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On the road to environmental sustainability: the role of ICT penetration, renewable energy, and investment freedom on load capacity factor

Mucahit Aydin[1,2,3] · Nazli Demirtas[4] · Yasin Sogut[5] · Tunahan Degirmenci[2,4]

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Abstract
In an economy that supports clean sectors, investment freedom is pivotal in ensuring ecological sustainability, while information and communication technologies (ICT) facilitate the rapid spread of this positive impact. This study investigates the influence of renewable energy supply, investment freedom, and information and communication technologies penetration on the load capacity factor in Denmark from 1996 to 2021. The findings reveal that renewable energy supply and investment freedom positively contribute to ecological sustainability, while ICT exhibits a negative effect. The research underscores the significance of transferring technology and investment tools to the renewable energy sector to enhance ecological sustainability. Moreover, it highlights the potential of investment freedom in promoting green technologies and reducing environmental impacts. By minimizing losses in renewable energy through the development of ICT and ensuring economic freedom, progress towards a sustainable future can be accelerated.

Keywords ICT · Renewable energy · Economic freedom · Load capacity factor · Ecological sustainability

1 Introduction

Nowadays, tools and information communication technologies (ICTs) are crucial to a nation's economic growth. Governments now understand how ICT penetration can boost the economy and convert resources into information sharing (Vu, 2011). Thus, society's extensive use of ICT tools has increased economic activity (Farhadi et al., 2012). ICT penetration is now a crucial component in the shift to a knowledge-based economy and society in the digital era. ICT is acknowledged as a change agent for a culture and economy that are more competitive, sustainable, inclusive, and egalitarian (Gouvea et al., 2018). ICT penetration affects the political, cultural, social, technological, economic, and environmental domains in both good and harmful ways (Maiti et al., 2020). ICT reduces carbon footprint by supporting ecological sustainability (ES) through energy efficiency, resource management, and digitalization. While enabling the protection of ecosystems through environmental monitoring systems, it can also increase digital consumption habits, leading to rapid

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resource depletion. However, the high energy demand of data centers and the short lifespan of electronic devices magnify e-waste problems and accelerate the depletion of natural resources (International Telecommunication Union, 2023a). As these technologies have the potential to both protect and destroy the environment, the right policies and practices need to be adopted to balance their impact. When tackling the problems posed by global climate change in the modern digital age, it is crucial to comprehend how ICTs affect the environment (Usman & Ali, 2024). ICT penetration and the environment might interact directly, indirectly, or rebound. Rebound is the result of using ICTs directly or indirectly, particularly when energy-efficient transportation is used extensively. Energy use and electronic waste are among the direct effects; ICT applications are among the indirect effects (Charfeddine et al., 2023; Plepys, 2002).

A significant shift in the ICT design paradigm is required to combat the CO2 emissions that the ICT sector causes. One set of resources that can facilitate this change is renewable energy (REN). REN has emerged as a viable substitute for conventional fossil fuels in the wake of environmental concerns raised by the usage of fossil fuels. However, climate change has different regional impacts on REN, with some regions gaining and others facing losses (Osman et al., 2023). The resilience of REN systems under changing climate conditions depends on technological advances, regional planning, and adaptive policies. The focus should be optimizing renewable energy systems for changing climate conditions, increasing resilience, and ensuring sustainable integration with local environments. First, a renewable society and, later, a fully decarbonized society are the goals set forward by the Danish government. In this regard, the Climate Act 2020 was passed by the Danish government as a signatory to the climate agreement. Denmark hopes to attain a fully decarbonized society by 2050 and a 70% reduction in GHGs by 2030 with the help of this climate legislation. According to the legislation, a new national climate objective with a 10-year perspective must be determined every five years (The Danish Climate, 2020).

Several proposals and tactics on the most effective ways to carry out these political goals were made and deliberated as part of the political process. The effects of economic freedom (EF) on the ecology are multifaceted. Investment freedom (IF), a sub-index of EF, is employed in this study. The environment, ICT penetration, and REN variables are connected to the IF index. Governments find investing in ICT and REN transformation simpler when there are no obstacles to investment in the nation. In this regard, nations that value ICT adopt laws that encourage the integration of these technologies across sectors and foster investment.

Denmark's use of internet connections is as follows: 97% of the population aged 15–89 have access to the internet at home. In the 75–84 age group, this is 91%. 92% go online daily or almost every day (5–7 times a week). This rate is 69% among those aged 75–84. 86% use a mobile phone or smartphone to access the internet, 63% use a laptop, and 40% access the internet via a tablet (Danish Agency for Digital Government, 2024). In Fig. 1, Denmark has the most excellent internet penetration score (98.2 out of 100) out of 169 economies, according to the ICT Development Index 2023 (International Telecommunication Union, 2023b).

The EKC hypothesis (EKCH), proposed by Grossman and Krueger (1991), explains the inverted U-shaped link between economic expansion and ecological development. Only the ecological degradation brought on by human demand for natural resources is examined by Wackernagel and Rees' (1998) ecological footprint (ECOF). A comprehensive indicator that considers soil and water contamination is necessary to develop environmental pollution regulations that work and produce more precise data. Numerous studies have examined how environmental factors affect ECOF. The load capacity curve

Fig. 1 Number of Internet Users in Denmark as a Percentage of the Population. Source: International Telecommunication Union (2023b)

(LCC) hypothesis and the EKCH have gained favor as an environmental quality (EQ) variable in recent years. Siche et al. (2010) proposed the load capacity factor (LCF) as a proxy for EQ. In this instance, the link between LCF and national income is U-shaped. First, rising incomes cause the quality of the ecology to decline. Both the supply and demand sides of the ecology are covered by the LCF—biological capacity divided by ECOF yields LCF, a crucial and highly effective metric for evaluating ES. The state of the environment is unsustainable if this factor is less than one. A number higher than one indicates that biological capacity is higher than ECOF. Exceeding this capacity disrupts the balance of ecosystems, leading to severe problems such as environmental degradation, loss of biodiversity, and depletion of natural resources. The principle of sustainability aims to prevent such negative impacts and requires action within the limits of load capacity. In this context, staying within the load capacity regarding sustainability is essential. This is vital for safeguarding natural resources and ensuring the needs of future generations are met. An environmental indicator approach that is more complementing is using ECOF and LCF for carbon emissions (Pata & Isik, 2021). This study uses the EQ indicator LCF rather than ECOF.

