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Renewable Energy, Innovation and Adaptation to Climate Change: Evidence from Europe and Central Asia

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ABSTRACT

The aim of this research is to examine the effect of renewable energy consumption and innovation on adaptation to climate change in Europe and Central Asia over the period 2000-2021. In this study, we use several panel data methods such as fixed effects method, two step system GMM estimator and panel corrected standard errors estimator to account for endogeneity, simultaneity and cross-sectional dependence. Our results show that renewable energy has overall positive link with adaptation to climate change, proxied by ND Gain index. We also document that innovation measured by number of patents has positive effect on ND Gain index in Europe and Central Asia. We conduct robustness tests by including additional socio-economic variables. The results remain robust. The study offers policy implications and suggests avenue for future research.

Keywords: Renewable Energy, Innovation, Adaptation to Climate Change, Europe, Central Asia
JEL Classifications: Q20

1. INTRODUCTION

Climate change has emerged as a significant impediment to achieving the Sustainable Development Goals by exacerbating vulnerabilities in essential systems such as food and water security. An estimated half of the global population now experiences periods of acute water scarcity annually, driven by a confluence of climatic variability and structural socio-environmental factors. Economic disruptions attributable to climate change are increasingly evident across highly climate-dependent sectors, including agriculture, forestry, fisheries, energy, and tourism. At the individual level, climate-induced shocks—ranging from the destruction of critical infrastructure to the erosion of assets and livelihoods—have compromised human health and nutritional stability, while simultaneously deepening pre-existing gender disparities and social inequities (IPCC, 2023).

Over the past decade, academic research has extensively examined factors that are associated with the reduction of environmental degradation and the promotion of sustainable economic growth (Ulucak and Khan, 2020; Irmatova et al., 2025; Nigmatullaeva et al., 2025). Among these factors, renewable energy has emerged as one of the most consistently validated drivers of environmental improvement (Depren et al., 2022). A growing body of empirical studies—spanning different countries, time periods, and econometric techniques—has found robust evidence that greater reliance on renewable energy sources leads to significant reductions in CO_2 emissions and enhances environmental quality. Indeed, many developing countries acknowledging the importance of renewable energy in stimulating economic growth and reducing CO_2 emissions have adopted legislative policies to stimulate renewable energy sector development. For example, in Uzbekistan the Law On the Use of Renewable Energy Sources highlights directions of state policy on renewable energy focus on setting priorities and implementing programs to expand its use, enhancing energy security by diversifying the energy mix, and promoting the production of electricity, heat, and biogas from renewable sources. Policies also aim to stimulate innovation, improve energy efficiency, localize technology production, and involve businesses through legal and organizational reforms. Additionally, the state provides support and incentives to both renewable energy producers and technology manufacturers.

However, at the same time escalating threat of climate change to both societies and the natural environment has strengthened the call to transition from resource-intensive economic growth to development pathways driven by innovation and human capital. In light of the intensifying ecological and climatic challenges, scholarly research has increasingly highlighted the pivotal role of human capital and innovation in advancing public understanding of climate change mitigation and promoting pathways toward sustainable development (Khan, 2020; Payab et al., 2023). Related studies document that various measures of innovation such as R&D intensity (Chen and Lee, 2020), patent applications (Dauda et al., 2021) and R&D spending (Fernández et al., 2018) play important role in explaining environmental sustainability and adaptation to climate change. Furthermore, environmental sustainability can be affected by other socio-economic variables such as economic development, urbanization and international trade. Furthermore, dependence on natural resources can pose significant challenges to achieving sustainable development (Cong and Ren, 2023). Overreliance on extractive industries may also generate environmental degradation, including deforestation, biodiversity loss, and increased greenhouse gas emissions, thereby undermining long-term ecological sustainability.

In view of the above, it is evident that an increasing number of countries are prioritizing investments in education, science, and technology. In this context, countries in Europe and Central Asia (ECA) have made substantial progress. The region reports 3,467 researchers in R&D per one million people—significantly exceeding the global average of 1,515. Moreover, the number of resident patent applications rose from 90,542 in 1990 to over 215,000 by 2020. R&D expenditure in the ECA region stands at nearly 2% of GDP, compared to 0.7% in Arab countries, 0.63% in South Asia, and just 0.44% in Sub-Saharan Africa.

