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Energy innovations and pathway to carbon neutrality in Finland

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ABSTRACT

Given the determination to maintain the status of a low-carbon energy and clean energy technology country, Finland has remained committed to facing out coal energy and subsequently halve the domestic utilization of fossil oil all by 2030. To assess these laudable national targets, this study applies a two-scenario approach to examine the environmental effects of Finland's disaggregated energy mix for the period between 1974 and 2019. The first scenario of analysis focuses on the environmental effect of the disaggregated energy mix with environmental technologies, while the second scenario explores the case of without environmental technologies. The application of the autoregressive distributed lag (ARDL) technique for the analysis revealed some insightful results. Firstly, the deployment of environmental technologies in coal energy development will yet exert a significant environmental cost. Secondly, with innovations in the development of oil, natural gas, and nuclear energy sources, a statistically significant environmental benefit is attainable. Thirdly, without the deployment of environmental technologies, the utilization of the disaggregated energy forms (coal, natural gas, nuclear, and oil) will continue to constitute an environmental nuisance. Furthermore, the environmental Kuznets curve hypothesis is only valid for Finland when the environmental technologies deployed in the country's disaggregated energy utilization are considered. Lastly, the independent deployment of environmental technologies mitigates carbon emission with an elasticity of 0.1 in the long run. Intuitively, the result suggests that energy and climate financing policy that promotes innovation via research and development is vital to achieving the decade-long target.

Introduction

The global community is being increasingly faced with the growing need to decisively pursue carbon neutrality. This need is becoming progressively paramount as more updates emerge regarding the environmental and climatic dangers ahead of humanity if the world sustains or increases its current trajectory of the global greenhouse gas (GHG) emissions. The Intergovernmental Panel on Climate Change (IPCC, 2021) has provided some insights examining the imminent dangers of the risks of global warming using different scenarios[2]. Over the decades, emissions have been cumulatively growing. The IPCC (2021) noted that there has been an estimated 0.27 °C to 0.63 °C rise in surface temperature on a global level for every 1000 gigatons of cumulative CO_2 emissions. This means that we want to save our planet, there is a need to ensure that the global emission rate is cut down. Several studies have

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[2] Global warming predictions were conducted under five major emissions scenarios, namely the very low and low GHG emissions scenarios, the intermediate emission scenario, and the high and very high GHG emissions scenarios. Given how the world has sustained a constant CO2 emission reduction from 2015 until a net zero level in 2050 as assumed in the low or very low scenario, it is mostly unlikely that we will exceed 2^0C of global warming even in the long-term period of this century (2081–2100). However, this level of global warming is most likely to be exceeded in the mid-term period of the century (2041–2060), given the intermediate, high and very high emissions scenarios (IPCC, 2021). The undesirably likely catastrophes of risking climate change due to unabated GHG emissions would include a rise in average precipitation. This has been noted to be much more prominent since the 1980s, as well as a rise in the global average sea level and global acidification of the ocean, and warmer global temperatures among other issues. All of these could bring about colossal damages in the form of the enormous economic cost due to the higher incidence of floods, fires, loss of biodiversity, and disease outbreaks among other challenges – see Anderson et al. [4], Risbey [48], IPCC (2021), and Whiteman et al. [66].

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Nomenclature

Abbreviations

EKC	Environmental Kuznets Curve
EU	European Union
IPCC	Intergovernmental Panel on Climate Change
GHG	Greenhouse gas
WDI	World Development Indicators
CO_2	Carbon dioxide
UNEP	The United Nations Environment Programme
USA	The United States of America
UNFCCC	United Nations Framework Convention on Climate Change
OECD	Organization for Economic Cooperation and Development
R&D	Research and development
OLS	Ordinary Least Squares
ECT	Error Correction Term
GMM	Generalized Method of Moment
ARDL	Auto Regressive Distributed lag
FMOLS	Fully Modified Ordinary Least Square
DOLS	Dynamic Ordinary Least Square
BRICS	Brazil, Russia, India, China, and South Africa
UK	United Kingdom
G7	The Group of Seven
P-value	Probability value

Fig. 1. Patents on environment technologies (Percentage of Total, 2000 – 2018). **Source**: Patents in environment-related technologies [40].

emphasized this crucial need as there are observable relationships between global warming and anthropogenic carbon emissions level. This is backed by Matthews et al. [38], Allen et al. [1], Ghommem et al. [16], Reisinger and Clark, [47], Takemura and Suzuki [57], and Alola et al. [2], among others.

