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Green Innovation and Energy Efficiency: Moderating Effect of Institutional Quality Based on the Threshold Model

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Abstract

Recent studies demonstrated that green innovation and environment-related technologies reduce energy intensity and improve energy efficiency, contributing to the reduction of carbon emissions. However, the existing studies employ linear estimation methods to examine the relationship between green innovation and energy intensity and do not consider the indirect implications of institutional quality for the effect of green technology on energy intensity. Institutional quality is found to be an essential driver of innovation, and countries may need to achieve at least a minimum level of institutional quality to promote green innovation and improve their energy intensity. To test this hypothesis, this paper examines the relationship between energy intensity and green innovation using a panel dataset from 72 countries between 1996 and 2017 and a panel threshold model when institutional quality is considered a threshold variable. The findings highlight that green innovation reduces the energy intensity if and only if countries surpass a certain threshold of institutional quality. Therefore, countries need to improve their institutional quality to promote green innovation and benefit from green technologies in improving their energy intensity.

Keywords Green innovation · Energy intensity · Energy efficiency · Institutional quality · Threshold model

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1 Introduction

Energy efficiency is considered to be one of the ways to reduce carbon emissions, contributing to reducing direct emissions from fossil fuel combustion or consumption and indirect emissions from electricity generation (International Energy Agency 2019). Additionally, energy efficiency is considered a major factor behind the decoupling of energy-based carbon emissions from economic development and reduces energy consumption. Even though energy efficiency improvements (measured by lower energy intensity) lead to a reduction in energy consumption and carbon dioxide (CO_2) emissions, one should take into consideration the problem linked to Jevon's paradox, which points out that the energy efficiency improvements might provoke higher energy consumption (Cansino et al. 2019).

After almost ten years since the Paris Agreement, the results of the measures implemented have shown to be insufficient to limit the long-term increase in average global temperatures to 1.5 °C, and more ambitious objectives should be established. The net zero emissions foreseen by 2050 requires the implementation of additional actions in key sectors (among them, the energy sector, responsible for three-quarters of global greenhouse emissions) and the commitment to improve energy efficiency to reduce environmental impacts of production processes, but also to ensure sustainable development (International Energy Agency 2021).

The potential energy efficiency gains of OECD and non-OECD countries between 2005 and 2013 were analyzed by Liddle and Sadorsky (2021), concluding that globally, there was a lack of energy efficiency improvements, although the non-OECD countries notably increased their energy efficiency. Considering a larger period, Tajudeen et al. (2018) demonstrated that improvements in energy efficiency reduced CO_2 emissions at the macro level for 30 OECD countries between 1975 and 2015. Similarly, Mirza et al. (2022) identified that energy efficiency significantly contributed to CO_2 emissions reduction for 30 developing countries between 1990 and 2016.

Globally, the International Energy Agency (2021) identifies lower energy efficiency improvements (measured by primary energy intensity) between 2017 and 2021 (an annual average of 1.3%) than the previous period between 2011 and 2016 (2.3%), being far from the expected energy efficiency improvement (4%) described in the Net Zero Emissions by 2050 Scenario over 2020–2030. However, if efficiency had not improved since 2000, emissions would have been nearly 4 Gt CO_2-equivalent, or 12%, higher in 2017 (International Energy Agency 2019). Therefore, energy efficiency improvements have been an essential ingredient for decarbonization.

Green innovation and technologies are found to be critical contributors to energy efficiency. The existing studies that examine the relationship between energy intensity (efficiency) and green innovation found that green innovation decreases energy intensity. Using a data set for 17 OECD countries between 1975 and 2005 and analyzing energy intensity in 14 industrial sectors, Wurlod and Noailly (2018) demonstrated that green innovation led to a decline in energy intensity in most sectors. Using a different set of panel data techniques (i.e., fixed effects, dynamic ordinary least squares estimator, panel fully modified ordinary least squares, and autoregressive distributed lag), Paramati et al. (2022) examined the relationship between green technologies and energy efficiency in 28 OECD countries between 1990 and 2014 and demonstrated that green technologies improved energy efficiency. Using a relatively larger data set consisting of 71 countries, Sun et al. (2019) found that green innovation reduced energy intensity.

Rodríguez-Pose and Di Cataldo (2015) found a positive association between the quality of government and the capacity of European regions to innovate, and ineffective and corrupt governments hinder the innovative capacity. Tebaldi and Elmslie (2013) and Boudreaux (2017) showed that institutional quality promotes innovation by examining cross-country patent data. Similarly, firm-level innovation and patenting are positively associated with institutional quality and improvements in institutional quality (e.g., Clò et al. 2020; D'Ingiullo and Evangelista 2020; Hussen and Çokgezen 2021; Wu et al. 2015). Institutional quality was also essential for green innovation and green technology deployment. The institutional quality is found to increase renewable energy deployment and green technologies (Bhattacharya et al. 2017; Uzar 2020; Pinar 2024). Chen et al. (2021) found that countries with better democratic institutions channel more economic resources for renewable energy deployment compared to countries with non-democratic institutions.

Overall, there is clear evidence that green innovation reduces energy intensity and improves energy efficiency. However, the existing literature examines the relationship between green innovation and energy intensity using linear estimation methods. This paper aims to analyze the potential nonlinear relationship between green innovation and energy intensity. Therefore, the novelty of this paper is that institutional quality will be used as the threshold variable, considering it is an essential driver of green innovation, thus contributing to the existing literature that shows a clear interlinkage between green innovation and institutional quality. Additionally, institutional quality is assumed to promote energy efficiency through its effect on green innovation. Our hypothesis is that countries with stronger institutions could protect the property rights of the individuals and firms that invest in green technologies, and therefore, green innovation could promote energy efficiency if and only if countries have strong institutions and protection of property rights. However, if property rights are not protected, green innovation and its impact on energy intensity may be limited. To test whether institutional quality plays a role in energy efficiency through its effect on green innovation, we use a panel data set from 72 countries between 1996 and 2017 and employ a panel threshold model to examine the effect of green innovation on energy efficiency by using institutional quality as a threshold variable.

The rest of the paper is organized as follows. A literature review on the determinants of energy intensity and efficiency is offered in Sect. 2. Section 3 provides the data set and panel threshold methodology. Section 4 provides cross-sectional dependence and unit root test results, and empirical findings with the linear and threshold models. Finally, Sect. 5 concludes and provides policy recommendations.

2 Literature review

The importance of energy efficiency for climate policy favors the interest in analyzing the main drivers of energy intensity. Among many factors, technological advancements have lowered the energy use per unit of output produced and increased energy efficiency (Timma et al. 2017; Li and Lin 2018). Additionally, innovation is linked to technological improvements and helps countries improve their energy efficiency (Cagno et al. 2015). Among these innovations, the green innovation stands out in improving energy efficiency (Song et al. 2018).

There are several structural factors that can be identified that influence energy efficiency. The relative weight of the economic sectors in the economies and their comparative growth during the expansion and recession periods play an essential role in the energy consumption of these economies and, therefore, in their energy efficiency improvements (Román-Collado and Colinet 2018). The empirical evidence indicates that economic growth implies an increase in CO_2 emissions through higher and more energy-intensive consumption (Mendonça et al. 2020). However, economic growth can lead to the dematerialization of the economy and lower energy-intensive sectors, therefore leading to a decline in energy intensity (Dargahi and Khameneh 2019).

It has been found that trade openness could increase economic activity and hamper environmental quality (Afesorgbor and Demena 2022; Chen et al. 2022a; Chhabra et al. 2023; Zheng et al. 2023). However, some studies also found that trade openness could improve environmental quality due to access to better technologies (Zhang et al. 2017). Furthermore, trade openness is also a relevant factor for energy efficiency. Analyzing panel data from Bolivia, Colombia, Ecuador, and Peru between 1971 and 2014, Koengkan (2018) shows that trade openness is positively associated with energy consumption. On the other hand, using panel data covering 30 Chinese provinces during 2006–2015, Wang and Zhou (2023) demonstrated that trade openness improves energy efficiency because trade openness allows Chinese regions to access advanced low-pollution technologies (see also Chen et al. (2022b), Pan et al. (2019) and Wang and Zhou (2023) for similar findings). Therefore, the relationship between trade openness and energy efficiency is ambiguous and the relationship between these two factors could be positive or negative.

Another factor that explains the energy intensity is the population density. The literature shows that the impact of the population density (urbanization) on energy intensity could be either positive or negative. For instance, analyzing the effect of urbanization on energy intensity in 10 Asian countries, Bilgili et al. (2017) found that urbanization led to a reduction in energy intensity. On the other hand, analyzing energy intensity across 30 provinces of China between 2000 and 2012, Yan (2015) found that urbanization increased the energy intensity. He et al. (2023) show that the effect of population density on energy efficiency depends on the urbanization model. Similarly, Otsuka and Goto (2018) identify that population density positively influences energy intensity in Japan and that the effect of population density on energy intensity differs across regions. Finally, Zarco-Periñán et al. (2021) show that population density is positively associated with energy intensity except for the densest cities.

