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Low-Carbon Energy Risk and Renewable Energy Development: Insigths from Method of Moments Quantile Regression

Feruz Kalandarov[1]*, Samariddin Makhmudov[2,3,4], Dilshad Ibadullaev[5], Murodjon Matniyozov[1], Farangis Nasretdinova[1], Khamid Sabirov[6], Nu'monkhon Bahodirov[7]

[1]Faculty of Socio-economic Sciences, Urgench State University, Urgench, 220100, Uzbekistan, [2]Department of Economics, Mamun University, Khiva, Uzbekistan, [3]Alfraganus University, Tashkent, Uzbekistan, [4]Termez University of Economics and Service, Termez, Uzbekistan, [5]Department of Economics, Urgench State University, Urgench, 220100, Uzbekistan, [6]Department of Economics, Urgench Ranch University of Technology, Urgench 220100, Uzbekistan, [7]Fergana Polytechnic Institute, Faculty of Mechanics and Machine Engineering, Fergana, Uzbekistan. *Email: feruzkalandarov@gmail.com

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ABSTRACT

The current work investigates the effect of low-carbon energy risk on renewable energy development for the first time in the literature. The annual data used in the work contains the sample of 137 countries. For the empirical estimations, Method of Moments Quantile Regression (MMQR) is applied, considering the heteroscedastic nature of the data and energy markets as well. The results provide valuable findings that a decrease in low-carbon energy risk leads to a rise in renewable energy across all the quantiles. Moreover, the results remain robust when the sample is divided into developed and developing countries, further validating theoretical linkage. Policymakers should consider the components of low-carbon energy risk in the decision-making process to enhance renewable energy development.

Keywords: Low-Carbon Energy Risk, Renewable Energy, MMQR
JEL Classifications: Q42, Q01, C31

1. INTRODUCTION

One of the key elements of the sustainable development goals aimed at combating climate change is the production of renewable energy (Wang et al., 2022). Renewable energy, characterized by its sustainable and non-polluting features, is vital in enhancing cleaner manufacturing processes and achieving environmental sustainability (Lee et al., 2022; Fang et al., 2023). In response to the increasing global emphasis on climate change, environmental issues, and the soaring costs of oil, governments worldwide have been driven to implement new regulations encouraging the wider adoption of renewable resources (Razmjoo et al., 2021; Barkhordar et al., 2022). Moreover, some countries are prioritizing renewable energy development to facilitate the shift towards low-carbon electricity generation (Wei et al., 2024). The International Energy Agency (IEA) (2023) reports that global renewable energy generation rose from 4208.62 terawatt-hours (TWh) in 2010 to 8598.65 TWh in 2022, with its share of overall global electricity production growing from 19.5% to 29.6%. However, this rapid growth has led to a new challenge of decreased output from wind and solar sources, hindering the sustainable advancement of renewable energy (Xia et al., 2020). Additionally, the growth in renewable energy consumption is significantly bolstered by the Paris Agreement established in 2016 (Yahya and Lee, 2023), and a 2021 report from the IEA forecasts that renewable energy sources will supply around 90% of the world's energy requirements by 2050 (IEA, 2021). This suggests that the adoption of renewable energy has become a vital tool in the effort to reduce world carbon emissions (Guo et al., 2023).

Tian et al. (2022) states that renewable energy sources including wind, solar, and bioenergy are more prioritized in the energy transition towards low-carbon emissions than conventional fossil fuels. The goal of this shift is to reduce CO_2 emissions without obstructing expansion of the economy (Wang et al., 2024). Energy transition is therefore a key tactic for developing countries for addressing global warming. As a result of factors like depleting storage of fossil fuels, increased demand for energy, public obligations to cut emissions, and deteriorating environmental quality, governments are actively looking for carbon neutral as well sustainable energy sources to substitute their current energy supply (Kamali Saraji et al., 2023). In a similar vein for the purpose of to avoid the catastrophic consequences of climate change, the IPCC (2018) suggests nations to look for proxy to traditional fuels and switch at minimum 80% of their energy mix to low-carbon sources by 2050. Nevertheless, institutional, economic, political, social, environmental, and technological obstacles make the low-carbon energy transition very difficult for governments, even with increased global awareness (Kamali Saraji and Streimikiene, 2023). Although there are significant efforts being made by governments, corporations, academic institutions, and communities to tackle climate change, the main indicator of success is the decrease in the amount of greenhouse gases (GHG) in the world atmosphere (NOAA, 2021). In addition to being a pressing necessity to address environmental concerns on a global scale, the zero-carbon transition is also a vital step towards achieving sustainable development for everyone on earth (Jiang et al., 2024).