Despite the economic importance of innovation, the impact of innovation on environmental sustainability has not received considerable attention in the literature, with only recent studies examining its effect on CO_2 emissions. While numerous studies have examined the relationship between innovation and CO_2 emissions, many of them adopt a narrow environmental perspective that overlooks the multidimensional nature of sustainable development. CO_2 emissions viewed as major driver of climate change, however, focusing solely on emissions fails to capture broader issues such as climate change vulnerability, readiness, and adaptive capacity. As a result, there is a growing need to employ more comprehensive proxies that reflect the complex and interconnected aspects of environmental sustainability.

Given that innovation is a fundamental driver of economic growth and improvements in quality of life, this study examines it as a relatively underexplored determinant of CO_2 emissions. Innovation may play a pivotal role in shaping adaptive responses to climate change, making it a critical component in the pursuit of environmental sustainability. To the best of our knowledge, ours is the first study that explores the effects of innovation on environmental sustainability of Europe and Central Asia, using various panel data techniques. The contribution of this study is manyfold. First, we use patent applications as a proxy for innovative activities. Unlike R&D spending or the number of researchers per million people, which reflect input-oriented measures, patent applications represent the actual outcomes of innovative activity. Patents also provide a standardized, internationally comparable metric that can be tracked across time and countries, offering insights into the dynamics of technological advancement across countries. Therefore, patent applications serve as a robust and outcome-based indicator well-suited for empirical analysis of innovation's impact on sustainable development. Another important contribution of this study lies in its methodological approach, which employs both fixed effects and two-step system GMM estimators to ensure robust and reliable inference. While fixed effects control unobserved time-invariant heterogeneity across countries, the two-step system GMM addresses potential endogeneity, reverse causality, and dynamic relationships between innovation and sustainable development. A further key contribution of this study is the use of the ND-GAIN Country Index as a comprehensive measure of environmental sustainability and climate resilience. Unlike studies that rely solely on single-dimensional indicators such as CO_2 emissions or deforestation rates, the ND-GAIN Index captures the multifaceted nature of climate vulnerability and adaptive capacity. It integrates over 40 core indicators to assess both a country's exposure to climate disruptions and its institutional, economic, and social readiness to leverage public and private investment for adaptation.

The rest of the study is structured as follows. Section 2 reviews the recent empirical literature. Section 3 presents data and methodology, and Section 4 discusses main results. Finally, Section 5 concludes the paper.

2. REVIEW OF RELATED LITERATURE

Over the past two decades, ample studies have examined the relationship between renewable energy and climate change (Baloch et al., 2019; Wang et al., 2021). These studies explore the role of renewable energy in mitigating climate change focusing on single country (Abbasi et al., 2021; Qi et al., 2014; Dogan and Ozturk, 2017) or cross-country settings (Sadorsky, 2009; Islami et al., 2022; Chen et al., 2022; Ozturk, 2017). For example, Al Araby et al. (2019) explore the effects of renewable, non-renewable energy, economic growth on CO_2 emissions in a sample of 25 Mediterranean countries over the period 2002-2016. Using Hausman and panel unit root tests the study verifies that data is stationary. The findings from the GLS and cointegration methods show that renewable energy decreases CO_2 emissions, while economic growth contributes to environmental degradation. Mahmoodi (2017) explored the relationship between renewable energy, economic growth and CO_2 emissions in a sample of 11 developed countries over the period 2000-2014. Using VECM and panel cointegration techniques, the study finds that there is long run relationship between variables. The causality tests suggest that economic growth increases CO_2 emissions, while renewable energy consumption mitigates CO_2 emissions. Hasnisah et al. (2019) explored the relationship between renewable energy, economic growth and CO_2 emissions in a sample of 13 developing nations in Asia over the period 1980-2014. The authors using cointegration tools such as FMOLS and DOLS, find that GDP per capita has inverted U shaped relationship with CO_2 emissions. Moreover, renewable energy is shown to have no significant impact on environmental degradation. Haseeb et al. (2019) investigates the role that renewable energy sector may have in economic well-being of Malaysia over the period 1980-2016. The study using time series data methods such as ARDL test reports that renewable energy sector growth contributes positively to economic well-being of local population. Güney and İnce (2024) investigates the effects of solar energy and economic growth on CO_2 emissions. The study using data for 26 nations over the period 2000-2019 and adopting CCEMG estimator reports that there is bi-directional causality between renewable and CO_2 emissions. The authors suggest that promoting the adoption of solar energy and supporting investments in this sector has become increasingly important, especially for countries with favorable geographical conditions. This trend highlights that leveraging solar energy does not necessarily depend on globalization but rather on local natural advantages. To enhance environmental sustainability, it is crucial for governments to offer tax incentives and investment support to companies that integrate solar energy into their production processes. Such measures can lead to a significant reduction in carbon emissions and contribute to a cleaner, greener environment. Raihan and Tuspekova (2022) investigated the potential for achieving environmental sustainability in Kazakhstan by examining the effects of economic growth, renewable energy consumption, and technological innovation on CO□ emissions. Utilizing time series data from 1996 to 2018, the authors applied the Dynamic Ordinary Least Squares (DOLS) method. Their findings indicate that while economic growth and fossil fuel consumption exacerbate CO□ emissions, renewable energy use and technological innovation significantly mitigate emissions, thereby supporting environmental sustainability. The study offers policy recommendations aimed at promoting Kazakhstan's transition to a low-carbon economy, including the development of renewable energy, investment in technological advancements, and the implementation of sustainability-oriented policies.