Achieving the task of emission reduction and ultimately carbon neutrality means that the current global energy profile must be adjusted, among other issues. Fossil fuel energy sources, primarily oil, gas, and other solid resources like coal, account for approximately 80% of the total global energy consumption as of 2015[67]. As such, fossil energy consumption accounts for the largest share of the global emissions with economies like China, the USA, India, and the European Union (EU) being the top emitters[60,63]. In the wake of the Paris Agreement and other global environmental submits, some of these countries, especially those in the EU, have started putting in place gradual measures to ensure that they make the necessary adjustments in their current conventional energy profile to achieve carbon neutrality. However, some of the measures taken to achieve carbon neutrality have been deemed insufficient so far[61,26]. Many studies including the work of Dimitrov [12], Hsu et al. [22], Liobikienė and Butkus [36], and Wang et al. [64] among others have noted that the global community needs to do more for global environmental sustainability.

Environmental technological innovations are often seen as one of the central propelling forces in terms of helping to achieve clean energy targets and emissions reduction policies. The significance of the innovations concerning the actualization of various climate agreements has resonated among researchers in some studies including the work of Jaffe et al. [27], Hopwood et al. [21], and Feijoo et al. [13] among others. Besides the environmental benefits, technological advancement is undoubtedly a major component of economic growth. This has been captured and demonstrated in various growth models including Solow's [55] model, as well as the models of Krugman [33], Romer [49], and Löschel [37]. Technological innovation catalyzes production activities and overall consumption. Its effects can be seen in the drastic rise in energy consumption over the last few decades. With innovations, there have been advancements in various fossil fuel-based technologies, especially in the aftermath of the Industrial Revolution of the eighteenth century[45,65].

As a result, studying the significance of environmental technological innovations in terms of energy dynamics and emissions profiles has become a critical step in assessing the progress of the carbon neutrality agenda among different nations. In the current study, we examine the significance of innovations in relation to fostering carbon neutrality in the Finnish economy as an EU member state where the number of environmental technological innovations have considerably grown in recent times.

According to the available data from the OECD [40], the percentage of total environmental technology patents from the Finnish economy has grown by more than double over the past two decades as seen in Fig. 1. This translates to an average of 11.10% of the total environmental-related patents over the period between 2000 and 2018. This performance is comparatively high compared to the averages of 9.04%, 9.59%, 9.63%, 10.43%, 10.73%, and 10.74% from G7 member countries like Italy, the US, the UK, Canada, France, and Japan respectively, except for Germany with an average of 12.25% over the same period.

This development is expected to translate to impacts on the emission rates vis-à-vis possible changes in the energy profile and emissions level amidst the economic development in Finland over this period. Going by the extant literature, the case of Finland as a single country has been given limited attention. This is perhaps considering the country's success in terms of its energy-environmental sustainability drive. Besides, almost all of the extant studies that have addressed the matter of carbon emissions with respect of the energy profile as part of the Finnish economy were carried out in a combined study looking into the case of the general EU member countries. For example, Többelmann and Wendler [58], Fernández et al. [14], Jurgilevich et al. [31], and Mongo et al. [39] have all examined the EU bloc. The shortfall in such an approach is that the roles of country-specific differences on environmental performances vis-à-vis the differences in their energy profiles could be lost. This is so much more imperative given the disparity in each individual country's level of innovation. Hence, the novelty of this study hinges on the following:

a. Assessing the role of disaggregated main energy sources in CO_2 emission levels, thereby providing insights into the carbon neutrality goal of the Finnish economy.
b. Examining how the moderating role of innovations in disaggregated main energy sources impacts the carbon neutrality targets and environmental sustainability push in the Finnish economy.
c. Assessing the income-environmental nexus through the EKC phenomenon in a country-specific context in the case of the Finnish economy.

The rest of the manuscript is outlined as follows. Section 2 covers the literature review while Section 3 consists of the empirical methodology. The results and discussion of the findings has been organized in Section 4 while the study concludes with the recommendations and initiatives for authorities and policymakers.