The public's focus has switched to energy transitions due to increased worries about global warming (IEA, 2022). The shift to low-carbon energy, that advocates for the rising utilization of renewable energy sources (such as solar, wind, hydro, and biofuel) to substitute traditional fossil fuels, has also received a lot of attention from the academic community (Tian et al., 2022). Previous studies (Jiang et al., 2024) considers renewable energy more effective among other choices, because infrastructure development, green technology innovation, and environmental laws all have a direct impact on energy efficiency. According to Shahzad et al., (2024), clean energy utilization is greatly increased in OECD countries by environmental policies and GDP, the use of sustainable energy is also little impacted by economic globalization. It is recommended that governments in every country promote the implementation of clean energy in order to lower greenhouse gas emissions. Meanwhile, Shahbaz et al. (2020) verifies that there is a long-term correlation between economic growth and the use of renewable energy. It is also suggested that governments, energy organizers, international cooperation agencies, and related organizations should work together to boost investments in renewable energy for low-carbon growth in the majority of economies. Through the lens of green finance, other academics have examined the low-carbon energy transition and come to the conclusion that strategies like improving the economic system, increasing energy supply capability, fostering environmental consciousness, and developing energy replacement technologies are crucial for advancing low-carbon energy transitions (Wang et al., 2024). But at present, there is little empirical literature on the impact of renewable energy on the low-carbon energy transition, additionally, there is currently no complete paradigm that explains the impact mechanism underlying these two energy transitions.

Current literature does not provide any studies that explore an effect of low-carbon energy risk on renewable energy even though they exercise the impact of components of low-carbon energy risk on renewable energy. Therefore, to fill in this gap of the literature, this work examines the relation from low-carbon energy risk on renewable energy. As market volatility imposes an impact on energy sector as well, MMQR is employed to assess the association taking heterogeneity into account. To robust the results and further validate the theoretical linkage, the panel data sample is divided into the groups of countries by the economic development stage.

The rest of the manuscript is shaped as the following: the second section represents literature review; the third section provides the definition for data and methodology; the fourth section contains the empirical findings, and the fifth section concludes.

2. LITERATURE REVIEW

2.1. Theoretical background: Impact of low carbon energy risk on renewable energy

In academic literature, impact of low carbon energy risk on renewable energy has been discussed restrictively among scholars. For the reason that low carbon energy risk is an emerging variable. These studies frequently reference terms such as "risk," "climate risk," "low-carbon transition risk," and "energy transition risk" (Sun et al., 2024). Low-carbon energy risk pertains to the potential for negative consequences arising during the transition to a low-carbon economy. These risks can be categorized as technological, economic, environmental, social, political, and institutional[1]. These composites of low-carbon energy risk variables might serve to relate its link to renewable energy since there are no any other studies applying this novel variable itself.

Number of studies analyse the impact of political risk on renewable energy. More specifically, Jiang et al. (2024) studied the relationship between foreign renewable energy investment and political risk, highlighting the mediating role of vulnerability. They find that the impact of political risk on foreign renewable energy investment is various based on the legal and political environments of different countries. Yuen and Yuen (2024) examined how geopolitical tensions, along with economic and political uncertainties, influence government decision-making in allocating resources for renewable energy research and development. They reveal that governments are prioritizing research in renewable energy to tackle geopolitical and economic challenges. In addition, according to the investigation by Zhao et al. (2023) geopolitical risks, rising CO_2 emissions, and declining natural resource revenues negatively impact renewable energy demand and climate policies, while higher per capita income and economic globalization positively affect renewable energy adoption.

Another strand of literature addresses to explore the effect of technological innovation on renewable energy. More precisely,

1. Definitive: The data sources are LSEG Sovereign Sustainability Solutions.

Behera et al. (2024) explore the effect of technological development on renewable energy across ten European Union countries, and their findings reveal that the political and financial barriers effect negatively on renewable energy while green technological innovation could help minimize the negative impacts of carbon emissions. Zhang et al. (2025) explore the relationship between key factors such as renewable energy technology innovation, climate risk, and carbon emissions. Accordingly, renewable energy technologies play a crucial role in lowering carbon emissions. Solarin et al. (2022) explored that the technological innovations in renewable energy will greatly enhance energy production across all countries. Nations with lower energy production, such as India and South Africa, are expected to benefit the most from these innovations, as their current energy output is lower compared to others.

The impact of economic issues on the development of renewable energy is the subject of another body of literature. In other words, Eren et al. (2019) look into how India's use of renewable energy is affected by economic growth and financial development. Therefore, technological developments in this area have the potential to create jobs in the renewable energy market by achieving economies of scale, lowering costs, and luring investment. Using a panel dataset, Tiwari et al. (2022) investigate the effect of equity market development on the use of renewable energy. Their findings suggest that Asia's use of renewable energy is not much impacted by stock markets. Some writers research how trade openness, economic expansion, and technical advancements affect renewable energy. Using the autoregressive distributed lag (ARDL) method, Alam and Murad (2020) investigate the short- and long-term effects of economic growth, trade openness, and technological advancement on the use of renewable energy in Organization for Economic Co-operation and Development (OECD) countries. The empirical research demonstrates that the usage of renewable energy is greatly encouraged by economic growth.