Apart from renewable energy and economic growth, another strand of studies examined the effect of technological innovation on CO_2 emissions. For example, Hao et al. (2021) assessed the role of economic growth and technological innovation in reducing environmental pollution through the application of the STIRPAT model. The study concludes that in developing Asian countries, technological development, innovation, and sustained economic growth are key drivers of carbon emissions reduction and enhanced environmental protection capacity. Mughal et al. (2022) explored the causal relationships between technological innovation, environmental pollution, energy consumption, and sustainable economic growth in selected South Asian countries. Using annual time series data from 1990 to 2019 obtained from the World Development Indicators and employing the Fully Modified Ordinary Least Squares (FMOLS) technique, the study identifies a notable decline in environmental quality across the region, underlining the need for environmentally conscious policy interventions. Hysa et al. (2020) analyzed selected indicators of the circular economy to assess its impact on environmental and economic performance. Through a rigorous panel data analysis, the study finds a robust positive relationship between circular economy practices and economic growth. Investments in non-waste and circular initiatives were found to play a crucial role in fostering sustainability, innovation, and wealth generation.

Raihan et al. (2022) examined the influence of various factors - including economic growth, renewable energy consumption, urbanization, industrialization, technological innovation, and forest coverage—on environmental sustainability in Bangladesh. The study applied the Autoregressive Distributed Lag (ARDL) bounds testing approach for time series data from 1990 onwards, supplemented by DOLS estimation in 2019. The results demonstrate that while economic growth, urbanization, and industrialization contribute to increased CO□ emissions, renewable energy use, technological innovation, and greater forest area help reduce emissions and advance environmental sustainability objectives. Ahmad et al. (2023) utilized the Autoregressive Distributed Lag (ARDL) method with four decades of data to investigate the role of technological innovation in promoting sustainable development in China. The study also aimed to identify the mechanisms through which technological innovation contributes to sustainability. The findings demonstrate that technological innovation significantly fosters economic growth while simultaneously enhancing environmental sustainability. Moreover, financial development plays a vital role in supporting China's sustainable development by both reducing carbon dioxide (CO□) emissions and stimulating economic expansion.

Omri (2020) examined the impact of technological innovation on economic growth, environmental quality, and social development across 75 countries categorized by income levels (low, middle, and high). The study revealed that the effects of technological innovation vary depending on a country's stage of development. In high-income countries, innovation supports all three pillars of sustainable development - economic, social, and environmental. In contrast, middle-income countries benefit primarily in the economic and environmental domains, while no significant effect is observed in low-income countries. Recognizing economic growth as a core indicator of national development, Mohamed et al. (2022) explored the influence of technological innovation on economic performance in developing countries. Employing an Error Correction Model (ECM) and time series data spanning from 1990 to 2018, the study found that the variables became stationary after first differencing, confirming the model's suitability. The results indicate that technological innovation positively affects the sustainability of economic growth. The authors emphasize the importance of implementing policies that attract international investment in research and development to enhance innovation-led growth in developing economies.