Literature review

Since the current study presents an empirical insight into energy innovations and the pathways to carbon neutrality, a review of the extant empirical literature has been provided to identify the salient points to be addressed. It was observed that there are some extant studies in the empirical literature that have examined the possible environmental benefits of technological innovations. However, the studies generally vary in different regards. Firstly, the adopted methodology of the analysis differs. Secondly, there are also differences in the approaches adopted to measure technological improvements. Overall, there is no consensus as most results vary in terms of the sample observation from one country or groups of countries to another. Many studies have pointed out the desirable impact of innovations related to achieving environmental sustainability vis-à-vis a reduction in GHG emissions as part of actualizing their decarbonization targets. This is as observed in the studies by Többelmann and Wendler [58], Khurshid et al. [32], Ganda [15], and Ibrahiem [23], among others. However, some studies have not established a sufficient foundation of empirical evidence in that direction.

Feijoo et al. [13] argued that achieving a targeted emission budget in the US economy would require speedy distribution and the use of technological innovations that promote energy conservation. Többelmann and Wendler [58] carried out an examination of the impact of environmental innovation on twenty-seven European economies (EU-27). The study was conducted in a dynamic panel environment using the Generalized Method of Moment (GMM) approach. Their study shows that unlike general innovations, environmental innovations specifically help to reduce the level of CO_2 in the EU-27. This finding was further supported in a different study by Khurshid et al. [32]. In the latter, the OLS method was combined with the Non-linear ARDL approach to analyze the impact of technological innovations on carbon emissions. Khurshid et al. [32] adopted trademarks and eco-patents as proxies for innovations among European countries. Unlike the study by Többelmann and Wendler [58], Khurshid et al. [32] focused on select Western and Southern European economies including Belgium, France, Austria, Ireland, Spain, Germany, Netherlands, Italy, Malta, Portugal, Greece, Turkey, Luxembourg, and Cyprus. Their results show that environmental innovations significantly help to mitigate carbon emissions in the selected countries. Furthermore, Ganda [15] noted that the expenditure on research and development (R&D) reduced the emissions levels in the OECD member countries.

Further afield, Shahbaz et al. [53] used the bootstrapping ARDL method to examine the impact of technological innovations on carbon emissions in China. They determined there to be negative impacts due to innovations on the CO_2 emissions, meaning that innovations aid the improvement in environmental quality in China. The empirical analysis by Santra [52] also showed a similar result to the findings of Shahbaz et al. [53] in the case of BRICS economies. Santra [52] noted that green technological innovations have helped to specifically abate production-based carbon emissions among the selected BRICS economies. Ibrahiem [23] utilized a combination of approaches including the ARDL, FMOLS, and DOLS methodologies to examine the impact of technological innovations on carbon emissions in Egypt for the period between 1971 and 2014. Their study reveals that environmental quality is improved by technological innovations in the case of the Egyptian economy. The study further suggests that the environmental quality is not improved by technological innovations alone but also by utilizing alternative energy resources as supported by several other empirical studies such as the work of Onifade et al. [42], Gyamfi et al. [20], Onifade et al. [43], and Bekun et al. [6] among others.

However, even though there is large-scale evidence to support the emission-reducing impact of environmental innovations, some studies have not established sufficient empirical evidence in that direction. For instance, the study by Mongo et al. [39] looking into fifteen European economies shows that the carbon mitigating effect of innovation is only visible in the long run but not in the short run. They utilized the ARDL approach to the data from the fifteen EU countries between 1991 and 2014. Besides, the study by Fernández et al. [14] also shows that innovations, as captured by the spending on research and development (R&D), mainly contribute to CO2 abatement in the case of developed economies. The impacts may vary in the case of developing economies. In line with this observation, the study by Ullah et al. [59] showed that there is an asymmetric effect in terms of technology innovations and the CO_2 emissions nexus in Pakistan in the long run.

Furthermore, the study by Clement [9] using environmental data from the US between 1963 and 1997 concluded that technological innovations have only resulted in a minimal environmental gain as far as carbon emission levels are concerned. In addition, using samples that cover 1996 – 2018, Chen and Lee [7] conducted a cross-country examination of ninety-six countries to examine the technological innovation-emission nexus. They noted that there is no significant impact due to innovation on carbon emissions as part of their global consideration. They further argued that attention should be paid to a country's individual characteristics to ensure environmental sustainability.