2.2. The Impact of Control Variables (Economic Development, Environmental Quality and Institutional Quality) on Renewable Energy

The relation between renewable energy and low-carbon energy risk is affected by additional control variables. More specifically, economic development, environmental quality and institutional quality serve as mediators impacting on the association between renewable energy and low-carbon energy risk. The justifications based on literature review are provided.

The connection between economic development and renewable energy usage has drawn the attention of environmental economists and policymakers from all around the world in the current energy literature (Shahbaz et al., 2020). It is believed that energy has a major role in economic expansion (Sadorsky, 2009). The work of Rahaman et al. (2023) states that the issue of economic development is so important, researchers, world leaders, and all governments are always trying to find solutions. Hence, using renewable energy can be promoted in order to preserve the planet's environment and long-term economic viability. Numerous studies in the context of current energy economics research have examined the causal relationship between GDP growth in the medium and long term and energy consumption from aggregate sources (including renewable and nonrenewable), with a focus on energy consumption variables and electricity consumption (Shahbaz and Lean, 2012; Shahbaz et al., 2013; Polemis and Dagoumas, 2013; Hamdi et al., 2014; Aslan et al., 2014; Shahbaz et al., 2017; Alam et al., 2017). Furthermore, many studies such as Apergis and Payne (2011), Pao et al. (2014), and Chang et al. (2015) explain the connection between economic growth and renewable energy consumption. Another study by Alam and Murad (2020) investigates both the short and the long-term impacts of trade openness, technological advancements and economic growth on the usage of renewable energy in countries that are members of the Organization for economic Co-operation and Development (OECD). The estimated findings show that long-term usage of renewable energy in OECD countries is strongly influenced by economic development, trade openness and technological advancement. In addition, Shahbaz et al. (2021) examines how 34 upper middle-income developing nations' usage of renewable energy was affected by financial development between 1994 and 2015. The results of the study indicate a long-term relationship between financial development and renewable energy use. Besides, the need for renewable energy rises in tandem with financial development. Similarly, Eren et al. (2019) elucidates that economic growth and financial development have a positive and statistically significant influence on the use of renewable energy in India.

The environmental, social, and governance (ESG) index applies to corporate behavior, which involves these three issues in the management and operation processes of organizations (Li et al., 2023). As environmental challenges get more attention, the idea of ESG has emerged as a key initiative to support environmentally friendly innovation (Wang and Chang, 2024). It has been more popular in recent years to investigate how environmental factors influence energy factors. In some studies, the impact of climate risk on energy variables (energy technology, energy innovation, and energy consumption) is examined as a substitute for environmental variables that are part of the ESG environmental score. In particular, Xie and Li (2024) examine how climate risk affects the development of energy-saving technologies and come to the conclusion that climate risk encourages the development of energy-saving technologies. Girgibo et al. (2024) analyze the climate change hazards to energy resources, and their findings indicate that renewable energy has negligible risks. Furthermore, the global energy sector's carbon risk is affected by sustainable climate governance, and it claims that improved climate governance procedures lead to lower carbon emissions from energy firms (Liêu et al., 2024). The influence of climate change-related investments in clean energy on reducing the threats to energy security is estimated by Iyke (2024), and it is suggested that the risk to energy security is increased by climate change. Another group of academics has conducted extensive research on ESG and its dimension; for instance, Lu and Li (2024) delve into the effect of ESG rating adaptation on low carbon finance in renewable energy firms. It is stated that the dynamic shift of ESG scoring will cause an influence on the environmental behavior of the firm. According to their research, it is exposed that an increasing ESG rating indicates ongoing environmental performance optimization, and also by raising the environmental responsibility of company management, it can consistently encourage low carbon investment in renewable energy enterprises. Moreover, Zhan et al. (2025) test the impact of ESG scores on the green innovation of Chinese listed companies from 2007 to 2022. The research findings show that the company's green innovation is significantly impacted by ESG ratings. It is important to note that only environmental performance has a great impact on green innovation, while S and G scores demonstrate the opposite. There exist numerous research studies that empirically test the impact of ESG on green innovation and low carbon investment in renewable energy companies; however, studies regarding the impact of environmental performance on renewable energy sources are insufficient. Therefore, this study is one of the pioneers to examine the influence of environmental performance on clean energy resources.