Wang et al. (2023) investigated the contributions of economic growth, renewable energy adoption, and technological innovation toward achieving Malaysia's Paris Agreement targets through CO□ emissions reduction. Using time series data from 1990 to 2019 and applying the Dynamic Ordinary Least Squares (DOLS) method, the study found that while economic growth adversely affects environmental quality, both renewable energy use and technological innovation contribute to emissions reductions. The study underscores the necessity of implementing policies that support a low-carbon economy, encourage renewable energy, and foster innovation to meet Malaysia's climate commitments. Abid et al. (2022) analyzed panel data from 14 emerging European Union economies between 1995 and 2020 using second-generation panel econometric techniques, including the Augmented Mean Group (AMG) and Common Correlated Effects Mean Group (CCEMG) estimators. The results suggest that these countries can improve environmental performance by advancing clean technologies, even in the absence of targeted incentives. Based on the empirical findings, the authors recommend promoting financial development, encouraging green technological innovation, and attracting foreign direct investment in renewable energy sectors as key strategic priorities. Ghorbal et al. (2024) examined the relationship between patents, FDI, economic growth and CO_2 emissions in South Korea for the years 1980-2018. Using ARDL estimator and Granger causality tests the study finds that resident patents increase CO_2 emissions, while non-resident patents decrease CO_2 emissions. Moreover, economic growth leads to higher levels of environmental degradation. Cheng et al. (2021) explore the role of innovation in mitigation CO_2 emissions in OECD member states over the period 1996-2015. The study based on panel quantile regression results reports that patent applications decrease CO_2 emissions, however, this effect is not uniform across countries.

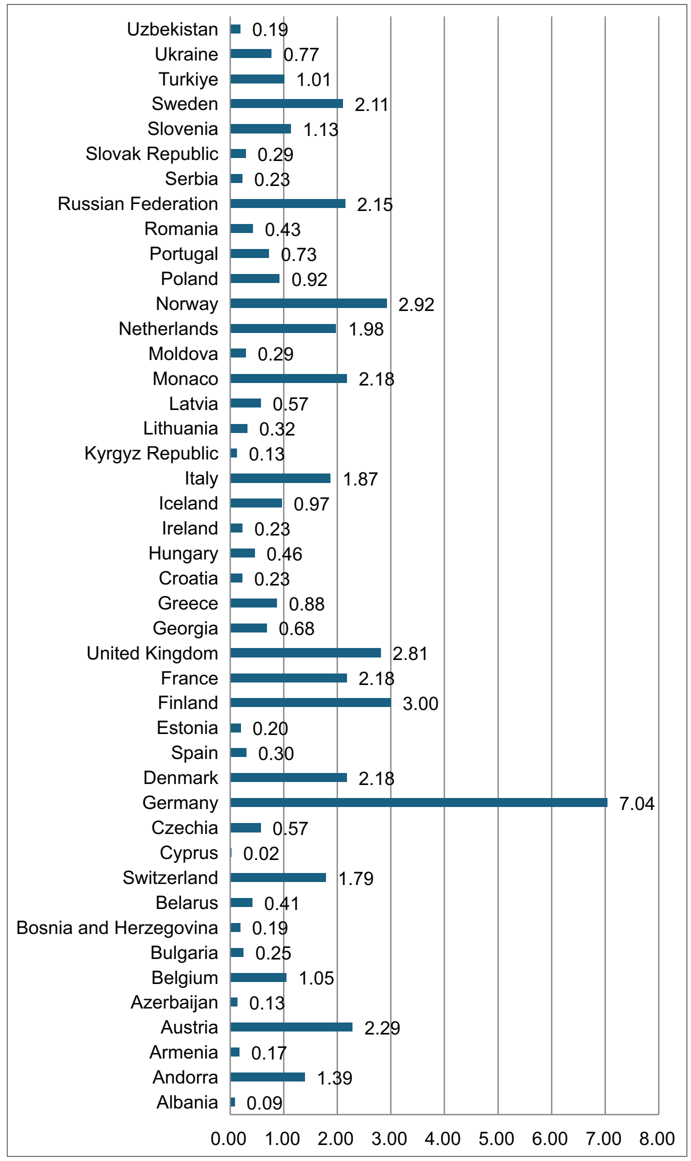
Overall, these studies conclude that renewable energy and innovation has positive effect on sustainable development by reducing CO_2 emissions. However, to the best of our knowledge ours is the first empirical study to examine the effects of these variables on sustainable development in the context of Europe and Central Asia.

3. DATA AND METHODOLOGY

Following Sarkodie and Strezov (2019) and Andrijevic et al. (2020), we use ND-Gain Country Index which is derived based on two key dimensions of adaptation: vulnerability and readiness. The ND-GAIN Country Index compiles over 40 key indicators to assess the vulnerability and preparedness of 182 UN member states. The final ND-GAIN score is estimated by subtracting the vulnerability score from the readiness score for each nation and rescaled to range from 0 to 100.