The aforementioned indicates that any assertions and conclusions on the innovation-environmental nexus need to be backed up by a comprehensive disaggregated analysis of individual country-level environmental profiles. The case of Finland as a single country has attracted no attention. This is perhaps considering the country's comparative success regarding its energy-environmental sustainability drive. Also, most of the extant studies that accommodated the Finnish economy were carried out as part of an aggregated study looking into the case of the EU bloc such as in the work of Többelmann and Wendler [58], Fernández et al. [14], Jurgilevich et al. [31], and Mongo et al. [39]. The shortfall in such an approach is that the role of country-specific differences in environmental performance can be overlooked. Furthermore, conducting a disaggregated country-specific analysis becomes more beneficial when considering the disparities between the individual countries' level of innovation in the face of the differences in

Table 1
Dataset description.

Variable	Code	Description, unit of measurement, and source.
Carbon emission	CE (sourced from British Petroleum database).	Million tonnes of carbon dioxide
Economic growth	Y (sourced from World Bank database).	Constant 2010 United States dollars
Coal energy	C (sourced from British Petroleum database).	Coal energy consumption measured in Exajoules
Natural gas energy	G (sourced from British Petroleum database).	Natural gas consumption measured in million cubic
Nuclear energy	N input equivalent (from British Petroleum database).	Nuclear energy consumption measured in Exajoules
Oil energy	O (sourced from British Petroleum database).	Oil consumption measured in million tonnes
Innovation	Ino (sourced from OECD database).	Measured by environmental technologies patent

Note: OECD is The Organization for Economic Co-operation and Development.

energy profile.

The present study provides a comprehensive country-specific analysis of the innovation-carbon emission nexus for the Finnish economy which has been previously sidelined in the extant studies. Importantly, a two-scenario approach was adopted to examine the environmental effects of Finland's disaggregated energy mix for the understudied period. The first scenario of analysis focuses on the environmental effect of the disaggregated energy mix with environmental technologies, while the second scenario explores the case without environmental technologies. By doing so, the study addresses the environmental goals of the Finnish economy in terms of achieving carbon neutrality. Finally, the study assesses the income-environmental nexus through the EKC phenomenon in the country-specific context of the environmental sustainability push of the Finnish economy.

Data, models, and methodology

The employed dataset is comprised of Finland's main energy sources, carbon emissions, economic variables, and innovations related to the aspect of environmental technologies from 1974 to 2019 (accounting for 46 observations). In Table 1, the details of the dataset and the sources are presented in a clearer format.

While mirroring the environmental benefit of income growth assertion, named the environmental Kuznets curve (EKC) of Grossman and Krueger [19] as derived from the earlier work of Kuznets [35], the current is captured in the framework of the EKC hypothesis. While the EKC hypothesis has been tested using several cases, the empirical framework has also been captured in the perspectives of other socio-economic, financial, and environmental-related factors. In the current context, while measuring the impact of the main energy sources in Finland on the country's environmental quality, the moderating role of environmental technology in energy development further provides a more reflective observation. Thus, two separate models as presented below have been inferred in this study.

$$\mathrm{CE} = f(\mathrm{Y}, \mathrm{Y2}, \mathrm{CIno}, \mathrm{GIno}, \mathrm{NIno}, \mathrm{OIno}) \tag{1}$$

$$\mathrm{CE} = f(\mathrm{Y}, \mathrm{Y2}, \mathrm{C}, \mathrm{G}, \mathrm{N}, \mathrm{O}, \mathrm{Ino}) \tag{2}$$

where CIno, GIno, NIno, and OIno are proxies for the innovations or environmental technologies deployed in coal energy, natural gas, nuclear energy, and oil respectively. These variables (CIno, GIno, NIno, and OIno) are derived from the interactions of innovation with each of the energy forms.