The economy's sectoral structure is another critical factor that might contribute positively or negatively to energy efficiency. For instance, Voigt et al. (2014) carried out a sectoral analysis of energy efficiency across 40 major economies and found that energy efficiency gains were relatively large in the industrial sector in China, Brazil and India. While Dargahi and Khameneh (2019) showed that the growth of the industry's share in Iran's GDP reduced energy intensity in Iran, Adom (2015) found that the share of industrial production is positively associated with energy intensity in Nigeria. Therefore, it has been found that the industrial production share plays a significant role in explaining energy intensity, but the effect of industrial production on energy intensity may vary across different countries.

Furthermore, countries' energy structures (energy mix) also significantly influence energy intensity. Policymakers use energy efficiency and the promotion of renewable energy sources (RES) to fight climate change. Recent studies showed that energy mix and renewable energy consumption significantly affect energy intensity. For instance, Gyamfi et al. (2023) examined panel data of 26 European Union countries covering the period 1990–2019 and demonstrated that renewable energy consumption reduces energy intensity. In fact, the results for the EU show that energy efficiency is quite relevant for RES target achievement since the RES share is set as a percentage of gross final energy demand (del Río 2010). In the same lines, Yu et al. (2022) showed that renewable energy consumption reduced energy intensity based on their analysis of a panel dataset for 82 countries from 1996 to 2016.

The existing literature also identified a bidirectional causal relationship between CO_2 emissions and energy intensity. Examining a panel data set of 50 African countries from 1980 to 2018, Namahoro et al. (2021) identified a bidirectional causal relationship between energy intensity and CO_2 emissions in lower-middle-income and high-income African countries and a unidirectional causal relationship from CO_2 emissions to energy intensity in low-income African countries. Ajmi et al. (2015) examined a panel data set of G7 countries from 1960 to 2010 and found that there is a bidirectional causal relationship between energy consumption and CO_2 emissions in the United States of America. Antonakakis et al. (2017) examined the directional causal relationship between energy consumption, CO_2 emissions and real GDP across different income groups of 106 countries over the period 1971–2011, and found that there is a bidirectional causal relationship between CO_2 emissions and total energy consumption in high-income countries. Abban et al. (2020) show that energy intensity has a bidirectional association with CO_2 emissions in low-, upper-middle-, and high-income Belt and Road initiative countries during the 1995–2015 period.

Energy prices are also among the factors that impact the use of energy sources. Most of the existing studies found that energy prices are negatively associated with energy intensity (Dong et al. 2018; Petrović et al. 2018). However, the energy prices could lead to an increase in energy intensity in some cases. For instance, Samargandi (2019) found that oil prices are positively associated with energy intensity in OPEC countries. Hang and Tu (2007) found that the effect of oil and coal prices has a negative impact on energy intensity, but electricity prices have a positive effect on energy intensity. Wang et al. (2019) found a positive but not significant relationship between oil prices and energy consumption and pointed out that the increase in energy prices does not alter energy consumption significantly. On the other hand, Antonietti and Fontini (2019) found that oil price is positively or negatively associated with energy intensity depending on the geographical region of the world. At the micro-level, it has also been found that surges in energy prices harm firm performance (Calì et al. 2022, 2023); however, a rise in fuel prices increases machinery turnover, which makes firms more likely to use technology closer to the frontier (i.e., firms being more efficient and environmentally friendly) and thus make them more competitive internationally (Blackman and Wu 1999; Guadalupe et al. 2012; Brucal et al. 2019). Furthermore, André et al. (2023) documented that firms in the less energy-intensive sectors that had experienced mild price shocks had higher productivity in the medium run. Therefore, even though a surge in energy prices harms firm performance in the short run, firms tend to gain in the long term by using productive electricity-powered capital equipment (Calì et al. 2022) and using more energy-efficient technologies (Calì et al. 2022; André et al. 2023).

Finally, among the institutional quality that is found to be an important factor in promoting energy efficiency (Chang et al. 2018; Sun et al. 2019; Barrera-Santana et al. 2022). International agencies and citizens may put pressure on energy efficiency due to higher carbon emissions, and international agreements to reduce carbon emissions may incentivize governments to increase their energy efficiency. Furthermore, firms have no incentive to increase their efficiency to meet environmental standards if government officials are bribed (Yu et al. 2019; Deng et al. 2020). The existing literature also found that corruption (i.e., low institutional quality) significantly increases energy intensity (Fredriksson et al. 2004; Ozturk et al. 2019; Pei et al. 2021).

3 Data and methodology

3.1 Data

This paper mainly examines the role of green patents (green technology or innovation) on energy efficiency and the effect of institutional quality for energy efficiency through its impact on green technology. Therefore, we collected the annual data from five main sources: U.S. Energy Information Administration (2022), OECD (2022), World Development Indicators of the World Bank (2022a), Worldwide Governance Indicators of the World Bank (2022b) and the Statistical Review of World Energy of the British Petroleum (2022).

The dependent variable considered is the energy intensity (EI). Total energy consumption is obtained from the U.S. Energy Information Administration (2022), which is divided by the gross domestic product (in constant 2015 US dollars) to obtain the dependent variable: total kilowatt energy consumption per 2015 US$ of GDP.

The existing studies have widely used green technology patents to measure green innovation (e.g., Wurlod and Noailly 2018; Sun et al. 2019; Danish and Ulucak 2020; Paramiti et al. 2022). The environment-related patent (EP) data is obtained from the OECD (2022) for 72 countries, and this consisted of patents filed in European, Japanese and US patent offices (see Table 7 of Appendix 1 for the list of countries).

Khan et al. (2023) argued that a stronger rule of law (institutional quality) is essential to pursue laws to have strict environmental policies and regulations and found that the rule of law reduced carbon emissions in Brazil, Russia, India, China and South Africa. Similarly, Rahman and Sultana (2022) pointed out that countries with low levels of corruption and effective governments promote higher renewable energy consumption. On the other hand, Danish and Wang (2019) show that better governance of countries (i.e., countries with lower corruption, better regulatory quality and rule of law, etc.) is essential in improving environmental quality. Clò et al. (2020) found that the protection of property rights (i.e., better institutional quality) is essential in promoting innovation and better technologies. Dam et al. (2023) also argue that countries with stronger institutions can better enforce environmental regulations, protect property rights, and promote sustainable development. Therefore, overall, institutional quality is found to be an important factor in promoting sustainable development. We use various institutional quality proxies from the Worldwide Governance Indicators of the World Bank (2022b) because these institutional quality proxies have been extensively used by the existing literature (Bhattacharya et al. 2017; Chang et al. 2018; Danish and Wang 2019; Clò et al. 2020; Apergis and Pinar 2021; Rahman and Sultana 2022; Dam et al. 2023; Khan et al. 2023). We use the rule of law (RoL) proxy as the main institutional quality proxy because the rule of law measures the protection of property rights, which promotes innovation (Clò et al. 2020) and environmental quality (Khan et al. 2023). Furthermore, we also use other institutional quality proxies (i.e., control of corruption (CC), government effectiveness (GE) and regulatory quality (RQ)) from the Worldwide Governance Indicators in our robustness analysis. These institutional quality proxies range between −2.5 and +2.5, and higher scores represent better governance (institutional quality).[1] Furthermore, another reason why we have chosen various

[1] Worldwide governance indicators have yearly data set; however, it does not provide data for 1997, 1999 and 2001. To capture a longer period, we use the averages of the preceding and subsequent years to obtain institutional quality proxies for countries in 1997, 1999 and 2001.

Table 1 Descriptive statistics

	Mean	Standard deviation	Maximum	Minimum
EI	0.8459	0.6306	3.3069	−0.7665
EP	1.6709	2.0174	8.1712	0.0000
CO_2	−0.8784	0.7636	1.6063	−2.9343
Trade	83.3584	50.3524	437.3267	15.6356
REC	2.4614	1.4309	4.4850	−4.7069
GDP	9.2392	1.1464	11.3635	6.4809
POPDEN	4.2988	1.3111	8.9766	0.3995
IndValue	3.2869	0.2543	4.2011	2.3011
Oil	4.0271	0.5572	8.2582	2.3128
CC	0.4469	1.0397	2.4700	−1.5273
GE	0.5773	0.8914	2.4370	−1.2146
RQ	0.5803	0.8410	2.2605	−1.7690
RoL	0.4572	0.9592	2.1297	-1.4272

All variables, except institutional quality measures (CC, GE, RQ, and RoL), are in logarithms

institutional quality proxies from the World Governance Indicators is that these indicators have been available for more than 200 countries since 1996, allowing us to have a more extensive panel data set. The measurements and definitions of the variables are presented in Table 8 of Appendix 2.