In scientific works, the effect of institutional quality on renewable energy is an emerging topic among authors. Only a limited number of studies have identified economic and institutional factors as significant influences on the development of renewable energy sources. To exemplify, Rahman and Sultana (2022) study impacts of institutional quality, economic growth, and exports on renewable energy approaching panel PMG-ARDL for several emerging countries between 2002 and 2019. The finding provides vital guidance for emerging countries to enhance their institutions, improve effectiveness, and reduce corruption. This will enable them to sustain economic growth while better developing and utilizing renewable energy resources. Some researchers investigate the empirical analysis of the relationship between financial development, renewable energy consumption, and institutional quality within the European Union. According to Vatamanu and Zugravu (2023), it is highlighted that there is a lack of research which the core ideas is the role of institutional quality in promoting renewable energy consumption. Furthermore, the findings provide a clearer understanding of the implications of financial development and institutional quality on renewable energy consumption. In a separate study, designing policies for the advancement of renewable energy through governmental support was explored using a novel system dynamics (SD) modeling approach. More specifically, Hashemizadeh (2024) conducted comprehensive analysis of different aspects, including the economy and investment, the environment, policies, and technical details to determine which factor is significant. The results showed that government support can significantly speed up the development of renewable energy projects by allowing the import of equipment. Tax exemptions are the best way to boost the processes, production, and sales of renewable energy projects. These findings highlight how important government action is for developing renewable energy, which is crucial for meeting energy needs and reducing environmental impact. Moreover, government effectiveness can be proxied by economic policy uncertainty since it is associated with the government functioning. Shafiullah et al. (2021) in the context of USA, find negative and/or nonlinear impact of population and economic growth on renewable energy uptake while a stable policy environment is positively related to renewable energy consumption. Similarly, Yi et al. (2023) used the data from the top nine nations that use renewable energy from 2003 to 2020 is used to analyze how financial development and economic policy uncertainties affect the use of renewable energy while taking into account the role that economic globalization plays in the demand function for renewable energy. The findings imply that the use of renewable energy is significantly impacted directly by economic expansion, financial development, and globalization.

3. DATA AND METHODOLOGY

3.1. Data

The article employs an annual panel data of 137 countries stretching between 2000 and 2022 (with respect to availability of the data). The response variable, renewable energy (RENERGY), is deemed as the percentage of electricity generated from renewable sources relative to total electricity generation. It is obtained from Our World in Data website (https://ourworldindata.org/renewable-energy). The core explanatory variable is low carbon energy risk score (LCENRISK), measured as a score, and downloaded from Refinitiv[2]. The score of low carbon energy risk ranges from 0 to 100. Higher values of the score represent low risk, whereas lower values denote high risk.

Per capita GDP in US dollars—reflects economic development (ECDEV), ESG's environment pillar (ESG)—provided as an index that mirrors environmental quality[3], and finally, as a proxy for institutional quality (IQ)—the index of government effectiveness[4] are the control variables of the study. The data of per capita GDP and government effectiveness index are extracted from World Bank Open Data (https://data.worldbank.org). The ESG environment pillar as well as the energy risk data is acquired from Refinitiv.

Table 1 presents the descriptive statistics showing the number of observations, the variables under study, and the mean, minimum, maximum, skewness, and kurtosis values for the panel data consisting of 137 nations spanning the years 2000-2022. Based on these data, the outcome variable RENERGY has a mean value of 38.497, whereas the core explanatory variable LCENRISK has a mean value of 42.068. The mean values of the control variables ECDEV, ESG and IQ are 12869.2, 52.552 and 0.024 respectively. With respect to skewness, the distribution of RENERGY is somewhat positively skewed, LCENRISK is roughly symmetric, ECDEV is strongly right-skewed, while the data of ESG is slightly left-skewed and IQ is moderately right-skewed. Based on the kurtosis normality test, the variables' values are not normally distributed, indicating heterogeneity; RENERGY, LCENRISK, ESG and IQ exhibit platykurtic kurtosis, whereas ECDEV exhibit leptokurtic kurtosis.

The variables, LCENRISK, ECDEV and ESG are transformed into natural logarithm for data smoothing such as LOGLCENRISK, LOGECDEV and LOGESG. RENERGY and IQ cannot be used in logarithmic transformation since the former is given in percentage while the latter contains negative values.

2 Accessed by Prof. Massimiliano Caporin, Department of Statistical Sciences, University of Padova, Italy. email: massimiliano.caporin@unipd.it

3 The index ranges from 0 to 100, meaning high environmental performance for high value

4 The index ranges from approximately -2.5 to 2.5, meaning higher value for high institutional quality.

Table 1: Descriptive statistics

Variables	Observations	Mean	Minimum	Maximum	Skewness	Kurtosis
RENERGY	3151	38.497	0.037	100	0.601	2.021
LCENRISK	3151	42.068	0.01	100	0.036	1.627
ECDEV	3151	12869.2	110.461	133712	2.390	9.589
ESG	3151	52.552	0.19	100	−0.242	2.153
IQ	3151	0.024	−2.226	2.469	0.495	2.329

In the proceeding step, tests for heteroscedasticity are conducted to justify the use of the MMQR as the primary estimation technique. Establishing the presence of heteroscedasticity is essential, as MMQR is specifically designed to accommodate non-constant variance in the error terms across quantiles. To this end, two standard tests for heteroscedasticity are employed: White's test (White, 1980) and the Breusch–Pagan test (Breusch and Pagan, 1980). The results of both tests, presented in Table 2, confirm the presence of heteroscedasticity in the regression model, thereby supporting the application of the MMQR method in the empirical analysis.

