation and heteroscedasticity and has reasonable goodness of fit and the CUSUM graph indicates substantial stability (see Tables 7 and 8, Figs. 3 and 4 (Appendix)). Next is to check the cointegration properties of the time series variables using the Fourier-based ARDL bounds test. Traditionally, ARDL bounds testing refers to a cointegration estimator developed by Pesaran et al. (2001) to check long-run relationships among variables despite integration order (i.e., I(0) or I(1)). Second, the estimator can help derive the unrestricted error correction model (UECM) through very simple linear processes. Finally, the ARDL bounds approach has both short and long-run dynamics. Fourier-based ARDL bounds test has a reliable estimate because endogenous problems do not affect the size and power characteristics of the ARDL bounds test frame by using the asymptotic threshold of Monte Carlo simulation. The Fourier ARDL model (McNown et al., 2018) "is an improvement of the traditional McNown et al. (2018) Bootstrap ARDL test (sharp break), which can show aspects of breakpoints." The approach also applies despite the timeframe and has been validated by Yilanci et al. (2020).

The outcomes of the Fourier ARDL bounds test (as illustrated in Table 4) confirm that variables are integrated and suggest long-run cointegration relationship from the perspective of the frequency of Fourier approaches. These outcomes confirm the previous work of Gyamfi et al. (2021). As a next step, the present study employs the Fourier ARDL test to capture the effect of energy productivity on environmental degradation in Poland.

As reported in Table 5, the outcomes of the Fourier ARDL long-run estimates indicate that all confidence are statistically significant. However, for LEPR, the coefficient is negative, signifying that a unit rise in LEPR has negative effects on CO_2 emissions by 0.635%. This outcome indicates that energy productivity is one of the important factors to decline in CO_2 emissions in Poland. For the remaining variables which have positive coefficients, a unit rise, LGDP, LGLO, and LPEC have significant positive effects on CO_2 emissions by 0.115%, 0.263%, and 0.375%, respectively. These findings are in line with Hnydiuk-Stefan et al. (2021), who find the causes of CO_2 emissions in Poland to be largely due to a lack of investment in renewable technologies, cross-boundary effects, and continuous consumption of coal as a primary energy source. The outcome of Breusch–Pagan–Godfrey test in Table 7 shows no heteroskedasticity since null hypothesis is not rejected, while in Table 8 (Breusch–Godfrey serial correlation LM test), no serial correlation at up to 9 lags is observed. In addition, Cusum and Cusumsq figures are reported in Figs. 3 and 4.

The outcomes of the FMOLS and DOLS estimates (Table 6) for model robustness indicate that the independent variables cumulatively (i.e., LEPR, LGDP, LGLO, and LPEC) can explain the dependent variable, CO_2 emissions, by 98% using FMOLS and 99% using DOLS estimators respectively.

Discussion

In this study, we have empirically assessed the effects of energy productivity on environmental degradation in Poland while controlling economic growth, primary energy consumption, and globalization in Poland with data ranging between 1990Q1 and 2019Q4. The outcomes of the econometric analysis indicate in Poland; energy productivity over the long run contributes immensely to a fall in CO_2 emissions. The implications are that given Poland's over-reliance on coal energy sources for heating, the economy could stop this worrying trend by significant investments in renewable energy sourcing and reap the benefits of clean energy use. As already indicated, all forms of power generation cause varying degrees of environmental impacts on our air, water, and land. Efficient production of power has profound benefits. In Poland, coal has been popularly called "black gold," helping the economy achieve energy independence. However, this high-polluting fuel is linked to deadly diseases and the premature death of many, including children. Notwithstanding, we hesitate in our optimism since a large number of coal-dependent employees in Poland places the government in a policy dilemma (Brauers, & Oei, 2020).

Second, we find from this analysis that economic growth, globalization, and primary energy consumption have positive effects on CO_2 emissions in Poland. The effects of increasing economic growth require a corresponding rise in energy demand which will lead to rising carbon emissions polluting the air and creating global warming. Additionally, the increasing emission resulting from growth, with other factors including climate change, will concentrate particulate matter (PM 2.5) as well as ground-level ozone which has negative health and environmental consequences. The study outcomes first validate the hypothesis for this study on economic growth; and second, lend support to the EKC hypothesis on growth and its short- and long-term effects on the environment. This implies that Poland must rethink their economic growth policies.

Third, the outcomes indicate that globalization causes to increase in CO_2 emissions, meaning that our hypothesis on globalization for this study was not rejected. Lessons from China indicate that the industrial boom in China is largely propelled by a cheap global supply of coal which produces carbon dioxide. Additionally, while globalization can accelerate growth, it normally causes urbanization which presents negative environmental externalities (Khan et al., 2019). This study has confirmed that part of Poland's environmental degradation is due to regional spillovers. Like China, with Poland, is building coal plant continually for the production of global goods, the damming effects of pollution are difficult to quantify and will take years to deal with this, which will involve pulling down an available coal plant. The financial and health cost will be immense for Poland and its global citizen, just as we are witnessing China today with about 4000 loss of humans per day through pollution-related illnesses.