Based on the energy intensity (efficiency) literature, a set of control variables from the World Development Indicators of the World Bank (2022a) are chosen: trade openness (measured as the sum of the imports and exports as a percentage of GDP), population density (measured as the people per square kilometer of land area), renewable energy consumption (percentage of total final energy consumption), GDP per capita (constant 2015 US$), CO_2 emissions (kg per 2015 US$ of GDP), and the share of value-added by the industry as a percentage of GDP. Finally, we also control for the oil prices (measured using the spot price of Brent crude oil) from the Statistical Review of World Energy of the British Petroleum (2022), which is deflated with the consumer price index (CPI) from World Development Indicators from the World Bank (2022a).

Finally, based on the data availability of variables from different sources, a panel data set covering the period between 1996 and 2017 for 72 countries is obtained. Table 1 offers the descriptive statistics for all the variables in logarithm forms except for the institutional quality proxies.

3.2 Methodology

Among empirical methods, threshold regression stands out as the most suitable for our analysis. We select threshold regression as our econometric model, driven by several considerations. Firstly, threshold regression has been widely employed to capture nonlinearities in economic relationships, as evidenced by its use in exploring various phenomena such as public debt and economic growth (e.g., Chudik et al. 2017), inflation and economic growth (e.g., Kremer et al. 2013), testing asymmetric oil pricing (e.g., Godby et al. 2000; Chen et al. 2019), and examining the nexus between renewable energy consumption and economic growth (e.g., Chen et al. 2020). Secondly, nonparametric models are unsuitable for our case due to the significant curse of dimensionality and their challenging interpretability (see, e.g., Ichimura and Todd 2007; Kourtellos et al. 2016). Thirdly, in comparison to other common parametric nonlinear models, threshold regression offers greater flexibility by enabling the capture of nonlinear relationships through an unknown threshold value (see, e.g., Hansen 1999). Fourthly, compared with more complex parametric nonlinear models, threshold regression models provide more interpretable results (see, e.g., Hansen 2000; Seo and Shin 2016). By segmenting the sample into two regimes based on the threshold estimate, the model simplifies into a linear form within each regime, allowing for the examination of nonlinearity by comparing coefficient estimates between the two regimes. Lastly, the presence of threshold nonlinearity can be empirically tested using bootstrapped methods (see, e.g., Hansen 1996; Lee et al. 2011).

To examine the relationship between the environmental patent and the energy intensity, we have the following form:

$$\mathrm{EI} = \mathrm{f}(\mathrm{EP}, \mathrm{X}) \tag{1}$$

where EI is energy intensity, EP is the environmental patent, and X denotes other controlling variables, CO_2 emissions (CO_2), trade openness (Trade), renewable energy consumption (REC), GDP per capita (GDP), population density (POPDEN), industry value added (IndValue), oil price (Oil), and institutional quality measured by the rule of law proxy (RoL).

Therefore, the baseline linear model is of the following form:

$$\mathrm{EI}_{\mathrm{it}} = \alpha_0 + \rho_0 EP_{it} + \beta_0^T X_{it} + \mu_{it} \tag{2}$$

where subscripts $i = 1, \ldots, N$ represents the country, $t = 1, \ldots, T$ indexed the time, α_0 is a constant, X_{it} is a vector of control variables and μ_{it} is the idiosyncratic error term.

To explore the potential nonlinear relationship between the environmental patent and the energy intensity, we extend model (2) to allow for a threshold effect and propose the following panel threshold regression model:

$$\begin{aligned} \mathrm{EI}_{\mathrm{it}} &= \alpha_1 + \rho_1 EP_{it} + \beta_1^T X_{it} + \mu_{it},\ q_{it} \le \gamma_0 \\ \mathrm{EI}_{\mathrm{it}} &= \alpha_2 + \rho_2 EP_{it} + \beta_2^T X_{it} + \mu_{it},\ q_{it} > \gamma_0 \end{aligned} \tag{3}$$

where q_{it} is the threshold variable and γ_0 is the true threshold level. We use RoL as the threshold variable to generate our main results. In addition, we check the robustness by using a set of other institutional quality measures as the threshold variable, including control of corruption (CC), government effectiveness (GE), and regulatory quality (RQ). Model (3) reduces to model (2) if all $q_{it} \le \gamma_0$ or $q_{it} > \gamma_0$.

Following Seo and Shin (2016), to allow for contemporaneous endogeneity, we estimate models (2) and (3) via a GMM method. In particular, we construct the moment conditions using the lagged values as the instrumental variables. We employ a sup-Wald test through a bootstrapping following Hansen (1996) and Seo and Shin (2016) to test for nonlinearity.

4 Empirical Analysis

4.1 Cross-Sectional Dependence and Unit Root Tests

Prior to the linear and threshold regression analysis, we carried out the cross-sectional dependence test of Pesaran (2004). Since the first-generation panel unit root tests do not account for

Table 2 Cross-section dependence

Variable	Test statistic
EI	6.61***
EP	143.91***
CO_2	3.38***
Trade	65.56***
REC	8.14***
GDP	53.37***
POPDEN	0.43
IndValue	28.71***
Oil	217.5***
CC	2.80***
GE	3.23***
RQ	– 0.97
RoL	8.26***

***Significantly different from zero at the 1% level. Cross-section dependence test of Pesaran (2004) used where under the null hypothesis of cross-sectional independence, the statistic is distributed as a two-tailed standard normal

Table 3 Panel unit root tests

Variable	Test statistic
Level	
EI	– 2.386***
EP	– 3.580***
CO_2	– 2.198***
Trade	– 1.413
REC	– 2.166**
GDP	– 2.469***
POPDEN	– 2.600***
IndValue	– 1.548
Oil	– 2.983***
CC	– 1.585
GE	– 1.824
RQ	– 1.988
RoL	– 1.879
First difference	
Trade	– 3.751***
IndValue	– 4.010***
CC	– 3.765***
GE	– 4.254***
RQ	– 4.036***
RoL	– 3.746***

***Significantly different from zero at the 1% level, **significantly different from zero at the 5% level, * significantly different from zero at the 10% level. This table provides the results of the CIPS test of Pesaran (2007). We include a constant and trend and three lags the cross-sectional dependence, it is essential for us to check for cross-section dependence before the unit root tests. The recent papers analyzing energy efficiency also carried out a cross-sectional dependence test prior to their analysis (Bilgili et al. 2017; Danish and Ulucak 2020; Paramiti et al. 2022). Table 2 presents the cross-sectional dependence test of Pesaran (2004), where the null hypothesis suggests no cross-sectional dependence. With the exception of two variables (i.e., population density and regulatory quality), we reject the cross-sectional independence at the 1% level. Therefore, to account for the cross-sectional dependence in the unit root tests, we used the cross-sectionally augmented Im–Pesaran–Shin (CIPS) unit root test proposed by Pesaran (2007), and the results are presented in Table 3. We reject the null hypothesis of the unit root for the levels of energy intensity, environment-related technologies, CO_2 emissions, GDP per capita, population density, and oil prices. On the other hand, we reject the null hypothesis of non-stationarity at the 1% significance for the first differences of the rest of the variables (i.e., trade openness, industrial value-added, rule of law, control of corruption, government effectiveness, and regulatory quality). Therefore, we use the first differences for the trade openness, industrial value-added, and institutional quality proxies and levels for the rest of the variables in the GMM estimations.

4.2 Baseline Findings

Table 4 provides the linear and threshold GMM estimation results. First, a linear GMM estimation was carried out without considering the potential nonlinear relationship between explanatory variables and the dependent variable (i.e., column 1 of Table 4). Our findings are in line with the existing literature that green environment technologies lead to a decrease in energy intensity (Wurlod and Noailly 2018; Sun et al. 2019; Paramiti et al. 2022). A percentage increase in green patents leads to a reduction in energy intensity by 0.09%. On the other hand, a percentage increase in CO_2 emissions leads to an increase in energy intensity by 0.92%. Similarly, GDP per capita is positively associated with energy intensity due to increased economic activity (see e.g., Paramiti et al. 2022). Furthermore, the energy intensity is negatively associated with population density, and the increased population density leads to lower energy intensity. The increased concentration of the population leads to more efficient use of energy (see e.g., Bilgili et al. 2017). Finally, the rest of the control variables are not significant at the conventional levels.