The functional forms (in logarithmic) of the models are presented below for ease of interpretation of the results and as well to reduce the risk of potential outliers (causing heteroscedasticity) in the series.

$$\begin{aligned}\mathrm{LCE}_t &= \hat{a} \pm ¿_0 + \hat{a} \pm ¿_1\mathrm{LY}_t + \hat{a} \pm ¿_2\mathrm{LY2}_t + \hat{a} \pm ¿_3\mathrm{LCIno}_t \\ &\quad + \hat{a} \pm ¿_4\mathrm{LGIno}_t + \hat{a} \pm ¿_5\mathrm{LNIno}_t + \hat{a} \pm ¿_6\mathrm{LOIno}_t + \mu_t\end{aligned} \tag{3}$$

$$\begin{aligned}\mathrm{LCE}_t &= \hat{a} \pm ¿_0 + \hat{a} \pm ¿_1\mathrm{LY}_t + \hat{a} \pm ¿_2\mathrm{LY2}_t + \hat{a} \pm ¿_3\mathrm{LC}_t \\ &\quad + \hat{a} \pm ¿_4\mathrm{LG}_t + \hat{a} \pm ¿_5\mathrm{LN}_t + \hat{a} \pm ¿_6\mathrm{LO}_t + \hat{a} \pm ¿_7\mathrm{LIno}_t + \mu_t\end{aligned} \tag{4}$$

where t and μ are respectively the time period from 1974 to 2019 and the residual error parameter. The corresponding impact of each of the examined factors on carbon emissions in the country in both equations (3) and (4) are measured by $\hat{a} \pm ¿_1$ to $\hat{a} \pm ¿_6$ while the constant $\hat{a} \pm ¿_0$ is the intercept of the estimation.

Methodological procedures

Firstly, the analysis begins with the exploration of the data's descriptive properties alongside the correlation test that was performed to unearth the feasible relationships among the explanatory and dependent variables. To proceed with the investigation, preliminary tests were performed to establish the reliability of the endeavor with minimized or no errors arising from any misspecifications. Moving on, while considering the appropriateness of the possible estimation techniques to examine the short- and long-run relationships in the equations (3) and (4), it is important to establish the stationarity of the variables as well as to ascertain the existence of cointegration evidence in the model. In this case, the stationarity test was conducted using the augmented

Table 2
Common statistics of the dataset.

Statistics	CE	C	G	N	O	Y	INO
Mean	56.20	0.21	2.54	0.18	10.86	1.88E + 11	9.36
Median	56.32	0.21	2.66	0.20	10.85	1.74E + 11	8.71
Maximum	76.14	0.34	4.70	0.23	13.30	2.73E + 11	16.37
Minimum	42.98	0.10	0.44	0.01	8.94	1.02E + 11	4.82
Std. Dev.	7.69	0.06	1.35	0.07	1.00	5.67E + 10	3.05
Skewness	0.35	0.22	−0.06	−1.72	0.33	0.03	0.58
Kurtosis	2.63	2.62	1.60	4.49	2.99	1.53	2.33
Jarque-Bera	1.22	0.65	3.79	26.90	0.82	4.17	3.41
(Probability)	(0.54)	(0.72)	(0.15)	(0.00)*	(0.66)	(0.12)	(0.18)
Observations	46	46	46	46	46	46	46

Note: 1% statistically significant level is denoted by *.

Table 3
The short- and long-run inference for Model 1: ARDL (1,1,0,0,1,0,0) and Model 2: ARDL (1,1,1,1,1,1,0,0).

Variables	Long-run	Short-run	Long-run	Short-run
LY	102.00	30.05**	−1.65	−0.40
LY2	−1.96	−0.58**	0.03	0.01
LCIno			0.59*	0.39*
LGIno			−0.10	−0.03
LNIno			−0.41*	−0.12*
LOIno			−0.20	−0.20**
LC			0.38*	0.37*
LG			0.09***	0.10*
N			0.01	0.07*
LO			0.50**	0.46*
LIno			−0.07**	0.01
ECT (-1)			−0.29*	−0.43*
Robustness				
F-Bounds test	3.82** (F-statistic > 2.5% critical value)	103.18** (F-statistic > 1.5% critical value)		
Diagnostic				
Normality test	Jarque-Bera = 0.82; *P*-value = 0.67	Jarque-Bera = 1.27; *P*-value = 0.53		
Serial correlation	No serial correlation	No serial correlation		
Heteroscedasticity	No heteroscedasticity	No heteroscedasticity		
Stability of model	Model is stable	Model is stable		

Note: The 1%, 5%, and 10% statistically significant level are respectively denoted by *, **, and ***.