3.2. Methodology

3.2.1. Baseline model

To empirically evaluate the influence of low-carbon energy risk (LCENR) on the development of renewable energy (RENERGY), the regression model is formulated as follows:

$$RENERGY_{it} = \alpha_0 + \alpha_1\, LOGLCENRISK_{it} + \alpha_2\, LOGECDEV_{it} + \alpha_3\, LOGESG_{it} + \alpha_4\, IQ_{it} + \varepsilon_{it} \quad (1)$$

With the following specification:

- $RENERGY_{it}$ represents the share of renewable energy in total electricity generation for country i at time t,
- α_0 is the intercept term,
- α_1, α_2, α_3 and α_4 are the elasticity coefficients corresponding to:
  - $LOGLCENRISK_{it}$: The natural logarithm of low-carbon energy transition risk
  - $LOGECDEV_{it}$: A natural logarithm of economic development (per capita GDP in US dollars)
  - $LOGESG_{it}$: A natural logarithm of ESG environmental score
  - and IQ_{it}: institutional quality
- ε_{it} denotes the error term,
- i indexes countries, and
- t represents the time dimension.

Equation (1) represents the specification of the Pooled Ordinary Least Squares (POLS) method, which relies on standard assumptions such as normally distributed error terms, homoscedasticity, and a focus on conditional mean estimates. However, in real-world settings, these assumptions are often violated due to economic disruptions stemming from events such as wars, pandemics, and financial crises. These shocks introduce volatility and structural breaks, leading to heteroscedasticity in the data. To address this issue and capture the full distributional dynamics of the dependent variable, the MMQR approach is employed, offering a more robust and flexible estimation framework under such conditions.

Table 2: White's test and Breusch–Pagan test for heteroscedasticity

Test name	Chi-square	P-value
White's test	806.28	0.000
Breusch–Pagan test	171.27	0.000

***P<0.01

Quantile approach is the most commonly used nowadays, because energy sectors are receptive and susceptible to global shocks and market volatility (Boubaker et al., 2023). More specifically, Ozkan et al. (2024) examines using the Wavelet Quantile-on-Quantile Regression (WQQR) technique to examine the relationship between green technologies and renewable energy research and development spending in order to promote environmental sustainability in Germany. Khan et al. (2024) explores the challenges among renewable energy, urbanization, and financial development in shaping environmental outcomes in South Asian nations to achieve carbon neutrality. To this end, they employ panel quantile regression. Following previous studies who examine the interrelationship between renewable energy and the proxies for low-carbon energy such as green technologies and carbon neutrality, this paper as well incorporates the results of MMQR approach to reveal the effect of low-carbon energy risk on renewable energy.

3.2.2. Method of Moments of Quantile Regression (MMQR)

Regarding the POLS model presented in Equation (1) is based on mean regression, it is sensitive to outliers and may not adequately capture the distributional heterogeneity of the dependent variable. To overcome these limitations, the present study adopts the MMQR, which offers a more robust framework for estimating the effects of explanatory variables—including $LOGLCENRISK_{it}$, $LOGECDEV_{it}$, $LOGESG_{it}$, IQ_{it} across different quantiles of the response variable, $RENERGY_{it}$. This method allows for a comprehensive analysis of how the impact of covariates may vary across the distribution of renewable energy generation. Accordingly, following the approach of Machado and Santos Silva (2019), the MMQR specification derived from Equation (1) can be expressed as follows:

$$RENERGY_{it} = \alpha_i + X_{it}^{'}\beta + (\delta_i + Z_{it}^{'}\gamma)U_{it} \quad (2)$$

In Equation (2), β is the vector that includes the coefficients for the respective variables. α_i is the individual fixed effect, whereas δ is the i^{th} country's fixed effect which is specific to the quantile. Z_{it}^{i} is a vector that has developed differentiable transformations of the right-hand side variables satisfying the probability of $P\left\{\delta_i + Z_{it}^{'}\gamma > 0\right\} = 1$. U_{it} denotes a random factor which is not observed and correlated with independent factors. It has been moved to the normalization for meeting the moment conditions, given following: The expected value is zero for U_{it} which is $E(U_{it}) = 0$. And the expected absolute value is equal to one for U_{it} that is $E(|U_{it}|) = 1$.