Considering the previous literature, this study adds various insights to current knowledge. The study's time frame runs from 1996 to 2021. The study examines the impact of Denmark's internet penetration (IP), REN generation, and investment freedom (IF) on the LCF. The following points are expected to contribute to the literature: (i) Denmark's success in renewable energy patents and incentives, strategic government actions to encourage private sector participation in sustainability initiatives, and the balance between sustainable development and environmental responsibility is a model for other countries. In addition, ICT creates the infrastructure for a sustainable environment by enabling efficient use of resource consumption. To the authors' knowledge, this is the first study to examine the impact of IP, REN generation, and IF on LCF in Denmark. While the studies in the literature have considered REN consumption, this study examines the relationship between REN generation and LCF. Another rationale for exploring the relationship between these variables and EQ is that ICT facilitates the integration of REN sources by increasing energy efficiency; REN is a critical element in the transition to a low-carbon economy and supports ES; freedom to invest encourages more resources to be allocated to sustainable projects, enabling the private sector to offer innovative solutions. All these constitute the novelty of this study. Moreover, given the model used, the study is expected to fill an essential gap in the literature. The rest of the paper is structured as follows: (ii) Section two introduces the literature. (iii) Section three describes the data, econometric models, and methodological structure used in the study. (iv) Section four provides the econometric test results. (v) Sections 5 and 6 discuss the results, offer solutions to the problems identified, and provide a scientific pathway for future studies.

2 Literature review

In the literature, ICT, REN, and IF are considered among the indicators that have an impact on ecological quality. For this reason, we divided the literature review into three sections. In the first section, we examined the connection between information communication technology and EQ. In the second section, we discussed the literature on the relationship between REN and EQ. In the third section, to the best of the authors' knowledge, no direct study on investment freedom has been found in order to better understand its work; studies addressing the relationship between the EF indicator, including the investment freedom index, and environmental quality are included (Table 1).

When empirical research is examined, it has been observed that different results emerge between ICT and EQ. Khan et al. (2020a), Anser et al. (2021), Huang et al. (2022), and Saqib et al. (2024) concluded that ICT has positive effects on EQ. Alataş (2021), Kahouli et al. (2022), and Shobande et al. (2024) concluded that ICT was negative on EQ. Shobande and Asongu (2023), Appiah et al. (2023), and Jahanger and Usman (2023) obtained mixed results depending on the country groups they considered (Table 2).

In most empirical studies on the effect of REN on EQ, positive results about this relationship have been discovered. Thus, Khan et al. (2020b), Zafar et al. (2020), Ansari et al. (2021), Shan et al. (2021), Usman and Balsalobre-Lorente (2022), Ahmed et al. (2022), Kırıkkaleli et al. (2023), Apergis et al. (2023) and Adams and Fotio (2024) concluded that REN has positive effects on EQ. Contrary to these results, Radulescu et al. (2024) concluded that green energy has an insufficient effect on EQ in the long term. Pata et al. (2024) discovered in their study that there was a bidirectional causality between REN and EQ (Table 3).

While there are no studies on IF and EQ, there are limited studies on the relationship between EF and EQ. When the literature on freedom and EQ is examined, almost all researchers have studied certain groups of countries rather than a single country. For the country groups examined, both positive and negative results have been identified between economic independence and EQ. In conclusion, Agboola and Alola (2023), Babaki and Elyaspour (2021), Shahnazi and Shabani (2021), Sakariyahu et al. (2023), and Alola et al. (2023) concluded that the economic freedom index has negative effects on EQ. Karimi et al. (2022), Mamkhezri et al. (2022), and Nwani et al. (2023) discovered a negative effect between EF and EQ.

2.1 Evaluations

When the literature is examined comprehensively, the absence of any study on the relationship between ICTs, REN, and investment freedom with ecological quality shows the deficiencies in this field. Previous research on freedom and the environment has shown that consequences on EQ have been investigated using the general economic freedom index indicator. In addition, studies examining the effects of the variables used generally considered the effects on ECOF and CO2. In our study, the results regarding LCF, which better

Table 1 ICT and Environmental Quality

Author	Country	Period	Method	Result
Khan et al. (2020a)	91 Countries	1990–2017	PCSE	Lowers CO2
Anser et al. (2021)	26 European countries	2000–2017	Panel fixed effect regression model	Lowers CO2
Alataş (2021)	93 Countries	1995–2016	Dynamic Panel Data Analyses	Increases CO2
Huang et al. (2022)	E-7/G-7	1995- 2018	Dynamic Panel Data Analyses	Mixed results
Kahouli et al. (2022)	Saudi Arabia	1990- 2018	VECM	ICT negative effect on ECOF
Shobande and Asongu (2023)	Nigeria/South Africa	1980- 2017	VAR/VEC Granger causality	Mixed Results
Appiah et al. (2023)	110 Countries	2000- 2018	GMM	Mixed Results
Jahanger and Usman (2023)	44 Nations	1991–2019	Dynamic Panel Data Analyses	Mixed Results
Shobande et al. (2024)	OECD	2000–2020	GMM	Significantly increases CO2
Saqib et al. (2024)	9 Nations	1993–2020	CS-ARDL	Lowers CO2

Table 2 Renewable Energy and Environmental Quality

Author	Country	Period	Method	Result
Khan et al. (2020b)	Scandinavian Nations	2001–2018	DCCE	Lowers CO2
Zafar et al. (2020)	OECD	1995–2015	Second generation methodologies	Lowers CO2
Ansari et al. (2021)	Top clean energy-consuming Countries	1991–2016	Dynamic Panel Data Analyses	Lowers ECOF
Shan et al. (2021)	Turkiye	1990–2018	Bootstrap ARDL	Lowers CO2
Usman and Balsalobre-Lorente (2022)	Newly industrialized Countries	1990–2019	AMG	Lowers ECOF
Ahmed et al. (2022)	G-7	1985–2017	Second-generation econometric techniques	Lowers ECOF
Kırıkkaleli et al. (2023)	Portugal	1990–2019	NARDL	Lowers CO2
Apergis et al. (2023)	USA	1980–2015	Fourier estimation methods	Increasses LCF
Adams and Fotio (2024)	36 African Countries	1990–2018	D&K estimator	Positive effect
Pata et al. (2024)	USA	1961–2018	Fourier causality test with wavelet series	Significant relationship