Dickey and Fuller [11] unit root test while the cointegration test follows the approaches of Johansen [29] and Johansen and Juselius [30]. Based on the unit root evidence, the autoregressive distributed lag (ARDL) to bound testing by Pesaran et al. [46] was applied to estimate the needed coefficients. The ARDL approach has inherent advantages as noted by Pesaran et al. [46]. This has resulted in its vast application in many contemporary studies in the empirical literature such as in the studies by Göktuğ Kaya et al. [18] and Çoban et al. [10], among others. Firstly, the estimates from the ARDL approach are robust regardless of the differences in the order of integration of the variables. Pesaran et al. [46] noted that the technique is still efficient under the condition where the variables are characterized by both the I(1) and I(0) integration order. Secondly, the approach can produce both the short-run and long-run coefficients that helps to better understand the dynamic relationship among the understudied variables.

Results and discussion

The results discussion begins with the descriptive statistics of the series as displayed in Table 2. Given the Jarque-Bera statistics, only the nuclear energy (N) series is not normally distributed. Except for the natural gas (G) and nuclear energy series, all the series are positively skewed. Concerning the deviation of the series from the mean, coal energy has the least deviation which is closely followed by nuclear energy and oil energy. Additionally, regarding the correlation among the variables, especially between the explanatory and dependent variables (see Table A of the appendix), it suggests that the explanatory variables (except for innovation) are positively correlated with carbon emissions.

As captured in Table A (see the appendix), all energy forms and economic variables are positively related to carbon emissions. Innovation is negatively related to carbon emissions, thus preparing a pathway for the main investigation. The stationarity test used the augmented Dickey and Fuller [11] unit root test and affirms that the series has no unit root at most at the first difference (see Table B of the appendix), thus paving way for the cointegration test using the approaches of Johansen [29] and Johansen and Juselius [30]. As illustrated in Table C (see the appendix), there is statistically significant evidence of cointegration. Therefore, the results of the short-run and long-run estimates with their related diagnostic tests for the two scenario models are provided in Table 3.

Short-run and Long-run estimates

Given the results (see Table 3) from the baseline two scenario models, the discussion of the results is typically about the deployment and non-deployment of environmental technologies (innovation) in the Finnish energy development.

In the first scenario, where environmental technologies through innovations are deployed in the energy development in Finland, the first important thing to note is the validity of the EKC hypothesis. In this scenario, and similar to the study by Churchill et al. [8], the EKC is valid for Finland but only statistically significant in the short run. Specifically, economic growth in the country will spur environmental degradation by about a 30% increase with a 1% increase in output until the expansion in the economy is doubled, then resulting in a decline in environmental degradation by about 0.6% to a 1% increase in output. This is a desirable observation for the country in the short run considering that the EKC hypothesis has rarely been established for Finland in the literature. Notwithstanding, there is a tendency for achieving statistical significance in the long run, especially with the effective energy mix.

Interestingly, deploying environmental technologies in the coal energy development in the country seems to yield no desirable environmental benefit. With innovation, coal energy in the country spurs environmental degradation by about 0.4% and 0.6% in the short-run and long-run respectively when there is a 1% increase in coal energy utilization. In many countries as seen in the literature[28,44,3], Finland has for a long time been dependent on conventional energy, especially coal energy, for heating and power generation. This situation has been consistently linked with the country's challenge of attaining carbon neutrality promptly. Instead of deploying environmental technologies in coal production, an option that could be unlikely to yield significant environmental benefit as illustrated in the current result, the country has continued to push for the ban of coal energy sources by 2030[56]. Meanwhile, the deployment of environmental technologies for the development of oil, natural gas, and nuclear energy sources yields environmental benefits as reported in Table 3. Specifically, a 1% increase in the consumption of innovative oil and nuclear energy significantly mitigates environmental degradation by about 0.2% and 0.1% respectively, especially in the short run. The deployment of environmental technologies in natural gas development shows the potential of the environmental benefits. However, the evidence is not statistically significant in both the short- and long run.