As discussed previously, the effect of green technology on energy intensity may differ based on the institutional quality of the countries. Therefore, the rule of law is used as a threshold variable, and the threshold estimation method is used to test this. Firstly, the modified Wald statistic proposed by Seo and Shin (2016) is reported in Table 4, and the null hypothesis of the linear model is rejected at the 1% level. Therefore, the linear model is rejected at the 1% level, suggesting that the effects of the determinants of the energy intensity on energy intensity vary depending on the institutional quality of the countries. The significant threshold level of institutional quality is -0.1937, and the effects of the variables on the energy intensity are different for countries that have institutional quality below (above) this threshold level, which are presented as low and high regimes, respectively. We found that the green energy patents in the low institutional quality regime do not significantly affect energy intensity levels, but green innovation is negatively associated with the energy intensity in countries with stronger institutional quality. These results are aligned with the research literature considering that those countries with strong institutional quality rise in renewable energy consumption (Bhattacharya et al. 2017; Uzar 2020; Chen et al. 2021) but also increase green innovation

Table 4 Linear and threshold estimation results

Model	Linear	Threshold	
Threshold Variable		RoL	
Threshold		−0.1937***	
		Low	High
$\ln(EP_{it})$	−0.0926***	0.1051	−0.0949***
	(0.0121)	(0.0781)	(0.0330)
ΔRoL_{it}	−0.0624	−0.0944	0.0018
	(0.2194)	(0.5519)	(0.5097)
$\ln(CO_{2_{it}})$	0.9174***	1.1396***	0.7872***
	(0.0321)	(0.2056)	(0.0920)
$\Delta\ln(Trade_{it})$	−0.2421	−0.3660	−0.0664
	(0.1855)	(0.4507)	(0.3386)
$\ln(REC_{it})$	−0.0280	−0.0776	0.0201
	(0.0262)	(0.1038)	(0.0353)
$\ln(GDP_{it})$	0.2193***	0.0768**	0.3039***
	(0.0134)	(0.0387)	(0.0363)
$\ln(POPDEN_{it})$	−0.0383**	0.2339***	−0.2955***
	(0.0176)	(0.0667)	(0.0594)
$\Delta\ln(IndValue_{it})$	0.5704	0.7590	0.1591
	(0.4113)	(0.7521)	(0.8501)
$\ln(Oil_{it})$	0.0080	0.0536	0.0245
	(0.0215)	(0.0705)	(0.0511)
SupWald *P* value		0.0000	
SupWald Statistic		79.76	
Observations	1440	426	1014

***Significantly different from zero at the 1% level, ** significantly different from zero at the 5% level, * significantly different from zero at the 10% level. This table provides estimations of the panel linear and threshold regression model using the GMM method. Heteroskedasticity-robust standard errors are provided in brackets. The period spans from 1996 to 2017

(Pinar 2024) and contribute to lower energy intensity through its higher institutional efficiency (Chang et al. 2018; Sun et al. 2019; Barrera-Santana et al. 2022). On the other hand, low institutional quality contributes to the rise of some barriers against energy efficiency improvements (Otrachshenko et al. 2023) and increases energy intensity (Ozturk et al. 2019; Pei et al. 2021).

To illustrate the results provided in Table 4 more explicitly, we offer a set of figures. Figure 1 provides scatterplots between energy intensity (y-axis) and EP (x-axis) for the low and high regimes (i.e., countries with RoL scores below and above the threshold value). Panels (a) and (b) of Fig. 1 consist of observations for countries with institutional quality below and above the identified institutional quality threshold level of −0.1937. While there is no significant correlation between energy intensity and EP in the low regime (i.e., panel a of Fig. 1), a significant negative correlation exists between EP and energy intensity in the high regime (i.e., panel b of Fig. 1). This figure clearly shows that institutional quality

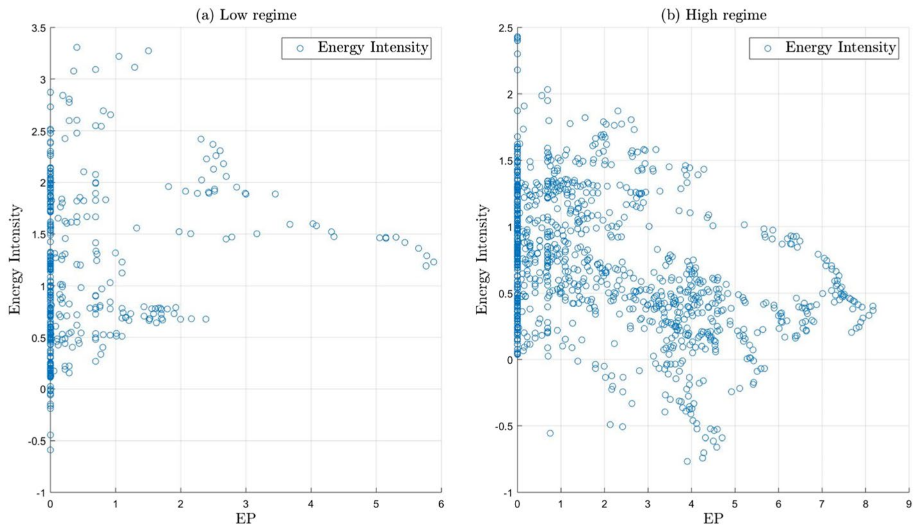

Fig. 1 Scatterplots of energy intensity vs. EP in low and high regimes

plays a significant role in the relationship between EP and energy intensity. On the other hand, the institutional quality threshold (i.e., RoL value of -0.1937) allowed us to classify the countries into two groups: (i) those countries with RoL scores above the threshold where green innovation contributes to reducing energy intensity, (ii) those countries with RoL scores below the threshold where the green innovation does not affect energy intensity significantly. To clearly show the list of countries, Figs. 2 and 3 highlight the list of countries that had RoL scores above and below the institutional quality threshold (i.e., countries listed in high and low regimes) in 1996 and 2017, respectively. Firstly, we identify 46 countries that had RoL scores above the threshold in 1996 and 2017, and 17 countries that had RoL scores below the threshold in 1996 and 2017. However, some other countries, such as Egypt, Philippines, Mongolia and Turkey, had RL scores above the threshold in 1996 but below in 2017, while some others, such as Jamaica, Bulgaria, Tunisia, Georgia and Croatia, had RL scores below the threshold in 1996 but their RoL scores were above the threshold in 2017. Appendix 3 provides the RoL scores and countries that had a RoL score above and below the threshold (i.e., countries that belong to high and low regimes, respectively) in 1996 and 2017.

Furthermore, based on the results reported in Table 4, the effect of other variables on energy intensity also varies in different institutional quality settings. For instance, an increase in GDP per capita leads to higher energy intensity in institutionally strong countries than in institutionally weak countries. Economic development levels of the institutionally strong regions are relatively higher compared to the institutionally weak countries (see e.g., Acemoglu et al. 2001; Pinar 2015; Rodrik et al. 2004), and therefore a percentage increase in GDP per capita leads to a higher percentage increase in energy intensity. On the other hand, an increase in population density reduces energy intensity in institutionally strong countries; however, population density leads to an increase in countries with low institutional quality. It has been found that infrastructure investments are more effective in institutionally strong regions (Crescenzi et al. 2016) and therefore, energy efficiency investments may be higher in densely populated areas in institutionally strong countries. Finally,

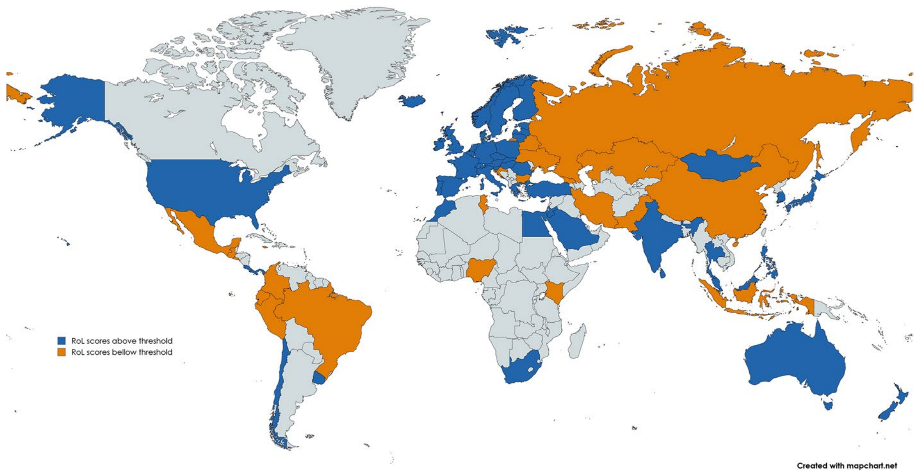

Fig. 2 Countries with RoL scores above and below the threshold in 1996

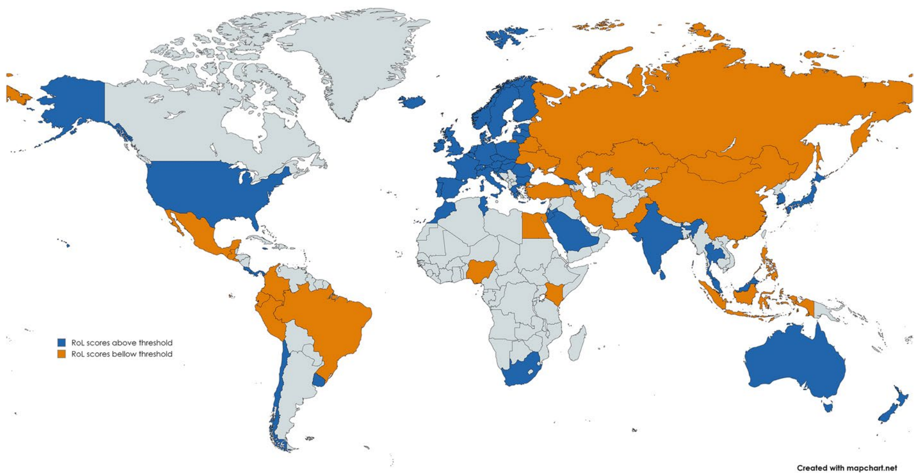

Fig. 3 Countries with RoL scores above and below the threshold in 2017

the results show that CO_2 emissions increase energy intensity more in both regimes, which aligns with the literature that there is bidirectional positive causality between energy intensity and CO_2 emissions (Abban et al. 2020; Ajmi et al. 2015; Antonakakis et al. 2017; Namahoro et al. 2021) although as Yuan et al. (2022) found out in the case of China, this correlation is more important in countries with stronger institutional quality.