Table 3 Freedom and Environmental Quality

Author	Country	Period	Method	Result
Agboola and Alola (2023)	Hong Kong	1995–2018	ARDL	Increases CO2
Babaki and Elyaspour (2021)	OPEC countries	1996–2014	ARDL	Increases CO2
Karimi et al. (2022)	Asia–Pacific countries	2000–2017	PFMOLS model	Lowers fishing footprint
Shahnazi and Shabani (2021)	EU countries	2000–2017	Spatial dynamic panel	U-shaped effect on CO2
Alola et al. (2023)	G-20	1990–2019	GMM	Increases EQ
Mamkhezri et al. (2022)	17 Asia–Pacific countries	2000–2017	Panel Data Analyses	Mixed Results
Nwani et al. (2023)	Selected African economies	1995–2017	Moments Quantile Regression	Lowers CO2
Sakariyahu et al. (2023)	31 African Countries	2000–2018	OLS/GLM	Increases ECOF and CO2
Alola et al. (2023)	G-7	2000–2016	AMG/CCEMG	Increases ECOF

represents EQ, were considered. ICT is an indicator that impacts environmental pollution depending on energy consumption. There is also a complex connection between REN and investments. Studies have mostly focused on using renewable energy and the resulting impact. The focus of our study is to reveal the effect of the relationship between ICT, REN, and investment freedom on ecological quality, along with the change in renewable energy supply resulting from investment freedom.

3 Data and model

This study's empirical tests are applied to Denmark's data from 1996 to 2021. The descriptions of data used in this study are presented in Table 4. The logarithmic values of all variables are used in the study. All data used in the study were obtained from international databases whose reliability has been proven by many studies in the literature.

We used three independent variables to determine the factors of environmental sustainability in Denmark. Model 1 was used to investigate these relationships.

$$lnLCF_t = \phi_0 + \phi_1 lnICT_t + \phi_2 lnREN_t + \phi_3 lnIF_t + u_t \tag{1}$$

where u_t is the error term. ϕ_0 indicates the constant term coefficient. $\phi_i,\ \ i = 1, 2, 3$ show the slope coefficients of the relevant variables. The theoretical expectations for Model 1, which are reported in the last column of Table 1, are that the coefficients of all variables are significant and positive.

4 Methodology and empirical findings

A three-stage strategy was determined for the empirical analysis. The first of these is the tests, also referred to as a priori tests. These are descriptive statistics, VIF values, and unit root tests. The variables' integration degrees were investigated using unit root tests at this stage. In the second stage, a cointegration test was applied for Model 1 to explore the main motivation of the study. In the last stage, the long-term coefficients of the detected cointegration were estimated with the help of different estimators. This three-stage strategy is presented in Fig. 2. This study's econometric methods are extended with Fourier functions to resist structural breaks. In this way, the results obtained are robust.

Table 4 Sources and Descriptions of the Variables

Dependent Variable	Unit	Source	Expected Sign
Load Capacity Factor	Biocapacity/Ecological Footprint (Global hectares per person)	Global Footprint Network (2024)	
Independent Variables			
Information and Communication Technology	Individuals using the Internet (% of population)	WDI (2024)	−/+
Renewable Energy	Total, % of primary energy supply	OECD (2024a)	+
Investment Freedom	Index	Heritage (2024)	+

Fig. 2 Empirical Strategy

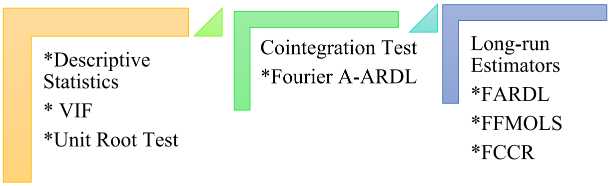

Table 5 Descriptive Statistics and VIF Values

Statistics	LCF	ICT	IF	REN
Mean	0.516262	74.72291	80.96154	20.16962
Median	0.507088	86.74500	87.50000	17.38000
Std. Dev	0.047678	29.37777	9.799922	10.44552
VIF	–	2.816252	3.586500	4.180309

Table 6 Unit Root Test Results

Variables	Fourier-ADF				ADF			
	Level	*p*/k	First Difference	*p*/k	Level	*p*	First Difference	*p*
lnLCF	−1.782	1/1	−2.679	2/4	0.237	2	−5.026*	1
lnICT	−4.120*	3/5	–	–	−14.667*	0	–	–
lnIF	−1.147	1/2	−3.420	0/3	−0.902	0	−3.532**	0
lnREN	−2.830	2/3	−7.001	0/2	−1.834	1	−6.824*	0

*$p<0.01$ and **$p<0.05$. p and k are lag and frequency numbers, respectively

Descriptive statistics and Variance Inflation Factor (VIF) values are preliminary estimates of the empirical analysis and are reported in Table 5. Accordingly, the average LCF is 0.51; ICT is 74.72; IF is 80.96; REN is 20.16. When the standard deviations are examined, the lowest standard deviation belongs to LCF, and the highest belongs to ICT. Finally, VIF values were calculated, and it was determined that there was no multicollinearity problem for Model 1.

The degree of integration of the variables was examined with the help of unit root tests. In this study, the FADF unit root test, which allows for smooth structural breaks and was introduced to the literature by Enders and Lee (2012), was used. In addition, the ADF test introduced to the literature by Dickey and Fuller (1981) was also used. The results are reported in Table 6. Accordingly, all variables except lnICT are stationary at the first differences but lnICT is stationary at the level. In other words, lnICT is I(0) while all other variables are I(1). Given all this information, the appropriate method to be used in the second stage was determined.