In the second scenario, as presented in the results in the leftmost part of Table 3, the disaggregate impact of the energy sources on carbon emissions and the effect of innovation are inferred. Here, it is interesting to find that the EKC hypothesis does not hold. Although not statistically significant, there is a tendency for the country to experience a U-shaped relationship between economic growth and environmental degradation

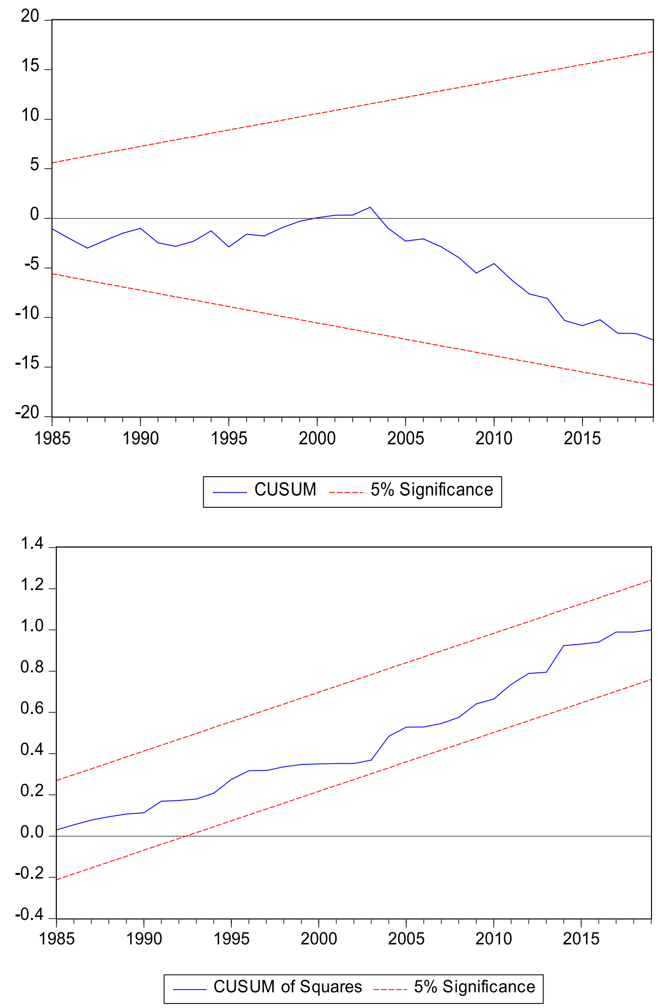

Fig. 2. Stability for ARDL (1,1,0,0,1,0,0).

especially when there is no conscious decision to deploy environmental technologies for energy production and utilization. Similar to what has been commonly observed regarding the case of Finland, the EKC hypothesis has mostly been invalidated[50,34,5]and sometimes conditionally observed[62]. However, the results indicate that innovation independently improves environmental quality since a 1% increase in environmental technology patents mitigates carbon emissions by about 0.07% in the long run.

By comparing these results with the previous scenario where innovation was deployed in energy utilizations, this second situation projects significant environmental costs arising from the lack of deployment of innovation in energy utilization. Specifically, the utilization of coal, natural gas, nuclear, and oil energy sources are found to be detrimental to the environment such that a 1% increase in each respectively worsens the environment by causing a 0.4%, 0.1%, 0.1%, and 0.5% increase in carbon emissions in the short run. Except for nuclear energy, which does not pose a significant impact, other energy forms exert a similar amount of positive impact on carbon emissions in the long run. This result largely justifies the findings from the existing literature that associate environmental degradation with conventional energy sources as seen in the studies of Sinha et al. [54], Ibrahim and Alola [24], Olanipekun and Alola [41], Ilham et al. [25], and Saint Akadiri et al. [51], among others.