There are various indicators to measure innovation at a national level. For example, R&D spending, high tech exports, and the number of researchers and engineers. In this study we use two measures to assess the effect of innovation on adaptation to climate change. Our first variable is total resident and non-resident patent applications per 100,000 people. Our second variable is total resident and non-resident patent applications per 1,000,000 GDP. Figure 1 displays

Figure 1: Patents per 100,000 people for the year 2021



Source: World Bank, author estimates

patent applications related to population for the year 2021. As can be seen, the innovation rates significantly differ across countries.

To examine the relationship between innovation and readiness to climate change can be presented as follows:

$$Y = f(X, Z) \tag{1}$$

where Y is the dependent variable (ND-Gain Index), X is one of our independent variables, Z is the set of control variables. We include GDP per capita, trade openness, natural resource rents and urbanization as baseline controls. The equation above can be reformulated as follows:

$$ND - Gain_{i,t} = \alpha_0 + \alpha_1 Patents_{i,t} + \alpha_2 GDP_{i,t} + \alpha_3 TO_{i,t} + a_4 Rents_{i,t} + \alpha_5 Urban_{i,t} + \varepsilon_{i,t} \tag{2}$$

where α_0 is intercept, α_1-α_5 parameters to be estimated, t denotes time(year), i denotes ith country and ε is an error term. The data for control variables comes from the World Bank. Table 1 reports summary statistics for main variables used in this study. Following a number of recent studies in the area of sustainable development (Kuldasheva and Salahodjaev, 2023; Salahodjaev and Sadikov 2024), in order to estimate Eq. (2), we use several panel data methods. First, we use fixed effects (FE) and random effects (RE) models. The major advantage of adopting FE estimator compared to other basic approaches such as pooled mean regression is that it enables us to partially resolve the issue of omitted variable bias by accounting for time invariant variables that are not captured by our data and empirical model. In addition, based on nascent papers (Asongu et al., 2018; Khan et al., 2019), we use two-step GMM estimator due to following important reasons. As discussed above in our study N (number of nations) is greater than t (years). Moreover, we include lagged ND-Gain index to account for inertia. Inclusion of lagged dependent variables may lead to biased results when used with OLS regression. Most importantly, two-step GMM estimator resolves the problem of endogeneity is panel data global studies (Roodman, 2009).

4. RESULTS

Baseline results are reported in Table 2. Columns 1 and 2 present the results for patents per 100,000 people using FE and RE models. As can be seen, innovation is positively associated with ND-Gain index. In a similar vein, patents relative to GDP are also positive and significant at the 1% level. For example, 1% increase in patents per 100 000 people leads to 9.5 units increase in ND Gain. Turning to control variables, the empirical results reveal that both GDP per capita and trade openness are positively associated with the ND-Gain index, which reflects a country's resilience and readiness to climate change. Higher GDP per capita likely enhances a country's capacity to invest in adaptive infrastructure, technology, and public services, thereby improving climate resilience. Similarly, greater trade openness may facilitate the diffusion of environmentally friendly technologies and best practices, strengthen institutional capacity, and provide access to resources that support adaptive strategies.

We observe that renewable energy has mixed effects on ND Gain: there is positive effect of renewables in sustainable

Table 1: Summary statistics

Variable	Description	Mean	Std. dev.	Min	Max
ND Gain	ND Gain Index	58.66	8.31	42.41	76.99
GDP	GDP per capita, log	9.59	1.39	4.92	12.39
Trade	Trade as % of GDP	102.97	49.83	22.49	393.14
$Patents_1$	Patents per 100,000 people	3.29	16.11	0.00	220.02
$Patents_2$	Patents per 1,000,000 GDP	0.02	0.04	0.00	0.47
Rents	Total rents as % of GDP	2.90	7.45	0.00	75.37
Urban	Urban population, %	66.50	18.51	14.30	100.00
Renewable	Renewable energy consumption, %	18.78	16.87	0	82.79

development under RE setting, while using FE model we find that renewable energy is negatively and nearly insignificantly linked to ND Gain. One potential explanation is that if within-country increases in renewable energy come from sudden policy shifts without long-term adaptation, the short-run effect might appear negative or insignificant. Moreover, this may imply that if renewable energy increases are not associated with immediate adaptation improvements (or happen during crises), the effect can turn negative or insignificant. The Hausman text results chi2 is 16.88 implying that fixed effects model is favorable.