Pesaran et al. (2001) proposed a bound test based on the ARDL with a general F-test approach to investigate the long-run relationship. The most basic assumption of this approach is that the dependent variable must be I(1). For independent variables, it allows a mixed degree of integration provided that there is no I(2). The decision rule is based on lower and upper limit values. If the resulting test statistic is below this lower limit, there is no cointegration; if it is above the upper limit, there is cointegration. The weak

Table 7 Fourier-based A-ARDL Cointegration Test and Long-run Estimation Results

		Diagnostic Tests	
Tests	Values	Tests	Values
ARDL(1,0,1,1)		Serial correlation	4.242 (0.057)
F-stat	14.556*	Heteroscedasticity	0.655 (0.705)
t-dep	−7.218*	Normality	0.113 (0.944)
F-indep	13.423*		
Long-run Coefficients	*Values*	*Prob.*	
lnICT	−0.075**	0.036	
lnREN	0.218*	0.000	
lnIF	0.372*	0.006	

*$p<0.01$ and **$p<0.05$

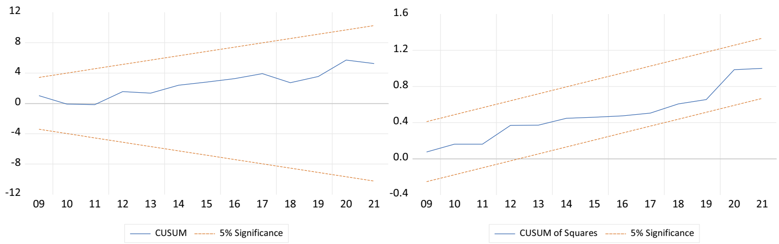

Fig. 3 Stability Diagnostics

point of the test is the test statistics that appear between these two values. This situation is considered unstable, and the test cannot be concluded. Sam et al. (2019) added new test statistics to the model to overcome these problems. With these three test statistics, the condition for the dependent variable to be I(1) is no longer present. Accordingly, the test statistics are as follows: overall ($F - stat.$), t-test ($t - dep.$), and ($F - indep.$) that considers lagged explanatory variables. The null hypotheses for the three test statistics are as follows: $F - stat.|H_0 : \beta_1 = \beta_2 = \beta_3 = \beta_4 = 0$, $t - dep.|H_0 : \beta_1 = 0$, and $F - indep.|H_0 : \beta_2 = \beta_3 = \beta_4 = 0$. This approach does not consider structural breaks, which are especially important for time series. Syed et al. (2023) overcame this problem with the help of Fourier terms. With the Fourier terms added to the A-ARDL method, the method also considers smooth structural breaks.

$$\begin{aligned} \Delta y_t = \alpha_0 + \sum_{i=1}^{p-1} \alpha_i \Delta y_{t-i} + \sum_{i=1}^{p-1} \gamma_i \Delta x_{t-i} + \sum_{i=1}^{p-1} \delta_i \Delta z_{t-i} + \sum_{i=1}^{p-1} \varphi_i \Delta v_{t-i} + \\ \beta_1 y_{t-1} + \beta_2 x_{t-1} + \beta_3 z_{t-1} + \beta_4 v_{t-1} + \beta_6 \sin\left(\frac{2\pi kt}{T}\right) + \beta_7 \cos\left(\frac{2\pi kt}{T}\right) + e_t \end{aligned} \quad (2)$$

where k indicates the Fourier terms' frequency. The existence of cointegration is only possible if all three test statistics are simultaneously significant. Table 7 shows the results, and they show that there is cointegration. Moreover, there are no diagnostic problems, namely serial correlation, heteroscedasticity, and normality. Figure 3 shows the cusum and cusumsq graphs, and they show that there is no problem in the ARDL model.

The long-run coefficients are also reported in Table 7, and lnREN and lnIF increase lnLCF, while lnICT decreases. We used two additional estimators for the robust results: FMOLS and CCR with Fourier functions in Table 8. The results are robust with the A-ARDL estimator.

5 Conclusion and policy recommendations

In today's increasingly globalized world, the use of ICT and investment freedom have become essential factors that significantly affect global economic and environmental dynamics. Transferring technology and investment tools to the REN sector is seen as a critical step in terms of ecological sustainability (Aydin et al., 2023). Environmental sustainability is a multifaceted concept that encompasses economic, social, and ecological dimensions. The role of ICT penetration, renewable energy, and investment freedom in fostering sustainability is increasingly recognized in both academic and policy discussions. While renewable energy sources mitigate environmental degradation, the effectiveness of their deployment is contingent on technological infrastructure and investment mechanisms that facilitate their large-scale integration. Investment freedom, in particular, is critical by enabling capital allocation towards sustainable projects, fostering innovation in green technologies, and accelerating the transition to low-carbon economies. Despite these benefits, ICT penetration can cause some negative externalities. While it increases efficiency and supports green energy management, it can also endanger ecological sustainability by increasing electronic waste and energy consumption. To achieve sustainability, integrating ICT with renewable energy systems to minimize energy loss in distribution and storage processes is challenging. Denmark exemplifies how a well-structured policy framework can align technological development with environmental goals. The Danish government's commitment to renewable energy and its investment-friendly regulatory environment have led to a higher share of renewables in the national energy mix, reducing dependence on fossil fuels. However, sustaining these advances requires further research into the long-term impact of ICT-driven energy efficiency on environmental quality.

ICT refers to using and developing communication and information technologies (Yan et al., 2018). The positive effects of these technologies on ecological sustainability can emerge through the opportunities provided by energy efficiency, energy saving, and digitalization (Lange et al., 2020). The opportunities provided by ICT penetration can reduce the use of physical resources and the carbon footprint. Investment freedom is a concept based on free market principles that encourage economic development and innovation. In this context, investments made under free market conditions may have positive effects on environmental sustainability (Alola et al., 2023). For example, investments in green technologies can reduce environmental impacts and promote sustainable economic

Table 8 Robustness

Variables	Fourier-based FMOLS		Fourier-based CCR	
	Coefficient	Prob.	Coefficient	Prob.
lnICT	−0.100*	0.007	−0.099*	0.000
lnREN	0.203*	0.000	0.211*	0.000
lnIF	0.297**	0.014	0.335*	0.004