4.3 Robustness Analysis

A robustness analysis is applied when different institutional quality proxies (i.e., control of corruption, government effectiveness and regulatory quality) are used as the threshold variables, and the results were obtained with the linear and threshold models. The results are presented in Table 5. Panels A, B and C of Table 5 report the results when control of corruption (CC), government effectiveness (GE) and regulatory quality (RQ) variables are included as threshold variables, respectively. It should be noted that the estimations include all the control variables but are not reported to preserve space, and the detailed results are provided in Table 10 in Appendix 4. First, the null hypothesis of the linear model is rejected in all of the specifications and the Wald test results suggest that the threshold model is preferred over the linear one. When CC, GE and RQ are used as a proxy for institutional quality, the Wald test statistics are 86.01, 71.14 and 48.78, respectively, and the null hypothesis of the linear model is rejected at the 1% level. In other words, the relationship between explanatory variables and energy intensity varies depending on whether countries have an institutional quality that is above (below) the identified institutional quality levels. The threshold levels are 1.3037, 1.3668 and -0.0763 when the CC, GE and RQ are used as institutional quality proxy, respectively. Based on these threshold levels, the estimations are carried out for low and high regimes (i.e., for countries with an institutional quality below and above these thresholds).

Based on the threshold models, the results show that EP is negatively associated with energy intensity as long as countries surpass a certain threshold of institutional quality

Table 5 Robustness analysis with different institutional quality proxies

Model	(1)	(2)	
	Linear	Threshold	
Threshold value		CC = 1.3037	
	Linear	Low	High
Panel A. Control of corruption (CC) is used as institutional quality prox			
$\ln(EP_{it})$	− 0.0923***	0.0224	− 0.2979***
	(0.0123)	(0.0200)	(0.0547)
SupWald Statistic		86.01***	
Threshold value		GE = 1.3668	
	Linear	Low	High
Panel B. Government effectiveness (GE) is used as institutional quality			
$\ln(EP_{it})$	− 0.0921***	0.0122	− 0.2752***
	(0.0123)	(0.0214)	(0.0541)
SupWald Statistic		71.14***	
Threshold value		RQ = − 0.0763	
	Linear	Low	High
Panel C. Regulatory quality (RQ) is used as institutional proxy			
$\ln(EP_{it})$	− 0.0907***	− 0.0134	− 0.1366***
	(0.0122)	(0.0314)	(0.0185)
SupWald Statistic		48.78***	

***Significantly different from zero at the 1% level, ** significantly different from zero at the 5% level, * significantly different from zero at the 10% level. This table provides estimations of the panel linear and threshold regression model using the GMM method. Heteroskedasticity-robust standard errors are provided in brackets. The period spans from 1996 to 2017. The estimations include all the control variables, but not reported to preserve space, and the detailed results are provided in Table 10 in Appendix 4 level (i.e., the coefficients on the EP in each scenario are negative and significant) irrespective of the institutional quality proxy used. On the other hand, the coefficients of EP are not significant for countries with institutional quality levels that are below the threshold levels. In other words, the EP significantly reduces energy intensity in countries with an institutional quality above a given threshold level. Furthermore, it should be noted that the magnitudes of the EP coefficients are relatively higher in high regimes. For instance, a one percent increase in EP reduces energy intensity roughly by 0.30%, 0.28% and 0.14% in the high regime when CC, GE and RQ are used as an institutional quality proxy, respectively. The size of the magnitude of the EP coefficients is relatively higher compared to the one identified by the linear estimation. In other words, the linear estimation model also undermines the importance of the energy patents in reducing energy intensity.

In summary, with all the institutional quality proxies, the findings show that environment-related patents reduce energy intensity if countries have a strong institutional quality above a given threshold. Our results align with the research literature, considering that institutional quality drives green innovation (e.g., Clò et al. 2020; D'Ingiullo and Evangelista 2020; Hussen and Çokgezen 2021). It should be noted that the novelty of this work lies in the fact that countries could benefit from green innovation to reduce energy intensity if they exceed a certain level of institutional quality.'

The findings concerning the control variables align with the baseline estimation when different institutional quality proxies are used (see Table 10 of Appendix 4 for the detailed results). The results highlight that CO_2 emissions increase energy intensity in line with the findings of Abban et al. (2020), Ajmi et al. (2015), Antonakakis et al. (2017) and Namahoro et al. (2021) with both linear and threshold estimations. Similarly, a percentage increase in GDP per capita increases energy intensity more in institutionally strong countries than in institutionally weak countries because institutionally strong countries tend to have higher income per capita. In line with the baseline findings, population density reduces energy intensity in institutionally strong countries, and the population density is either not significant or positively affects energy intensity in institutionally weak countries. These results align with those from He et al. (2023), concluding that population density reduces energy intensity through higher innovation, which is linked to strong institutional quality governments. Finally, even though oil prices were insignificant in the baseline estimations, oil prices are significantly important in explaining energy intensity with the threshold models when CC and GE are used as institutional quality proxy. While oil prices significantly reduce energy intensity in countries with strong institutional quality (i.e., high regime), oil prices increase energy intensity in institutionally weak countries (i.e., high regime). This finding is in line with those coming from Antonietti and Fontini (2019) because the effect of the energy prices on energy intensity varies based on the country-sample choice. Furthermore, the existing literature found that energy prices also increased energy intensity in OPEC countries (Samargandi 2019), Iran (Barkhordari and Fattahi 2017) and China (Hang and Tu 2007). These findings may support the findings of this paper as these respective countries have relatively low institutional quality. Finally, the energy prices do not significantly impact energy intensity when RQ is used as an institutional quality proxy.

The effect of explanatory variables on energy intensity may vary depending on geographical regions. For instance, Antonietti and Fontini (2019) found that the impact of energy price on energy intensity varies across geographical clusters. On the other hand, Saidi and Hammami (2015) demonstrated that the effects of carbon emissions, economic growth, population and capital stock on energy consumption show variation across Europe and North Asia, Latin America and Caribbean, Sub-Saharan, North African and Middle Eastern regions. Therefore, we carry out an additional robustness analysis to examine whether the effect of the EP has a different impact on EI based on the institutional quality level. The World Bank classifies countries into seven geographical clusters: East Asia & Pacific (EAP), Europe & Central Asia (ECA), Latin America & Caribbean (LAC), Middle East & North Africa (MENA), North America (NA), South Asia (SA) and Sub-Saharan Africa (SSA). The country sample used in this paper has 11, 35, 12, 7, 1, 3 and 3 countries from the EAP, ECA, LAC, MENA, NA, SA and SSA geographical clusters, respectively. As all the geographical group has a limited number of countries except for ECA geographical cluster, we carry out our baseline estimations by excluding each geographical cluster from our sample one at a time. The results of these estimations are reported in Table 6 when the RoL is used as an institutional quality proxy.

Panels A, B, C, D, E, F and G of Table 6 present the linear and threshold estimation results when countries from EAP, ECA, LAC, MENA, NA, SA and SSA geographical clusters are excluded from the sample, respectively. The estimations include all the control variables, but the detailed results are provided in Table 11 in Appendix 4. Firstly, the Wald test statistic results highlight that the null hypothesis of the linear model is rejected, suggesting that the threshold models are preferred over the linear model. Secondly, the results suggest that the baseline estimations hold that the EP reduces EI significantly irrespective of the geographical cluster excluded from the sample except for the EAP and these findings are consistent with those of Sun et al. (2019). In other words, regardless of the geographical groups excluded, EP significantly reduces EI if countries have an institutional quality that is above the threshold institutional quality level. When LAC and SA countries are excluded from the sample, the magnitude of the EP coefficients in the high regime (i.e., −0.1403 and −0.1271, respectively) is relatively higher than the EP coefficient obtained in the baseline estimations (i.e., −0.0949). On the other hand, when countries from the ECA, MENA and SSA are excluded from the sample, the magnitude of the EP coefficients in the high regime (−0.0589, −0.0760 and −0.0564, respectively) is lower than the EP coefficient obtained in the baseline estimations (i.e., −0.0949). Therefore, the exclusion of some countries alters the negative impact of EP on EI in high regimes, but the EP reduces EI in countries with high institutional quality. Overall, we find that the EP reduces EI significantly irrespective of the sample choice as long as countries have an institutional quality that is above a given institutional quality threshold level.