In Equation (2), β represents the vector of coefficients associated with the explanatory variables. The term α_i captures the individual fixed effects, while δ_i denotes the country-specific fixed effect that varies across quantiles. The vector Z_{it} consists of differentiable transformations of the explanatory variables on the right-hand side of the model, constructed to satisfy the condition $P\{\delta_i + Z_{it}'\gamma > 0\} = 1$, ensuring the validity of the moment conditions. The term U_{it} represents an unobserved random factor that may be correlated with the independent variables. To satisfy the moment conditions of the MMQR model, U_{it} is normalized such that its expected value is zero $E(U_{it}) = 0$, and its expected absolute value is equal to one $E(|U_{it}|) = 1$. Equation (2)'s parameters, α_i, β', δ_i, γ', $q(\tau)'$, are calculated applying the first moment conditions which consider the independent variables' exogeneity. The current approach complies with the method outlined by Machado and Santos Silva (2019). Hence, the model expressed in terms of the conditional quantile function is specified as follows:

$$Q_{RENERGY_{it}}\left(\tau \middle| X_{it}\right) = \left(\alpha_i + \delta_i q(\tau)\right) + X_{it}'\beta + Z_{it}'\gamma q(\tau) \quad (3)$$

Equation (3) calculates the conditional quantiles of the outcome variable ($RENERGY_{it}$) in association to the explanatory variables, it takes a panel of individuals into account which is observed across multiple time periods. The τ^{th} fixed effect quantile for i^{th} individual, in other words the distributional impact at τ, is described by the scalar parameter $i(\tau) \equiv (\alpha_i + \delta_i q(\tau))$ given in parenthesis. For the estimation of the model given above, one-step version of GMM estimator[5] is applied.

Equation 3 estimates the conditional quantiles of the dependent variable, $RENERGY_{it}$, as a function of the explanatory variables, while accounting for the panel structure of the data—that is, individuals (countries) observed over multiple time periods. The τ^{th} fixed effect quantile for the i^{th} individual, representing the distributional impact at quantile τ, is captured by the scalar parameter $i(\tau) \equiv (\alpha_i + \delta_i q(\tau))$, as indicated in parentheses. To estimate the model specified above, the one-step GMM estimator is employed, following the approach proposed by Machado and Santos Silva (2019).

3.2.3. Additional tests

3.2.3.1. Cross-sectional dependence and panel unit roots

As a prerequisite for the panel time series analysis, this paper applies a battery of tests to analyze cross-sectional dependence and variable heterogeneity. Breusch and Pagan (1980) proposed the following Lagrange Multiplier (LM) test statistic for analyzing cross-sectional dependence:

$$CD_{LM} = T\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}^2 \quad (4)$$

5 For more information on the model's estimation steps, refer to Machado and Silva (2019).

Where $\hat{\rho}_{ij}^2$ represents the estimated pairwise correlation coefficients of the residuals obtained through ordinary least squares regressions. This test has an asymptotic Chi-square distribution (χ^2) with $N(N-1)/2$ degrees of freedom. A test statistic that is statistically significant provides compelling evidence against the null hypothesis of no cross-sectional dependence, indicating that the residuals exhibit correlation across units. The existence of cross-sectional dependency indicates that the standard errors of the OLS could be biased, necessitating the use of alternative estimation methods.

LM test may generate biased results in the case of large sample. Pesaran (2004) proposed a cross-sectional dependence (CD) test to address this issue as both number of cross-sections (N) and time period (T) approach infinity. The CD statistic serves to evaluate the null hypothesis regarding the absence of cross-sectional dependency among panel units, and its calculation is as follows:

$$CD = \sqrt{\frac{1}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}(T\hat{\rho}_{ij}^2 - 1)} \quad (5)$$

The null hypothesis indicates that there is no cross-sectional dependence present.

The existence of cross-sectional dependency necessitates that panel time series methodologies address this issue appropriately. This study utilizes the cross-sectional CIPS panel unit root test to analyze the unit root properties of the variables, while considering cross-sectional dependence. To compute CIPS statistics, the regression model used for the cross-sectional augmented Dickey-Fuller (CADF) test is estimated as follows:

$$\Delta Z_{it} = \alpha_i + \rho_i Z_{i,t-1} + \beta_i \bar{Z}_{t-1} + \sum_{j=0}^{k}\gamma_{ij}\Delta\bar{Z}_{i,t-1} + \sum_{j=0}^{k}\delta_{ij} Z_{i,t-1} + v_{it} \quad (6)$$

The final step involves computing the CIPS statistic, which is the average of CADF statistics, using the formula:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} t_i(N,T) \quad (7)$$

3.2.3.2. Panel cointegration test

If unit root tests indicate the same level of integration of the series, the presence of long-run association among the variables can be investigated with panel cointegration tests. In this paper we employ (Westerlund, 2005) panel cointegration test to analyze cointegration. This test utilizes variance ratio statistics to ascertain whether the residuals from an estimated panel data regression have a unit root, based on the null hypothesis of no cointegration.

The test is capable of accommodating individual-specific short-run relationships, intercept and trend specifications, and slope parameters without necessitating the precise specification of the data generation process.