*$p < 0.01$ and **$p < 0.05$

growth. Therefore, investment freedom can be expected to increase ecological quality in an economy where there are incentives for green technologies and instruments are used to deter activities that cause polluting emissions. It is thought that in an economy where ICT penetration is developed and investment freedom is ensured, the transition to REN sources will be much more efficient and effective. As a clean energy source for environmental sustainability and a way to cut polluting emissions, this transformation can be very helpful in the fight against climate change (Apergis et al., 2023). Today, there is a big gap between the supply and consumption of REN. The most important reason for this is not having technologies that will ensure energy efficiency. Renewable energy suffers losses at many stages up to the consumption stage (distribution, storage, etc.) (Aydin & Degirmenci, 2023). Minimizing these losses is possible by developing ICT and ensuring economic freedom in an economy where there are incentives for clean technologies (Nwani et al., 2023). Using ICT penetration to optimize renewable energy sources or directing investment freedom towards green technologies can improve environmental quality and accelerate progress towards a sustainable future. Therefore, ICT, investment freedom, and renewable energy can come together to impact ecological sustainability positively. In light of this, this research examines the impact of REN supply, investment freedom, and ICTs penetration on the LCF for the 1996–2021 period in Denmark. According to the study results, while REN supply and IF positively affect ecological sustainability, ICT penetration affects it negatively. Theoretically, this study aligns with the EKC and LCF frameworks, which show the dynamic interplay between economic development and environmental sustainability. The findings reinforce the argument that investment freedom fosters a market-driven approach to sustainability by enabling capital flow towards renewable energy projects. The positive relationship between investment freedom and renewable energy aligns with neoclassical growth theory, which emphasizes the role of market liberalization in fostering technological advancement. Additionally, the study contributes to institutional economics by demonstrating how regulatory environments shape the effectiveness of sustainability policies. When investment freedom is supported by strong institutional frameworks, it enhances green innovation and accelerates the clean energy transition. On a policy level, the results suggest that countries aiming to enhance environmental sustainability should prioritize policies that facilitate both investment freedom and renewable energy integration. Governments can implement incentives such as tax credits, subsidies, and green bonds to attract private sector investment in renewable energy infrastructure. Furthermore, policy frameworks should focus on minimizing bureaucratic barriers to clean energy investments, ensuring stable regulatory environments that encourage long-term commitments to sustainability. Denmark's success highlights the importance of aligning investment policies with environmental objectives through feed-in tariffs and premium guarantees for renewable energy projects. Policymakers should also consider integrating digital tools to optimize renewable energy deployment and minimize inefficiencies in energy markets.

Compared to other economies, Denmark has a very high supply of REN and use of low-carbon energy. Low-carbon energy consumption for Denmark and some regions is presented in Fig. 4. In 2021, approximately 17% of Europe's total energy supply came from renewable sources, while OECD economies sourced around 11% and G7 economies approximately 10%, with Denmark meeting about 40% of its total energy supply from renewable sources. This high percentage underscores Denmark's strategic approach to energy sustainability and positions the country as a leader in green energy adoption. Additionally, Denmark prioritizes the development of clean technologies. In 2020, while the share of patents related to environmental technologies was 10% globally, 13% in Europe, and 11% in OECD economies, it stood at 22% in Denmark (OECD 2024). This suggests

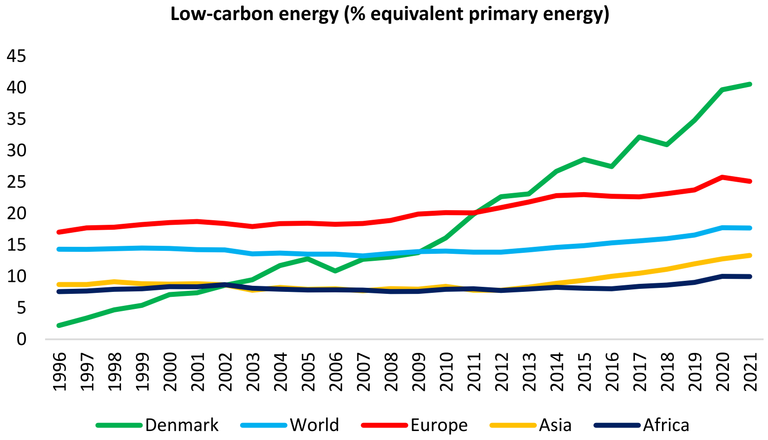

Fig. 4 Low-carbon energy consumption. Source: Our World in Data (2024)

that Denmark's innovation ecosystem is heavily geared toward addressing environmental challenges, further contributing to its REN success.

Additionally, the Danish government significantly encourages renewable energy investments. Electrical energy obtained from renewable sources is encouraged through premium tariffs and net metering. It supports the installation of pilot power plants through the state fund to produce wind and solar energy. Moreover, tax exemption is applied to producing, supplying, and consuming renewable energy for heating purposes. It is seen that Denmark seriously supports investment in this field with many other incentive practices regarding renewable energy power plants. These policy mechanisms have not only accelerated the renewable energy transition but also provided a robust framework for long-term energy security and ecological sustainability. Our empirical findings confirm the effectiveness of these measures, showing that investment freedom and green energy policies have been instrumental in Denmark's environmental success. Policymakers in other economies could adopt similar measures, such as tax incentives, research funding, and premium tariffs, to replicate Denmark's achievements. While Denmark's success offers a valuable model for other countries, the scalability of these findings may face challenges in economies with lower ICT penetration or limited renewable energy infrastructure. For example, countries with lower levels of internet access may struggle to integrate ICT solutions into their energy systems efficiently. Likewise, the absence of established renewable energy policies, technological expertise, or financial resources could hinder the replication of Denmark's outcomes. Such countries' policymakers may need to prioritize investments in basic digital infrastructure and renewable energy technologies before fully leveraging the benefits of ICT and investment freedom.

The negative impact of ICT on ecological quality can be attributed to several factors. With the widespread use of ICT, electricity consumption is increasing. Denmark currently meets approximately 60% of its energy needs from conventional sources (World Bank, 2023). Therefore, ICT may negatively impact ecological sustainability as it increases fossil fuel use. Also, ICT equipment has a short lifespan. Waste management after the use of this equipment may be difficult, and this may have negative ecological effects. Data centres, in particular, generate large amounts of heat and require cooling systems to manage this heat. Cooling systems also consume energy and increase environmental impact. Low use of energy efficient products and lack of implementation of ICT friendly policies harm the environment. (Sun, et al., 2023). Finally, the extraction and processing of materials used in the production of ICT equipment can lead to the depletion of natural resources and, thus, increased pressure on the environment.