The effects of the control variables on EI also align with the baseline estimations (see Table 11 of Appendix 4 for the detailed results). Firstly, in most of the specifications, CO_2 emissions and GDP per capita are positively associated with the EI in both regimes. While population density reduces EI in high regimes when countries from LAC, NA, SA and SSA are excluded from the sample, population density increases EI in high regimes when EAP, ECA and MENA countries are excluded from the sample. Whereas, the impact of population density on EI is negative (positive) in the low regime when countries from EAP, ECA and MENA (LAC, NA, SA and SSA) countries are excluded from the sample. The finding highlights that the impact of population density on EI varies depending on the country-sample choice, which explains the varying results obtained by the existing literature that distinguishes between urban or rural areas or urban structures (Otsuka and Goto 2018; He et al. 2023). Finally, even though renewable energy consumption is not significant in explaining energy intensity in the baseline estimations (Table 4), the results suggest that renewable energy consumption plays a significant role in explaining energy intensity when some geographical clusters are excluded from the sample. When countries from LAC and SSA geographical clusters are excluded from the sample, the results show that renewable energy consumption reduces energy intensity in both regimes. This finding aligns with the ones presented by Gyamfi et al. (2023) and Yu et al. (2022). In the same

Table 6 Robustness analysis with different geographical clusters

	(1)	(2)	
Model	Linear	Threshold	
Threshold value		RoL = 0.8837	
	Linear	Low	High
Panel A. Countries from East Asia & Pacific geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0869***	−0.0406	−0.0761
	(0.0160)	(0.0634)	(0.0554)
SupWald Statistic		158.60***	
Threshold value			RoL = −0.5787
	Linear	Low	High
Panel B. Countries from Europe & Central Asia geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0700***	−0.0659	−0.0589***
	(0.0053)	(0.0575)	(0.0080)
SupWald Statistic		64.91***	
Threshold value		RoL = 1.1963	
	Linear	Low	High
Panel C. Countries from Latin America & Caribbean geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0598***	0.0021	−0.1403***
	(0.0135)	(0.0283)	(0.0374)
SupWald Statistic		151.73***	
Threshold value		RoL = 1.0294	
	Linear	Low	High
Panel D. Countries from Middle East & North Africa geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0557***	−0.0180	−0.0760**
	(0.0103)	(0.0247)	(0.0328)
SupWald Statistic		376.12***	
Threshold value		RoL = −0.1937	
	Linear	Low	High
Panel E. Countries from North America geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0942***	0.1096	−0.0960***
	(0.0128)	(0.0788)	(0.0365)
SupWald Statistic		89.24***	
Threshold value		RoL = −0.2201	
	Linear	Low	High
Panel F. Countries from South Asia geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0953***	0.1141	−0.1271***
	(0.0111)	(0.0736)	(0.0273)
SupWald Statistic		77.42***	

Table 6 (continued)

Threshold value			RoL = 0.4226
	Linear	Low	High
Panel G. Countries from Sub-Saharan Africa geographical cluster excluded from the sample			
$\ln(EP_{it})$	−0.0945***	0.0129	−0.0564**
	(0.0115)	(0.0326)	(0.0287)
SupWald Statistic		114.07***	

***Significantly different from zero at the 1% level, ** significantly different from zero at the 5% level, * significantly different from zero at the 10% level. This table provides estimations of the panel linear and threshold regression model using the GMM method. Heteroskedasticity-robust standard errors are provided in brackets. The period spans from 1996 to 2017. The estimations include all the control variables, but not reported to preserve space, and the detailed results are provided in Table 11 in Appendix 4

lines, when countries from ECA geographical cluster are excluded from the sample, renewable energy consumption also reduces energy intensity in the high regime for countries that have a strong institutional quality. Institutional quality has been found to increase renewable energy consumption (Chen et al. 2021; Uzar 2020), and renewable energy consumption reduces energy intensity relatively more if they have higher renewable energy deployments (Yu et al. 2022). Therefore, renewable energy consumption in countries with stronger institutional quality reduces energy intensity significantly.

5 Conclusions and Policy Recommendations

The existing literature examined the role of green technology in explaining energy efficiency (Wurlod and Noailly 2018; Sun et al. 2019; Paramati et al. 2022). However, the existing literature has overlooked the role of institutional quality in the relationship between green technologies and energy efficiency. This paper used threshold regression models to examine the nonlinear relationship between green technologies and energy intensity by using a panel data set from 72 countries between 1996 and 2017. The findings highlight that environment-related technologies reduce energy intensity if and only if countries surpass a certain threshold of institutional quality. In other words, green technologies reduce energy intensity in countries with stronger institutions, but green technologies do not affect energy intensity significantly in countries with weaker institutions. This study also carried out a set of robustness analyses. Firstly, different proxies for institutional quality are used and the main finding is robust to the use of alternative institutional quality proxies, suggesting that green technologies reduce energy intensity if and only if countries have stronger institutions above a given threshold. Furthermore, analysis is carried out by excluding different geographical clusters from the country sample, and the main findings hold for most of the cases. Beyond the relationship between green technologies and energy intensity, the role of different factors in explaining energy intensity is explored. The findings highlight that energy intensity is relatively higher in countries with higher income per capita and CO_2 emissions and lower renewable energy consumption.

The findings of this paper have various policy implications. Firstly, to promote and increase the effectiveness of green patents in reducing energy intensity, governments should improve their institutional quality, such as the rule of law, control of corruption, government effectiveness and regulatory quality. It has been found that institutional quality increases green innovation (Clò et al. 2020; D'Ingiullo and Evangelista 2020; Hussen and Çokgezen 2021; Wu et al. 2015), renewable energy deployment (Uzar 2020; Rahman and Sultana 2022; Pinar 2024) and environmental quality (Danish and Wang 2019; Khan et al. 2023). The findings of this paper also highlight that institutional quality improves the effectiveness of green technologies in reducing energy intensity. To improve their institutional quality, governments could promote policies that increase their trade openness, foreign direct investment, human capital and tax revenues because these factors are found to improve institutional quality (Alonso et al. 2020; Grabowski and Self 2021). Secondly, countries should promote policies that aim to increase renewable energy deployment levels because renewable energy consumption reduces energy intensity. For instance, to increase renewable energy deployment, policymakers could develop decentralized renewable energy systems and overcome technical difficulties in renewable energy systems, such as reduction in load fluctuation in renewable electricity production (Abdmouleh et al. 2015). Furthermore, governments could promote feed-in tariffs and auction scheme instruments to increase renewable energy deployment (Bersalli et al. 2020). Thirdly, while environmental patents are not a significant factor in reducing energy intensity in institutionally weak countries, these countries could promote market-based environmental policies (e.g., feed-in tariffs to promote renewable energy, fossil fuel taxes and emission certification) to attract foreign cleaner technology to their countries (Verdolini and Bosetti 2017) and to increase energy efficiency investments by firms (García-Quevedo and Jové-Llopis 2021).

This study has various limitations and potential future research venues. Firstly, due to the availability of data, this paper examined the effect of green technology on energy intensity depending on the institutional quality of countries by using panel data from 72 countries between 1996 and 2017. Therefore, a future study could redo the analyses of this study by increasing the country coverage and covering recent years. Secondly, the existing study explores the effects of green technologies on energy intensity depending on the institutional quality levels of countries. However, a future study could investigate the role of green technologies on renewable energy consumption and environmental quality depending on the institutional quality levels. Finally, the analyses of this paper are at the macro (country) level, but a future study could explore the role of institutional quality in firms' decisions to innovate and integrate green technologies in their production and how these technologies affect firm performance.

6 Data, Materials and/or Code availability

The data set used in this article is publicly available, and the codes of the empirical analysis are available upon request from the authors.

7 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.

Ethics approval: No ethical clearance required.

Appendix 1. List of countries.

See Table 7.

Table 7 List of countries

Australia	Finland	Kenya	Romania
Austria	France	Korea, Rep	Russia
Belarus	Georgia	Latvia	Saudi Arabia
Belgium	Germany	Lithuania	Singapore
Brazil	Greece	Malaysia	Slovakia
Bulgaria	Guatemala	Mexico	Slovenia
Chile	Hungary	Mongolia	South Africa
China	Iceland	Morocco	Spain
Colombia	India	Netherlands	Sri Lanka
Costa Rica	Indonesia	New Zealand	Sweden
Croatia	Iran	Nigeria	Switzerland
Cyprus	Ireland	Norway	Thailand
Czechia	Israel	Pakistan	Tunisia
Denmark	Italy	Panama	Türkiye
Ecuador	Jamaica	Peru	Ukraine
Egypt	Japan	Philippines	United Kingdom
El Salvador	Jordan	Poland	United States
Estonia	Kazakhstan	Portugal	Uruguay

Appendix 2. Measurement and definition of the variables.

See Table 8.