To address potential endogeneity, unobserved heterogeneity, and dynamic effects in the relationship between innovation, renewable energy consumption, and sustainable development, in Table 3 we further estimate a two-step system Generalized Method of Moments (GMM) model. This approach allows us to control for the endogeneity of explanatory variables such as patenting activity and renewable energy, which may be jointly determined with sustainable development outcomes. The system GMM estimator combines equations in first differences and levels, using appropriate internal instruments to improve efficiency and minimize bias. Diagnostic tests, including the Hansen test of overidentifying restrictions and the Arellano-Bond test for autocorrelation, confirm the validity of the instruments and the absence of second-order serial correlation in the residuals. Hansen P values are 0.210 and 0.299 in columns 1 and 2, respectively. The results in Table 3 show that patents per capita and patents per GDP have significant positive effect on sustainable development. The results from the system GMM

Table 2: Baseline results

Variables	I	II	III	IV
ND Gain lagged	0.803	0.959	0.803	0.959
	(27.31)***	(108.74)***	(27.32)***	(109.47)***
GDP per capita, log	0.476	0.103	0.574	0.237
	(5.35)***	(1.93)*	(5.77)***	(3.50)***
Trade openness	0.008	-0.000	0.008	-0.000
	(3.46)***	(0.18)	(3.46)***	(0.18)
Patents per capita	0.095	0.135		
	(2.17)**	(5.26)***		
Rents	−0.042	0.002	−0.042	0.002
	(2.76)***	(0.46)	(2.76)***	(0.47)
Urbanization	0.047	0.001	0.047	0.001
	(2.25)**	(0.53)	(2.25)**	(0.54)
Renewables	−0.014	0.003	−0.014	0.003
	(1.99)*	(2.52)**	(1.98)*	(2.52)**
Patents per GDP			0.097	0.136
			(2.22)**	(5.16)***
Constant	3.759	1.582	3.308	0.961
	(3.55)***	(6.16)***	(3.11)***	(5.11)***
R^2	0.88		0.88	
Model	FE	RE	FE	RE
N	839	839	839	839

*P<0.1, **P<0.05, ***P<0.01

Table 3: Two step system GMM results

Variables	I	II
ND Gain lagged	0.986	0.993
	(62.26)***	(73.36)***
GDP per capita log	−0.165	0.017
	(2.27)**	(0.18)
Trade openness	−0.001	−0.001
	(0.64)	(0.42)
Patents per capita	0.336	
	(8.19)***	
Patents per GDP		0.263
		(6.02)***
Rents	−0.027	−0.029
	(4.44)***	(4.56)***
Urbanization	−0.005	−0.001
	(0.63)	(0.09)
Renewables	−0.016	−0.016
	(3.28)***	(3.14)***
Constant	3.599	2.433
	(6.21)***	(4.42)***
AR (1)	0.000	0.000
AR (2)	0.773	0.793
Hansen P value	0.210	0.299
N	839	839

*P<0.1, **P<0.05, ***P<0.01

model reinforce the main findings and offer greater confidence in the causal interpretation of the effects. This implies that fostering patenting activity not only benefits economic growth as suggested by extant research (Iwaisako and Futagami, 2013) but also promotes environmental sustainability. Turning to control variables similarly to Cong and Ren (2023), we find that natural resource dependence inhibits sustainable development. Renewable energy sector growth is also negatively linked to ND Gain index in our analysis.

We conduct robustness test in Table 4. First, we use Panel-corrected standard errors model. Panel-corrected standard errors (PCSE) improve upon traditional fixed effects regression by providing more reliable standard error estimates in the presence of cross-sectional dependence and panel heteroskedasticity. Unlike fixed effects models that assume homoscedastic and uncorrelated errors across panels, PCSE adjusts for contemporaneous correlation and heteroskedasticity, leading to more accurate inference. Second, we compare the results in Table 4 to baseline results obtained through Fixed effects model in Table 2. In column 1 we add FDI as % of GDP from World Bank. A number of regional studies show that FDI is important modeling environmental degradation across regions (see e.g. Blanco et al. (2013) for Latin America). In column 2, we include economic freedom index to capture the effect of quality of market institutions on sustainable development. In column 3 and 4, following O'Neill et al. (2012) and Chen (2022) we control for government size and age dependency ratio from the World Bank. Of all variables only economic freedom has positive effect on ND Gain index. Turning to our variables of interest, we observe that innovation is again robustly and positively linked to sustainable development. Renewable energy sector growth once we account for cross-sectional dependence and panel heteroskedasticity is also positively related to sustainable development.