While these challenges are significant, Denmark's environmental policies provide a pathway for mitigating these impacts. By prioritizing renewable energy and promoting ICT-friendly measures, Denmark offers a model for addressing the ecological challenges of ICT penetration. For instance, increasing the share of REN in the national energy mix can directly reduce the ecological footprint of ICT activities, such as data centers and electronic manufacturing. Furthermore, encouraging the adoption of energy-efficient ICT devices and implementing stricter regulations for e-waste management can alleviate resource depletion and waste-related environmental pressure.

Denmark's successful environmental policies, particularly regarding investment freedom and green energy, serve as a model for promoting sustainability. To further enhance ecological quality, policymakers should prioritize measures such as incentivizing the development and adoption of energy-efficient ICTs, promoting circular economy practices to manage electronic waste effectively, and investing R&D for sustainable materials used in ICT production. Additionally, the focus should be on increasing the transition to REN and implementing policies that encourage the use of clean technologies. It must keep ICT under control unless it meets most of its energy needs from clean energy. By integrating these steps into environmental strategies, policymakers can accelerate progress toward achieving SDGs and mitigating the negative impacts of ICT on ecological sustainability.

5.1 Limitations

Limitations of this study include the focus on Denmark only, potentially limiting generalizability to other contexts. Moreover, the analysis covers the period up to 2021. First of all, it is assumed in the study that investment freedom and ICT will affect the supply side of the energy sector rather than the demand side. REN generation does not mean that the clean energy transition in an economy has been achieved to a large extent. Renewable energy supply may not fully reflect the development of this sector. Therefore, the increase in renewable energy supply cannot be attributed entirely to technological developments. Although energy production increases, without innovative technologies, there may be significant amounts of energy losses in the distribution and storage stages. Therefore, these results for Denmark may not generalize to the green energy transition. On the other hand, although investment freedom positively affects ecological quality, this indicator does not only include investments in clean sectors. Denmark is an economy that largely supports clean sectors. In other economies, investment freedom may reduce ecological quality. Future research could explore the adaptability and limitations of Denmark's sustainability model in countries with varying levels of ICT penetration, renewable energy capabilities, and technological advancement. By investigating diverse settings, particularly less developed or resource-constrained economies, clearer conclusions can be drawn regarding the influence of these factors on ES.

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Declarations

Conflict of 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.

References

Adams, S., & Kaffo Fotio, H. (2024). Economic integration and environmental quality: Accounting for the roles of financial development, industrialization, urbanization and renewable energy. *Journal of Environmental Planning and Management, 67*(3), 688–713. https://doi.org/10.1080/09640568.2022.2131510

Agboola, M. O., & Alola, A. A. (2023). The energy mix-environmental aspects of income and economic freedom in Hong Kong: Cointegration and frequency domain causality evidence. *Journal of Environmental Economics and Policy, 12*(1), 63–78. https://doi.org/10.1080/21606544.2022.2085183

Ahmed, Z., Ahmad, M., Rjoub, H., Kalugina, O. A., & Hussain, N. (2022). Economic growth, renewable energy consumption, and ecological footprint: Exploring the role of environmental regulations and democracy in sustainable development. *Sustainable Development, 30*(4), 595–605. https://doi.org/10.1002/sd.2251

Alataş, S. (2021). The role of information and communication technologies for environmental sustainability: Evidence from a large panel data analysis. *Journal of Environmental Management, 293*, 112889. https://doi.org/10.1016/j.jenvman.2021.112889

Alola, A. A., Doganalp, N., & Obekpa, H. O. (2023). The influence of renewable energy and economic freedom aspects on ecological sustainability in the G7 countries. *Sustainable Development, 31*(2), 716–727. https://doi.org/10.1002/sd.2390

Ansari, M. A., Haider, S., & Masood, T. (2021). Do renewable energy and globalization enhance ecological footprint: An analysis of top renewable energy countries? *Environmental Science and Pollution Research, 28*, 6719–6732.

Anser, M. K., Ahmad, M., Khan, M. A., Zaman, K., Nassani, A. A., Askar, S. E., & Kabbani, A. (2021). The role of information and communication technologies in mitigating carbon emissions: Evidence from panel quantile regression. *Environmental Science and Pollution Research, 28*, 21065–21084. https://doi.org/10.1007/s11356-020-10901-0

Apergis, N., Degirmenci, T., & Aydin, M. (2023). Renewable and non-renewable energy consumption, energy technology investment, green technological innovation, and environmental sustainability in the United States: Testing the EKC and LCC hypotheses with novel Fourier estimation. *Environmental Science and Pollution Research, 30*(60), 125570–125584. https://doi.org/10.1007/s11356-023-30901-1

Appiah-Otoo, I., Acheampong, A. O., Song, N., & Chen, X. (2023). The impact of information and communication technology (ICT) on carbon dioxide emissions: Evidence from heterogeneous ICT countries. *Energy & Environment, 34*(8), 3080–3102. https://doi.org/10.1177/0958305X221118877

Aydin, M., & Degirmenci, T. (2023). The impact of clean energy consumption, green innovation, and technological diffusion on environmental sustainability: New evidence from load capacity curve hypothesis for 10 European Union countries. *Sustainable Development*. https://doi.org/10.1002/sd.2794

Aydin, M., Degirmenci, T., Gurdal, T., & Yavuz, H. (2023). The role of green innovation in achieving environmental sustainability in European Union countries: Testing the environmental Kuznets curve hypothesis. *Gondwana Research, 118*, 105–116. https://doi.org/10.1016/j.gr.2023.01.013

Babaki, R., & Elyaspour, B. (2021). The effect of economic freedom on environmental quality in OPEC countries (by using Panel-ARDL approach). *Journal of Economics and Regional Development, 27*(20), 74–100. https://doi.org/10.22067/erd.2021.18828.0

Charfeddine, L., & Umlai, M. (2023). ICT sector, digitization and environmental sustainability: A systematic review of the literature from 2000 to 2022. *Renewable and Sustainable Energy Reviews, 184*, 113482. https://doi.org/10.1016/j.rser.2023.113482

Danish Agency for Digital Government (2024). ICT use in Denmark - 2020. https://en.digst.dk/numbers-and-statistics/

Dickey, D. A., & Fuller, W. A. (1981). Likelihood ratio statistics for autoregressive time series with a unit root. *Econometrica: Journal of the Econometric Society*. https://doi.org/10.2307/1912517

Enders, W., & Lee, J. (2012). The flexible Fourier form and Dickey–Fuller type unit root tests. Economics Letters*, 117*(1), 196–199.