Table 8 Measurement and definition of the variables

Variable	Measurement/Definition
Energy intensity (EI)	Total energy consumption is obtained from the U.S. Energy Information Administration (2022), which is divided by the gross domestic product (in constant 2015 US dollars): total kilowatt energy consumption per 2015 US$ of GDP
Environmental patent (ep)	Total number of environment-related technology patents filed in European, Japanese and US patent offices (OECD 2022)
Rule of law (RoL)	Rule of Law captures perceptions of the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police, and the courts, as well as the likelihood of crime and violence. The proxy ranges between −2.5 and +2.5 and a higher score represents a better rule of law
Control of corruption (CC)	Control of Corruption captures perceptions of the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as "capture" of the state by elites and private interests. The proxy ranges between −2.5 and +2.5 and a higher score represents better control of corruption
Government effectiveness (GE)	Government Effectiveness captures perceptions of the quality of public services, the quality of the civil service and the degree of its independence from political pressures, the quality of policy formulation and implementation, and the credibility of the government's commitment to such policies. The proxy ranges between -2.5 and +2.5 and a higher score represents more effective government
Regulatory quality (RQ)	Regulatory Quality captures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development. The proxy ranges between -2.5 and +2.5 and a higher score represents better regulatory quality
CO_2 emissions (CO_2)	CO_2 emissions are measured as a kg per 2015 US$ of GDP
Trade openness (TRADE)	Trade openness is obtained as the sum of the imports and exports as a percentage of GDP
Population density (POP)	Population density is measured as the number of people per square kilometer of land area
Renewable energy consumption (REC)	Renewable energy consumption is measured as the renewable energy consumption as a percentage of total final energy consumption
GDP per capita (GDP)	GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2015 U.S. dollars

Table 8 (continued)

Variable	Measurement/Definition
Industry value-added (IndValue)	Industry corresponds to ISIC divisions 05–43 and includes manufacturing (ISIC divisions 10–33). It comprises value added in mining, manufacturing (also reported as a separate subgroup), construction, electricity, water, and gas. Value added is the net output of a sector after adding up all outputs and subtracting intermediate inputs. The industrial value-added share is measured as the share of value-added by the industry as a percentage of GDP
Oil prices (Oil)	The spot price of Brent crude oil is obtained from the Statistical Review of World Energy of British Petroleum (2022), which is deflated with the consumer price index (CPI) from World Development Indicators from the World Bank (2022a)

Appendix 3. RoL scores and regime classifications of countries in 1996 and 2017.

See Table 9.

Table 9 RoL scores and regime classifications of countries in 1996 and 2017

Country	RoL in 1996	Regime in 1996	RoL in 2017	Regime in 2017
Australia	1.7134	High	1.6865	High
Austria	1.8082	High	1.8424	High
Belarus	−0.7990	Low	−0.8187	Low
Belgium	1.3669	High	1.3585	High
Brazil	−0.2235	Low	−0.2469	Low
Bulgaria	−0.3450	Low	−0.0883	High
Chile	1.1137	High	1.1492	High
China	−0.5456	Low	−0.2667	Low
Colombia	−0.7518	Low	−0.3630	Low
Costa Rica	0.6182	High	0.4693	High
Croatia	−0.6342	Low	0.3588	High
Cyprus	0.8573	High	0.8882	High
Czech Republic	0.9153	High	1.1242	High
Denmark	1.8208	High	1.8473	High
Ecuador	−0.4497	Low	−0.8108	Low
Egypt, Arab Rep	0.0013	High	−0.5438	Low
El Salvador	−0.8702	Low	−0.8106	Low
Estonia	0.5744	High	1.2858	High
Finland	1.9079	High	2.0694	High
France	1.4837	High	1.4364	High
Georgia	−1.2563	Low	0.3208	High
Germany	1.6095	High	1.6150	High
Greece	1.0535	High	0.0750	High
Guatemala	−1.1265	Low	−1.0579	Low
Hungary	0.9105	High	0.5663	High
Iceland	1.6015	High	1.6111	High
India	0.3135	High	−0.0012	High
Indonesia	−0.4899	Low	−0.3497	Low
Iran, Islamic Rep	−0.9403	Low	−0.6824	Low
Ireland	1.5010	High	1.4188	High
Israel	1.2789	High	1.0249	High
Italy	1.0564	High	0.3488	High
Jamaica	−0.3350	Low	−0.1615	High
Japan	1.3478	High	1.5706	High
Jordan	0.2769	High	0.2986	High
Kazakhstan	−1.1865	Low	−0.4141	Low
Kenya	−1.0216	Low	−0.4157	Low
Korea, Rep	0.7987	High	1.1672	High
Latvia	0.1337	High	0.9347	High
Lithuania	0.4499	High	0.9961	High
Malaysia	0.5211	High	0.4977	High
Mexico	−0.7266	Low	−0.5586	Low
Mongolia	0.2014	High	−0.3065	Low
Morocco	0.2212	High	−0.1665	High

Table 9 (continued)

Country	RoL in 1996	Regime in 1996	RoL in 2017	Regime in 2017
Netherlands	1.6953	High	1.8013	High
New Zealand	1.8584	High	1.9279	High
Nigeria	−1.2897	Low	−0.8708	Low
Norway	1.9233	High	2.0255	High
Pakistan	−0.6253	Low	−0.7242	Low
Panama	−0.1670	High	0.0318	High
Peru	−0.6967	Low	−0.5033	Low
Philippines	0.0745	High	−0.4177	Low
Poland	0.7675	High	0.4414	High
Portugal	1.2863	High	1.1386	High
Romania	−0.0219	High	0.4195	High
Russian Federation	−0.7942	Low	−0.7937	Low
Saudi Arabia	0.1146	High	0.1009	High
Singapore	1.2393	High	1.8277	High
Slovak Republic	0.1596	High	0.5430	High
Slovenia	1.0687	High	1.0270	High
South Africa	0.0879	High	−0.0425	High
Spain	1.4351	High	1.0594	High
Sri Lanka	0.1613	High	0.0485	High
Sweden	1.7959	High	1.8619	High
Switzerland	1.9316	High	1.9329	High
Thailand	0.5396	High	0.0373	High
Tunisia	−0.3034	Low	0.0587	High
Turkey	−0.1388	High	−0.2548	Low
Ukraine	−0.8235	Low	−0.7120	Low
United Kingdom	1.6287	High	1.6862	High
United States	1.5002	High	1.6493	High
Uruguay	0.5618	High	0.5833	High

Appendix 4. Detailed robustness results.

See Table 10, 11.

Table 10 Robustness analysis with different institutional quality proxies

Model	Linear	Threshold		Linear	Threshold		Linear	Threshold	
Institutional variable	CC			GE			RQ		
Threshold		1.3037***			1.3668***			−0.0763***	
		Low	High		Low	High		Low	High
$\ln(EP_{it})$	−0.0923***	0.0224	−0.2979***	−0.0921***	0.0122	−0.2752***	−0.0907***	−0.0134	−0.1366***
	(0.0123)	(0.0200)	(0.0547)	(0.0123)	(0.0214)	(0.0541)	(0.0122)	(0.0314)	(0.0185)
ΔINS_{it}	0.3115	−0.0032	−0.6604	0.1693	0.0597	−0.7441	0.1317	−0.0399	0.3273
	(0.2193)	(0.2286)	(0.9357)	(0.2065)	(0.2040)	(0.7417)	(0.2433)	(0.3684)	(0.2581)
$\ln\left(CO_{2_{it}}\right)$	0.9136***	0.6964***	1.7071***	0.9153***	0.7323***	1.5150***	0.9189***	0.9777***	0.7660***
	(0.0324)	(0.0668)	(0.2870)	(0.0326)	(0.0836)	(0.2975)	(0.0322)	(0.1160)	(0.0589)
$\Delta \ln\left(Trade_{it}\right)$	−0.2484	0.1606	−0.2098	−0.2403	0.0176	−0.0321	−0.2391	−0.1067	−0.0833
	(0.1859)	(0.2007)	(1.1252)	(0.1862)	(0.2135)	(1.1764)	(0.1864)	(0.2848)	(0.2044)
$\ln(REC_{it})$	−0.0338	−0.0901	0.1842	−0.0311	−0.0704	0.1909	−0.0285	−0.0988	−0.0710
	(0.0264)	(0.0427)	(0.1668)	(0.0264)	(0.0546)	(0.1766)	(0.0261)	(0.0508)	(0.0238)
$\ln(GDP_{it})$	0.2189***	0.1639***	0.5440***	0.2207***	0.1535***	0.4748***	0.2187***	0.1136***	0.2446***
	(0.0134)	(0.0148)	(0.0779)	(0.0134)	(0.0153)	(0.0871)	(0.0136)	(0.0229)	(0.0190)
$\ln(POPDEN_{it})$	−0.0360**	−0.0115	−0.0847	−0.0375**	0.0188	−0.1032	−0.0369**	0.1755***	−0.0605***
	(0.0175)	(0.0313)	(0.0986)	(0.0175)	(0.0322)	(0.1046)	(0.0176)	(0.0398)	(0.0222)
$\Delta\ln\left(IndValue_{it}\right)$	0.6171	−0.3393	0.1504	0.5903	0.0778	0.3550	0.5380	0.2845	0.4080
	(0.4068)	(0.4337)	(1.3431)	(0.4073)	(0.4769)	(1.3889)	(0.4115)	(0.5323)	(0.4160)
$\ln(Oil_{it})$	0.0091	0.0720***	−0.3610***	0.0049	0.0617**	−0.2721**	0.0073	0.0400	−0.0216
	(0.0214)	(0.0259)	(0.1219)	(0.0215)	(0.0268)	(0.1252)	(0.0215)	(0.0428)	(0.0280)
SupWald *P* value		0.0000			0.0000			0.0000	
SupWald Statistic		86.01			71.14			48.78	
Observations	1440	1068	372	1440	1078	362	1440	359	1081