Additionally, the aforementioned results (of the two scenarios) are supported diagnostically and with robust evidence. As indicated in the lower part of Table 3, the results are robust in cointegration as indicated by the bound test with respective statistically significant F-statistics (3.82 and 103.18). Besides the evidence of normality and stability for

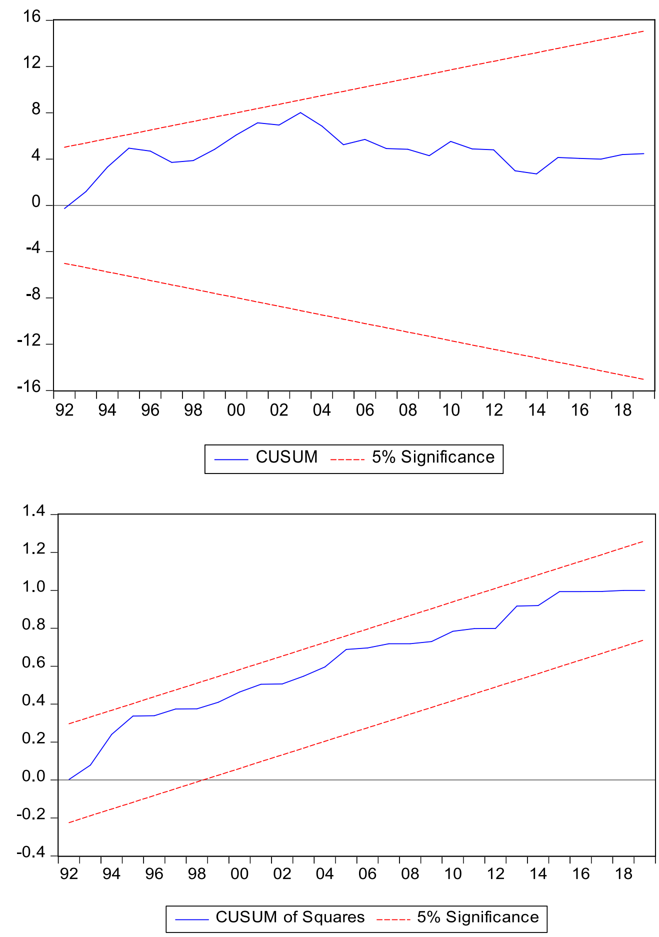

Fig. 3. Stability for ARDL (1,1,1,1,1,1,0,0).

the estimated coefficients over the experimental period, the diagnostic results from the scenarios illustrate that the models do not suffer from serial correlation and heteroscedasticity. The stability evidence is further supported by Figs. 2 and 3.

Conclusion and policy recommendations

Considering that Finland is among the world's low-carbon energy destination countries and the nexus of environmental degradation and economic growth or income vis-à-vis the EKC hypothesis that has not been widely covered in the literature, the current study explores this framework in a unique approach. A two-scenario approach was deployed to investigate the environmental effect of the main energy sources in Finland (i) with and (2) without the deployment of environmental technology over the period 1974 to 2019. The results of the investigation have been captured as follows: (a) the EKC hypothesis is only valid for a country where environmental technologies are deployed in the form of disaggregated energy utilization, (b) with the deployment of environmental technologies in coal energy development, there is no significant environmental benefit, (c) the deployment of environmental technologies for the development of oil, natural gas, and nuclear energy sources triggers an environmental benefit, and (d) without the deployment of environmental technologies, the utilization of the main energy forms (coal, natural gas, nuclear, and oil) will continue to constitute an environmental nuisance. Thus, these results are considered to be relevant to the energy development strategy of the country provided that the associated policies are not jettisoned.

Since the study reveals the importance of environmental technology in achieving the desired carbon neutrality target, there should be overwhelming energy and climate financing in the direction of research and development in eco-friendly investments. Boosting the financial support for eco-friendly investments is a crucial step because financial barriers can substantially inhibit the inherent benefits of innovations for environmental gains. For instance, among the EU manufacturing firms, it has been reported by Ghisetti et al. [17] that financial barriers create substantial setbacks regarding the usefulness of environmental technology since it exerts a negative impact on eco-friendly investments. Thus, the efficacy of technological innovations in tackling environmental problems can be better harnessed with adequate financial support of the tech and environmental-related industries through government and private sector partnerships. Moreover, the determination of the country to phase out coal energy and halve the domestic consumption of fossil oil by 2030 should be pragmatically followed by a necessary feasibility assessment of the country's energy-intensive sectors such as the manufacturing sector.

Limitations of the study and directions for future study

The extent of the applicability and generality of some of the important points and conclusions that have been drawn in the current study may be unique for the environmental context of the understudied Finnis economy. Hence, in line with the framework developed in this study and following the established approaches, future studies can be tailored to examine the country-specific context of other economies within or across the EU bloc to guide specific policy directives.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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