Farhadi, M., Ismail, R., & Fooladi, M. (2012). Information and communication technology use and economic growth. *PLoS ONE, 7*(11), e48903. https://doi.org/10.1371/journal.pone.0048903

Global Footprint Network. (2024). Ecological Footprint, https://data.footprintnetwork.org/#/exploreData, Accessed on 13.02.2024.

Gouvea, R., Kapelianis, D., & Kassicieh, S. (2018). Assessing the nexus of sustainability and information & communications technology. *Technological Forecasting and Social Change, 130*, 39–44. https://doi.org/10.1016/j.techfore.2017.07.023

Grossman, G. M., Krueger, A. B. (1991). Environmental Impacts of a North American Free Trade Agreement. Bureau of Economic Research Working Paper 3914. NBER, Cambridge. https://doi.org/10.3386/w3914

Huang, Y., Haseeb, M., Usman, M., & Ozturk, I. (2022). Dynamic association between ICT, renewable energy, economic complexity and ecological footprint: is there any difference between E-7 (developing) and G-7 (developed) countries?. *Technology in Society, 68*, 101853.

Heritage (2024). Ivestment Freedom Index, https://www.heritage.org/index/pages/all-country-scores, Accessed on 13.02.2024.

International Telecommunication Union. (2023a). Report on the implementation of the strategic plan and the activities of the Union from July 2022 to April 2023. https://www.itu.int/en/council/planning/Documents/Report-activities-2023-2024.pdf

International Telecommunication Union. (2023b). The ICT Development Index. https://www.itu.int/en/ITU-D/Statistics/Pages/IDI/default.aspx, Accesed on 2024–10–18.

Jahanger, A., & Usman, M. (2023). Investigating the role of information and communication technologies, economic growth, and foreign direct investment in the mitigation of ecological damages for achieving sustainable development goals. *Evaluation Review, 47*(4), 653–679. https://doi.org/10.1177/0193841X231156201

Kahouli, B., Hamdi, B., Nafla, A., & Chabaane, N. (2022). Investigating the relationship between ICT, green energy, total factor productivity, and ecological footprint: Empirical evidence from Saudi Arabia. *Energy Strategy Reviews, 42*, 100871. https://doi.org/10.1016/j.esr.2022.100871

Karimi, M. S., Khezri, M., Khan, Y. A., & Razzaghi, S. (2022). Exploring the influence of economic freedom index on fishing grounds footprint in environmental Kuznets curve framework through spatial econometrics technique: Evidence from Asia-Pacific countries. *Environmental Science and Pollution Research, 29*(4), 6251–6266. https://doi.org/10.1007/s11356-021-16110-8

Khan, F. N., Sana, A., & Arif, U. (2020a). Information and communication technology (ICT) and environmental sustainability: A panel data analysis. *Environmental Science and Pollution Research, 27*, 36718–36731. https://doi.org/10.1007/s11356-020-09634-7

Khan, S. A. R., Yu, Z., Belhadi, A., & Mardani, A. (2020b). Investigating the effects of renewable energy on international trade and environmental quality. *Journal of Environmental Management, 272*, 111089. https://doi.org/10.1016/j.jenvman.2020.111089

Kirikkaleli, D., Awosusi, A. A., Adebayo, T. S., & Otrakçı, C. (2023). Enhancing environmental quality in Portugal: Can CO2 intensity of GDP and renewable energy consumption be the solution? *Environmental Science and Pollution Research, 30*(18), 53796–53806. https://doi.org/10.1007/s11356-022-23586-5

Lange, S., Pohl, J., & Santarius, T. (2020). Digitalization and energy consumption. Does ICT reduce energy demand? *Ecological Economics, 176*, 106760. https://doi.org/10.1016/j.ecolecon.2020.106760

Maiti, D., & Awasthi, A. (2020). ICT exposure and the level of wellbeing and progress: A cross country analysis. *Social Indicators Research, 147*(1), 311–343. https://doi.org/10.1007/s11205-019-02162-9

Mamkhezri, J., Muhamad, G. M., & Khezri, M. (2022). Assessing the spatial effects of economic freedom on forest-products, grazing-land, and cropland footprints: The case of Asia-Pacific countries. *Journal of Environmental Management, 316*, 115274.

Nwani, C., Bekun, F. V., Agboola, P. O., Omoke, P. C., & Effiong, E. L. (2023). Industrial output, services and carbon emissions: The role of information and communication technologies and economic freedom in Africa. *Environment, Development and Sustainability, 25*(4), 3299–3322. https://doi.org/10.1007/s10668-022-02177-y

OECD. (2024). Renewable Energy, Total, % of primary energy supply, https://www.oecd.org/en/data/indicators/renewable-energy.html, Accessed on 13.02.2024.

Osman, A. I., Chen, L., Yang, M., Msigwa, G., Farghali, M., Fawzy, S., & Yap, P. S. (2023). Cost, environmental impact, and resilience of renewable energy under a changing climate: A review. *Environmental Chemistry Letters, 21*(2), 741–764. https://doi.org/10.1007/s10311-022-01480-3

Our World in Data. (2024). Share of primary energy consumption that comes from low-carbon sources. https://ourworldindata.org/grapher/low-carbon-share-energy?tab=table. Accessed on 13.02.2024.