***Significantly different from zero at the 1% level, ** significantly different from zero at the 5% level, * significantly different from zero at the 10% level. This table provides estimations of the panel linear and threshold regression model using the GMM method. Heteroskedasticity-robust standard errors are provided in brackets. The period spans from 1996 to 2017

Table 11 Robustness analysis with different geographical clusters

Model	Linear	Threshold		Linear	Threshold		Linear	Threshold	
Region excluded	East Asia & Pacific			Europe & Central Asia			Latin America & Caribbean		
Threshold		0.8837***			−0.5787***			1.1963***	
		Low	High		Low	High		Low	High
$\ln(EP_{it})$	−0.0869***	−0.0406	−0.0761	−0.0700***	−0.0659	−0.0589***	−0.0598***	0.0021	−0.1403***
	(0.0160)	(0.0634)	(0.0554)	(0.0053)	(0.0575)	(0.0080)	(0.0135)	(0.0283)	(0.0374)
ΔINS_{it}	0.1471	0.6451*	0.4946	0.0557	−0.0168	0.1480	0.0346	0.0614	0.3728
	(0.2352)	(0.3851)	(0.7588)	(0.1185)	(0.3185)	(0.1763)	(0.2334)	(0.3184)	(0.7919)
$\ln(CO_{2_{it}})$	0.9554***	1.1726***	−0.0719	0.8014***	1.1705***	0.7569***	0.9626***	0.8640***	0.2628
	(0.0359)	(0.0716)	(0.1463)	(0.0196)	(0.1253)	(0.0247)	(0.0331)	(0.0928)	(0.1643)
$\Delta \ln(Trade_{it})$	−0.2084	0.0030	0.1636	−0.0111	0.0783	−0.0648	−0.0938	−0.1350	.0806
	(0.1962)	(0.3052)	(0.9237)	(0.1082)	(0.2473)	(0.1497)	(0.1889)	(0.2421)	(1.1105)
$\ln(REC_{it})$	0.0092	0.0610	−0.0120	−0.0340***	0.1352*	−0.0614***	−0.0390	−0.1285**	−0.4539***
	(0.0315)	(0.0423)	(0.1071)	(0.0084)	(0.0693)	(0.0123)	(0.0246)	(0.0620)	(0.1293)
$\ln(GDP_{it})$	0.2374***	0.3682	0.0019	0.1755***	0.2170***	0.1741***	0.2184***	0.1543***	0.4448***
	(0.0171)	(0.0387)	(0.0779)	(0.0079)	(0.0360)	(0.0095)	(0.0136)	(0.0192)	(0.0940)
$\ln(POPDEN_{it})$	−0.0989***	−0.3776*	0.2015*	0.0531***	−0.1599**	0.0651***	−0.0285	0.0987**	−0.3280***
	(0.0240)	(0.0660)	(0.1074)	(0.0076)	(0.0665)	(0.0098)	(0.0193)	(0.0483)	(0.0852)
$\Delta\ln(IndValue_{it})$	0.6628	0.2249	−0.2299	0.2816	−0.0128	0.3460	0.1560	0.1048	0.7868
	(0.4542)	(0.6037)	(1.4933)	(0.2043)	(0.3758)	(0.3493)	(0.4547)	(0.5273)	(1.5688)
$\ln(Oil_{it})$	0.0033	0.0361	−0.1846	−0.0198	0.0844	−0.0319	−0.0065	0.0219	−0.2041
	(0.0216)	(0.0452)	(0.1207)	(0.0150)	(0.0522)	(0.0201)	(0.0213)	(0.0289)	(0.1336)
SupWald *P* value		0.0000			0.0000			0.0000	
SupWald statistic		158.60 75.1612			64.91			151.73	
Observations	1220	784	436	740	166	574	1200	818	382

Table 11 (continued)

Model	Linear	Threshold		Linear	Threshold		Linear	Threshold		Linear	Threshold	
Region excluded	Middle East & North Africa			North America			South Asia			Sub− Saharan Africa		
Threshold		1.0294***			−0.1937***			−0.2201***			0.4226***	
		Low	High		Low	High		Low	High		Low	High
$\ln(EP_{it})$	−0.0557***	−0.0180	−0.0760**	−0.0942***	0.1096	−0.0960***	−0.0953***	0.1141	−0.1271***	−0.0945***	0.0129	−0.0564**
	(0.0103)	(0.0247)	(0.0328)	(0.0128)	(0.0788)	(0.0365)	(0.0111)	(0.0736)	(0.0273)	(0.0115)	(0.0326)	(0.0287)
ΔINS_{it}	−0.4399**	0.1402	−0.1337	−0.0660	−0.0885	0.0072	−0.0872	0.1879	−0.0316	−0.0045	−0.1824	0.2142
	(0.1847)	(0.2722)	(0.5557)	(0.2207)	(0.5496)	(0.5094)	(0.1952)	(0.5676)	(0.4768)	(0.2092)	(0.3408)	(0.4929)
$\ln(CO_{2_{it}})$	1.0265***	1.2615***	−0.0336	0.9137***	1.1461***	0.7898***	0.8527***	1.3350***	0.6718***	0.9039***	0.7873***	0.8044***
	(0.0256)	(0.0771)	(0.1026)	(0.0326)	(0.1989)	(0.0970)	(0.0318)	(0.1974)	(0.0865)	(0.0301)	(0.0851)	(0.1149)
$\Delta \ln(Trade_{it})$	−0.1209	0.2156	−0.5611	−0.2457	−0.3738	−0.0532	−0.2032	−0.1295	0.0537	−0.1609	−0.1265	0.2434
	(0.1599)	(0.2443)	(0.6200)	(0.1865)	(0.4475)	(0.3445)	(0.1674)	(0.4719)	(0.3043)	(0.1821)	(0.3038)	(0.4126)
$\ln(REC_{it})$	0.1309***	0.2647***	0.1202	−0.0318	−0.0699	0.0158	−0.0423*	0.0365	−0.0407	−0.0143	−0.1463***	−0.1648**
	(0.0229)	(0.0570)	(0.0874)	(0.0263)	(0.1005)	(0.0363)	(0.0239)	(0.0987)	(0.0337)	(0.0243)	(0.0455)	(0.0769)
$\ln(GDP_{it})$	0.1657***	0.1873***	−0.0288	0.2187***	0.0789**	0.3081***	0.2143***	0.0825*	0.2791***	0.1956***	0.1281***	0.4207***
	(0.0098)	(0.0193)	(0.0609)	(0.0135)	(0.0387)	(0.0358)	(0.0123)	(0.0446)	(0.0320)	(0.0118)	(0.0221)	(0.0539)
$\ln(POPDEN_{it})$	−0.0279**	−0.1280***	0.1058*	−0.0362**	0.2340***	−0.3006***	−0.0317**	0.2227***	−0.2326***	0.0045	0.1293***	−0.3600***
	(0.0138)	(0.0343)	(0.0633)	(0.0179)	(0.0670)	(0.0592)	(0.0151)	(0.0647)	(0.0473)	(0.0148)	(0.0358)	(0.0678)
$\Delta\ln(IndValue_{it})$	0.0361	−0.3076	0.8121	0.5716	0.7585	0.2139	0.3804	0.1316	0.0131	0.3258	0.1969	−0.4838
	(0.3394)	(0.4883)	(1.1278)	(0.4063)	(0.7473)	(0.8410)	(0.3527)	(0.7998)	(0.7609)	(0.4164)	(0.6424)	(0.8068)
$\ln(Oil_{it})$	0.0241	0.0317	−0.0403	0.0092	0.0455	0.0254	0.0082	−0.0085	0.0315	0.0084	0.0536	−0.0907
	(0.0205)	(0.0368)	(0.1024)	(0.0218)	(0.0698)	(0.0522)	(0.0206)	(0.0809)	(0.0440)	(0.0210)	(0.0395)	(0.0563)
SupWald *P* value		0.0000			0.0000			0.0000			0.0000	
SupWald Statistic		376.12			89.24			77.42			114.07	
Observations	1300	852	448	1420	426	994	1380	388	992	1380	665	715

***Significantly different from zero at the 1% level, ** significantly different from zero at the 5% level, * significantly different from zero at the 10 % level. This table provides estimations of the panel linear and threshold regression model using the GMM method. Heteroskedasticity-robust standard errors are provided in brackets. The period spans from 1996 to 2017. The threshold variable used is rule of law (RoL)

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