To apply the Westerlund (2005) test, firstly the residuals are obtained from the estimation of Equation (1). Then they are tested for a unit root based on the following model following AR (1) process:

$$\hat{\varepsilon}_{it} = \rho_i \hat{\varepsilon}_{it-1} + u_{it} \tag{8}$$

The variance ratio statistics used for the analysis of cointegration are defined as follows:

$$VR_G = \frac{1}{N}\sum_{i=1}^{N} \frac{\sum_{t=1}^{T} E_{it}^2}{R_i} \tag{9}$$

$$VR_p = \frac{\sum_{i=1}^{N}\sum_{t=1}^{T} E_{it}^2}{R_i} \tag{10}$$

Where $E_{it} = \sum_{j=1}^{t} \varepsilon_{ij}$ and $R_i = \sum_{t=1}^{t} \varepsilon_{it}^2$. The test statistics' asymptotic distributions are derived under the null hypothesis of no cointegration, and the tests are demonstrated to be free of nuisance parameters. Cointegration of the entire panel is assessed by the panel statistic, VR_p, whereas cointegration of a subset of the panel is investigated with the group mean statistic, VR_G. Therefore, Westerlund (2005) panel cointegration test allows us to analyze the long-run equilibrium relationship between renewable energy (RENERGY) and its determinants under the presence of cross-sectional dependence and heterogeneity within the panel data.

4. EMPIRICAL RESULTS

4.1. Panel Time Series Results

In this section the first cross-sectional dependency among the residuals of the model is investigated with various cross-sectional dependence tests. The tests presented in Table 3, include the Lagrange Multiplier (LM) test, the adjusted LM test (LM adj*), and the cross-sectional dependence (CD) test. The results indicate significant cross-sectional dependence among the panel units, as evidenced by the significant test statistics of the three tests at one percent level of significance. This suggests that the residuals across different cross-sections are correlated, which is a common characteristic in panel data involving multiple countries or regions.

After evidencing for cross-sectional dependence unit root test and cointegration analysis are conducted to determine the long-run relationship among the variables. Table 4 reports the results of the CIPS unit root test. CIPS unit root test results reported in the panel (a) contains the results for the variables at both levels and first differences. The results show that all variables are non-stationary at levels but become stationary after first differencing, as indicated by significant test statistics obtained for the first differences. This indicates that the variables are integrated of order one, I (1).

As the variables have the same integration, Westerlund (2005) cointegration test is applied results reported in Table 5 indicate the presence of cointegration among the variables, as the variance

Table 3: Cross-sectional dependence test

Method	Statistic	P-value
LM	1.20	0.000
LM adj*	18.05	0.000
LM CD*	8.476	0.000

***Denote statistical significance at 1% level. Trend is included

Table 4: CIPS unit root test

Variable	Level	First difference
RENERGY	−1.902	−4.342***
LOGLCENRISK	−1.139	−2.746***
LOGECDEV	−2.477***	−3.686***
LOGESG	−1.617	−3.694***
IQ	−1.860	−4.485***

***Denote statistical significance at 1% level

Table 5: Westerlund cointegration test

Test	Statistic	P-value
Variance ratio	6.671	0.000

***Denote statistical significance at 1% level. Trend is included

ratio statistic is found to be significant at one percent level. This corroborates the presence of long-run equilibrium relationship between the renewable energy and the explanatory variables, including low-carbon energy risk, economic development, ESG environmental performance and institutional quality.

4.2. MMQR Results

According to the estimations given in Table 6, low-carbon energy risk (LOGLCENRISK) positively impacts the renewable energy (RENERGY) across all the quantiles, 10-90%. Since higher value of the score means less risk, the findings are in line with theoretical linkage. More specifically, decrease in low-carbon energy risk promotes renewable energy. According to Komendantova et al. (2010), regulatory risks are the most significant among political and force majeure risks. Hence, creating, enforcing, and implementing sound regulations in a transparent way could be a significant step in fostering cooperation between North African and European nations in the field of renewable energy. Additionally, Hille (2023) states that in order to improve energy security and lessens reliance on unstable foreign energy sources, countries that face energy supply instability as a result of geopolitical threats in countries that supply fossil fuels are probably going to embrace renewable energy more quickly.

As regards with economic development (LOGECDEV), it has a positive relation with RENERGY in lower quantiles from 10% to 25%. The similar conclusions are drawn by Sadorsky (2009) who reveals that rises in GDP per capita drives renewable energy consumption in case of G7 countries as well as 18 developing countries. Similarly, Aguirre and Ibikunle (2014) analyse for 38 countries as well as Omri and Nguyen (2014) for 64 countries. However, Chen et al. (2021) examines this relationship for 97 countries comprising both developed as well as developing economies and provides that in the entire sample, the growth of renewable energy consumption is inversely correlated with higher rates of economic growth, while it is positive for the developed economies.