Pata, U. K., & Isik, C. (2021). Determinants of the load capacity factor in China: A novel dynamic ARDL approach for ecological footprint accounting. *Resources Policy, 74*, 102313. https://doi.org/10.1016/j.resourpol.2021.102313

Pata, U. K., Wang, Q., Kartal, M. T., & Sharif, A. (2024). The role of disaggregated renewable energy consumption on income and load capacity factor: A novel inclusive sustainable growth approach. *Geoscience Frontiers, 15*(1), 101693. https://doi.org/10.1016/j.gsf.2023.101693

Pesaran, M. H., Shin, Y., & Smith, R. J. (2001). Bounds testing approaches to the analysis of level relationships. *Journal of Applied Econometrics, 16*(3), 289–326. https://doi.org/10.1002/jae.616

Plepys, A. (2002). The grey side of ICT. *Environmental Impact Assessment Review, 22*(5), 509–523. https://doi.org/10.1016/S0195-9255(02)00026-8

Radulescu, M., Mohammed, K. S., Kumar, P., Baldan, C., & Dascalu, N. M. (2024). Dynamic effects of energy transition on environmental sustainability: Fresh findings from the BRICS+ 1. *Energy Reports, 12*, 2441–2451. https://doi.org/10.1016/j.egyr.2023.11.123

Sakariyahu, R., Lawal, R., Etudaiye-Muhtar, O. F., & Ajide, F. M. (2023). Reflections on COP27: How do technological innovations and economic freedom affect environmental quality in Africa? *Technological Forecasting and Social Change, 195*, 122782. https://doi.org/10.1016/j.techfore.2023.122782

Sam, C. Y., McNown, R., & Goh, S. K. (2019). An augmented autoregressive distributed lag bounds test for cointegration. *Economic Modelling, 80*, 130–141. https://doi.org/10.1016/j.econmod.2018.11.001

Saqib, N., Abbas, S., Ozturk, I., Murshed, M., Tarczyńska-Łuniewska, M., Alam, M. M., & Tarczyński, W. (2024). Leveraging environmental ICT for carbon neutrality: Analyzing the impact of financial development, renewable energy and human capital in top polluting economies. *Gondwana Research, 126*, 305–320. https://doi.org/10.1016/j.gr.2023.09.012

Shan, S., Genç, S. Y., Kamran, H. W., & Dinca, G. (2021). Role of green technology innovation and renewable energy in carbon neutrality: A sustainable investigation from Turkey. *Journal of Environmental Management, 294*, 113004. https://doi.org/10.1016/j.jenvman.2021.113004

Shahnazi, R., & Shabani, Z. D. (2021). The effects of renewable energy, spatial spillover of CO2 emissions and economic freedom on CO2 emissions in the EU. *Renewable Energy, 169*, 293–307.

Shobande, O. A., & Asongu, S. A. (2023). Searching for sustainable footprints: Does ICT increase CO2 emissions? *Environmental Modeling & Assessment, 28*(1), 133–143. https://doi.org/10.1007/s10666-022-09859-w

Shobande, O. A., Ogbeifun, L., & Tiwari, A. K. (2024). Unlocking information technology infrastructure for promoting climate resilience and environmental quality. *Technological Forecasting and Social Change, 198*, 122949. https://doi.org/10.1016/j.techfore.2023.122949

Siche, R., Pereira, L., Agostinho, F., & Ortega, E. (2010). Convergence of ecological footprint and emergy analysis as a sustainability indicator of countries: Peru as case study. *Communications in Nonlinear Science and Numerical Simulation, 15*(10), 3182–3192. https://doi.org/10.1016/j.cnsns.2009.11.007

Sun, X., Xiao, S., Ren, X., & Xu, B. (2023). Time-varying impact of information and communication technology on carbon emissions. *Energy Economics, 118*, 106492. https://doi.org/10.1016/j.eneco.2023.106492

Syed, Q. R., Apergis, N., & Goh, S. K. (2023). The dynamic relationship between climate policy uncertainty and renewable energy in the US: Applying the novel Fourier augmented autoregressive distributed lags approach. *Energy, 275*, 127383. https://doi.org/10.1016/j.energy.2023.127383

The Danish Climate. (2020). https://www.ccacoalition.org/partners/denmark#:~:text=The%20Climate%20Act%20sets%20a,be%20set%20every%20five%20years

Usman, A., & Ali, A. Y. (2024). The impacts of ICT gadgets on climate change and mitigative solutions. *Journal of Computer, Software, and Program, 1*(2), 1–7. https://doi.org/10.69739/jcsp.v1i2.110

Usman, M., & Balsalobre-Lorente, D. (2022). Environmental concern in the era of industrialization: Can financial development, renewable energy and natural resources alleviate some load? *Energy Policy, 162*, 112780. https://doi.org/10.1016/j.enpol.2022.112780

Vu, K. M. (2011). ICT as a source of economic growth in the information age: Empirical evidence from the 1996–2005 period. *Telecommunications Policy, 35*(4), 357–372. https://doi.org/10.1016/j.telpol.2011.02.008

Wackernagel, M., & Rees, W. (1998). *Our ecological footprint: Reducing human impact on the earth* (Vol. 9). New society publishers.

WDI. (2024). World Development Indicators, Individuals using the Internet (% of population), https://data.worldbank.org/indicator/IT.NET.USER.ZS , Accessed on 13.02.2024.

World Bank. (2023). Renewable energy consumption. https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS. Accessed on 13.02.2024.

Yan, Z., Shi, R., & Yang, Z. (2018). ICT development and sustainable energy consumption: A perspective of energy productivity. *Sustainability, 10*(7), 2568. https://doi.org/10.3390/su10072568

Zafar, M. W., Shahbaz, M., Sinha, A., Sengupta, T., & Qin, Q. (2020). How renewable energy consumption contribute to environmental quality? The role of education in OECD countries. *Journal of Cleaner Production, 268*, 122149. https://doi.org/10.1016/j.jclepro.2020.122149

Authors and Affiliations

Mucahit Aydin[1,2,3] · Nazli Demirtas[4] · Yasin Sogut[5] · Tunahan Degirmenci[2,4]

✉ Tunahan Degirmenci
tunahandegirmenci@sakarya.edu.tr

Mucahit Aydin
aydinm@sakarya.edu.tr

Nazli Demirtas
nazli.demirtas@ogr.sakarya.edu.tr

Yasin Sogut
ysogut@kastamonu.edu.tr

1 Department of Econometrics, Faculty of Political Sciences, Sakarya University, Esentepe Campus, Serdivan/Sakarya, Türkiye

2 UNEC Research Methods Application Center, Azerbaijan State University of Economics (UNEC), Istiqlaliyyat Str. 6, Baku 1001, Azerbaijan

3 Department of Economics, College of Political Science and Economics, Korea University, 145 Anam-ro, Seoungbuk-gu, Seoul 02841, South Korea

4 Department of Public Finance, Faculty of Political Sciences, Sakarya University, Esentepe Campus, Serdivan/Sakarya, Türkiye

5 Department of Economics, Faculty of Economics and Administrative Sciences, Kastamonu University, Kastamonu, Türkiye