Table 4: Robustness test: additional controls

Variables	I	II	III	IV
ND Gain lagged	0.957	0.952	0.962	0.962
	(117.17)***	(98.75)***	(109.19)***	(110.26)***
GDP per capita	0.109	0.054	0.087	0.103
	(2.30)**	(0.97)	(1.72)*	(1.75)*
Trade openness	0.000	-0.000	-0.000	0.000
	(0.17)	(0.10)	(0.19)	(0.24)
Patents per capita	0.141	0.151	0.125	0.134
	(4.43)***	(4.52)***	(3.62)***	(3.90)***
Rents	0.001	0.007	0.002	0.002
	(0.26)	(1.00)	(0.29)	(0.31)
Urbanization	0.001	0.003	0.002	0.002
	(0.53)	(1.24)	(0.66)	(0.91)
Renewables	0.003	0.003	0.004	0.004
	(1.71)*	(1.93)*	(2.03)**	(2.00)**
FDI	−0.001			
	(0.33)			
Economic freedom		0.153		
		(2.44)**		
Age dependency			−0.006	
			(1.08)	
Government size				−0.008
				(1.30)
Constant	1.625	1.205	1.811	1.460
	(5.72)***	(3.19)***	(5.24)***	(4.65)***
R^2	0.99	0.99	0.99	0.99
N	835	779	839	779

*P<0.1, **P<0.05, ***P<0.01

5. CONCLUSION

This study provides novel empirical evidence on the role of innovation - measured through patent applications - in advancing environmental sustainability across Europe and Central Asia. By employing a range of panel data techniques, including fixed effects and two-step system GMM estimators, the analysis offers robust insights into the dynamic and potentially endogenous relationship between innovation and sustainable development outcomes. A comprehensive review of the related literature further confirms that both innovation and renewable energy have a consistent and statistically significant effect in reducing CO_2 emissions, underscoring their strategic importance in achieving environmental goals. The findings of this study indicate that innovation is positively and significantly associated with the ND-GAIN index, suggesting that countries with greater technological advancement exhibit higher levels of climate resilience and adaptive capacity. Additionally, renewable energy use is shown to contribute to a reduction in CO_2 emissions, while GDP per capita and trade openness further support environmental sustainability.

From a policy perspective, these findings emphasize the critical need for governments and regional bodies to prioritize investments in innovation ecosystems. Policies that incentivize patentable research, strengthen intellectual property rights, and promote the diffusion of green technologies can significantly enhance countries' ability to cope with climate-related risks. Moreover, integrating renewable energy strategies with innovation policy may generate synergistic effects, accelerating the transition toward sustainable and low-carbon economies. Trade openness and economic development should also be leveraged as complementary tools to facilitate access to clean technologies and environmentally sound practices.

To accelerate renewable energy adoption, developing countries should implement a mix of financial, regulatory, and institutional policies tailored to local contexts. First, governments can introduce targeted subsidies, tax incentives, and feed-in tariffs to make renewable technologies more financially attractive for investors and households. Second, developing robust regulatory frameworks - such as setting national renewable energy targets, simplifying licensing procedures, and ensuring grid access - can reduce uncertainty and attract private sector participation. Third, countries should invest in energy infrastructure, including modernizing grids and supporting off-grid solutions like solar home systems for rural areas. Finally, fostering partnerships with international donors and multilateral development banks can help mobilize funding, while supporting local R&D and vocational training programs can build the human capital needed for a sustainable renewable energy sector.

Despite its contributions, this study has several limitations. First, patent applications, while a strong proxy for innovation output, may not fully capture informal or non-patentable innovations that also influence environmental outcomes. Second due to the nature of data covering only years since 2000, we could not use complex panel data methods to unbundle the long run effects of renewable energy on ND Gain index.

Future research could explore disaggregated patent data by sector, assess the role of environmental regulation and institutional quality, and investigate how specific types of innovation (e.g., energy efficiency technologies or climate-smart agriculture) affect sustainability outcomes in different policy environments. In addition, future studies should examine the effects of other variables on ND Gain index (Janpolat et al., 2021).

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