Third, the outcomes suggest that primary energy consumption has positive effects on CO_2 emissions. This finding validates the hypothesis for this study and supports Sharma (2011), who found that primary energy consumption has positive effects on carbon emissions. In Poland, the major energy consumption source is primarily sourced from coal. This implies that though the government benefits immensely from coal to propel growth, not enough investments have been made over the years to develop alternative clean energy sources. A recent study by Księżopolski et al. (2020) finds increasing calls for changing heating sources from coal to clean energy, indicating coal has become a major environmental problem for Poland. This finding presents yet another validated evidence for policy response since the cost of inaction may be so severe (Siitonen et al., 2010). Figure 2 reports the main findings of the present study.

Conclusion

In this study, we have sought to empirically assess the effect of energy productivity on environmental degradation in Poland from 1990Q1 to 2019Q4, using novel Fourier-bases ADF unit root and Fourier-based ARDL approaches. In doing so, we have controlled economic growth, primary energy consumption, and globalization in the estimated models. The outcomes of the Fourier ARDL long-run estimates indicate that all coefficients are statistically significant, such that (i) energy productivity has long-run negative impacts on CO_2 emissions; and (ii) economic growth, globalization, and primary energy consumption cause rise in CO_2 emissions in Poland. There is a worrying trend observed in both economic growth and primary energy consumption which need policy focus since the parameters are a major cause of CO_2 emissions in Poland. Several of these findings validate previous research outcomes, including Brauers, & Oei (2020), Gyamfi et al. (2021), Liu et al. (2020), and Yilanci et al. (2020).

These findings on Poland present these policy implications and insights. To reduce carbon emissions in the short-term, an embargo on Russian fossil fuels requires alternative fuel sourcing from in-country or from Europe since the needed volumes to meet electricity, transport, heating, and industrial demand are substantial. When this happens, Poland's economy could be negatively affected if there are accompanying short-term oil price hikes. With the global crude oil market highly integrated, evidence shows that crude oil restrictions are compensated by resorting to other sourcing (Caldara et al., 2019). Poland can, in the medium-term, invest in renewable energy production and energy productivity. Policies on residential gas use and coal consumption can be made by renewable energy switch towards biomass obtained locally and heat pumps for poor and high-income households, respectively, and free up to 10% of the economy's total gas consumption. Sourcing energy from unutilized German nuclear power plants seems a feasible option. This option has been recently proposed in the Polish parliament and has yet to receive government support. Once this is done, oil and coal exporting countries could make up for this shortfall in imports from Russia. Coal be domestically produced, and the government could invest in building new gas pipelines and terminal capacities to reduce its vulnerability to the network and Russia LNG, and bolster its pipeline imports from the Baltic Pipe, for example. Poland could similarly call for immediate integration of EU internal energy and investments in transnational energy links to reduce energy substitution costs and reduce household energy costs by direct transfers as initiated in 2021 on special taxation and relief allowance payments (Brauers, & Oei, 2020). Given that this has had implementation failures for the disproportionately burdening households and discoursing investments in energy-efficient technologies, Poland could use energy vouchers as a targeted financial relief for low-income households as relief for rising energy costs (Sokołowski et al. 2020). Based on the outcomes of the study, Polish policymakers could (i) liberalize domestic energy markets so electricity consumers can switch operators and (ii) commit to current policies of decarbonizing energy supply by investing hugely in renewable energy, nuclear energy, e-mobility, and energy productivity measures. The study was limited to being a country study, and future studies could consider expanding the context to the region or taking a far wider area to enable a wider picture and comparative assessment of the effects of energy productivity on environmental degradation.

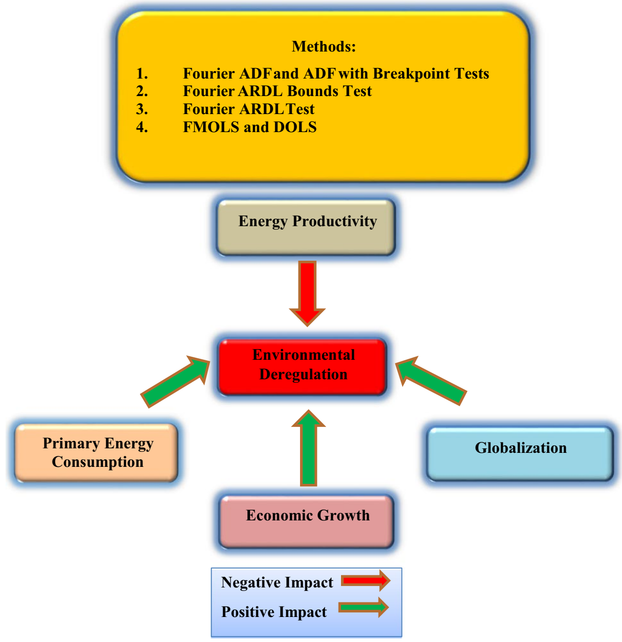

Fig. 2 Summary of empirical findings with methods

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Availability of data and materials The data that support the results are accessible from the World Bank and OECD.

Author contributions Dervis Kirikkaleli investigated and gathered the data. Kwaku Addai wrote the introduction and the literature review, while Dervis Kirikkaleli prepared the methodology and the empirical findings. In addition, Kwaku Addai helped to explain the results. Finally, as the corresponding author, I confirm that the final version of this paper was reviewed and endorsed by all authors.

Declarations

Ethical approval We declare this paper is original, has not been published before, and is not currently being considered for publication by another journal. Therefore, this research does not require ethical authorization or informed consent.

Consent to participate Not applicable

Consent for publication Not applicable

Competing interests The authors declare no competing interests.

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