Table 6: MMQR results of the whole sample

Quantiles	10%	25%	50%	75%	90%
Dependent variable: RENENERGY					
LOGLCENRISK	11.631***	12.124***	12.967***	13.823***	14.473***
LOGECDEV	1.758***	1.345***	0.641*	−0.072	−0.615
LOGESG	1.359*	1.620**	2.067***	2.520***	2.865***
IQ	−2.944***	−2.528***	−1.818**	−1.098	−0.550
Constant	−26.408***	−22.557***	−15.983***	−9.315*	−4.243

*, **, and *** denote statistical significance at 10%, 5%, and 1% levels, respectively

Environmental quality (LOGESG) has a positive effect on RENERGY in the quantiles of 25-90%. It aligns with Lu and Li (2024) who suggest ESG rating can encourage a 2.1% boost in investments on renewables as compared to businesses without it, also an improvement in the ESG rating will further support low-carbon investments in comparison to a drop and an unchanged rating. Additionally, Shahzad et al. (2024) find OECD environmental regulators' limitations (as a proxy of ESG) on the use of polluting raw materials like coal, oil, and natural gas for energy generation encourage the development of renewable energy. However, based on econometric analysis Bashir et al. (2021) suggest that environmental rules in OECD economies hinder the use of renewable energy.

Lastly, institutional quality (IQ) has a significant and negative impact on RENERGY in the lower and middle quantiles 10-50%. It is consistent with the findings of Mukhtarov et al. (2023) that show the corruption perception index positively and statistically significantly affect the use of renewable energy. The examination of long-term projections by Rafiq et al. (2024) also shows that increased institutional quality contributes significantly and uniquely to the promotion of renewable energy use. Additionally, Rahman and Sultana (2022); Wang et al. (2022) argue that high quality institutions and effective governance play a vital part in promoting renewable production and consumption as well.

Figure 1 shows that the marginal effect of low-carbon energy risk (LOGLCENRISK) on renewable energy (RENERGY) is also in line with the theory. More precisely, a decrease in additional unit of low-carbon energy risk also enhances renewable energy. The marginal effect of environmental quality (LOGESG) on RENERGY is also positive, whereas the marginal effects of economic development (LOGECDEV) and institutional quality (IQ) has a negative effect on renewable energy (RENERGY).

4.2.1. Sub-sample testing

The findings reported in Table 6 are estimated with the panel of 137 countries which validate the theoretical relation between renewable energy and low-carbon energy risk. Conducting the estimations based on the development stage of the countries also sheds lights into the analysis. More specifically, the nexus of low-carbon energy risk-renewable energy might be affected due to the economic development stage of the nations. Therefore, sub-sample tests are run dividing the sample into developed and developing countries.

Based on the MMQR estimates of developed economies in Table 7, renewable energy (RENERGY) is positively and highly significantly impacted by low-carbon energy risk (LOGLCENRISK) at all quantiles, from 10% to 90%. The results are consistent with theoretical linkage since a higher score indicate reduced risk. This output aligns with the studies that consider composites of the core explanatory variable. For instance, in a study comprising 15 developed economies parametric panel data methods employed by Ivanovski and Marinucci (2021) reveal a negative long-term relation between economic policy uncertainty and renewable energy consumption. Additionally, Sun et al. (2024) point to the similar results that while environmental degradation, technological developments, and environmental taxes have a positive impact on renewable energy usage in G7 countries, geopolitical threats have a negative effect.

Economic development (LOGECDEV) impacts RENERGY positively and highly statistically across all quantiles within advanced economies. It is in an alignment with the findings of Sadorsky (2009) providing that long-term gains in real GDP per capita found to be a significant driver of per capita consumption of renewable energy, according to panel cointegration estimations of G7 nations. Dogan et al. (2021) using the pooled OLS estimator, also find the GDP influencing the different renewable energy proxies positively and significantly. Despite, Menegaki (2010) reveals findings that do not suggest causal relation existing between renewable energy consumption and GDP among 27 European states applying multivariate panel framework, employing ARDL as well as Granger causality methods Mohamed et al. (2019) suggest that in the long run, economic growth increases renewable energy in France as well.

Only at 50% and higher quantiles in advanced economies does the environmental quality (LOGESG) impact on RENERGY appear to be positive and significant. Environmental technology patents, a proxy for the independent variable, can be thought of as effective mediating mechanisms for raising the consumption of renewable energy in OECD nations, according to similar findings reported by Onofrei et al. (2024). However, Marques et al. (2010) investigate CO_2 emissions, another element of the ESG index, and find that the higher these emissions, the lower the pledges to renewable energy in European countries.

Similarly, the results of IQ on RENERGY as well look significant starting from 50% and higher quantiles in developed nations, but with negative effect. Although, they contradict with the findings of Uzar (2020) who suggest that in a long-term the use of renewable energy is positively impacted by institutional quality in a sample of mostly developed 38 countries utilizing ARDL-PMG approach and Sequeira and Santos (2018) who systematically reviews relevant papers presenting evidence that democratic institutions promote renewables.

Figure 1: The marginal effect of LOGLCENRISK, LOGECDEV, LOGESG and IQ on RENERGY

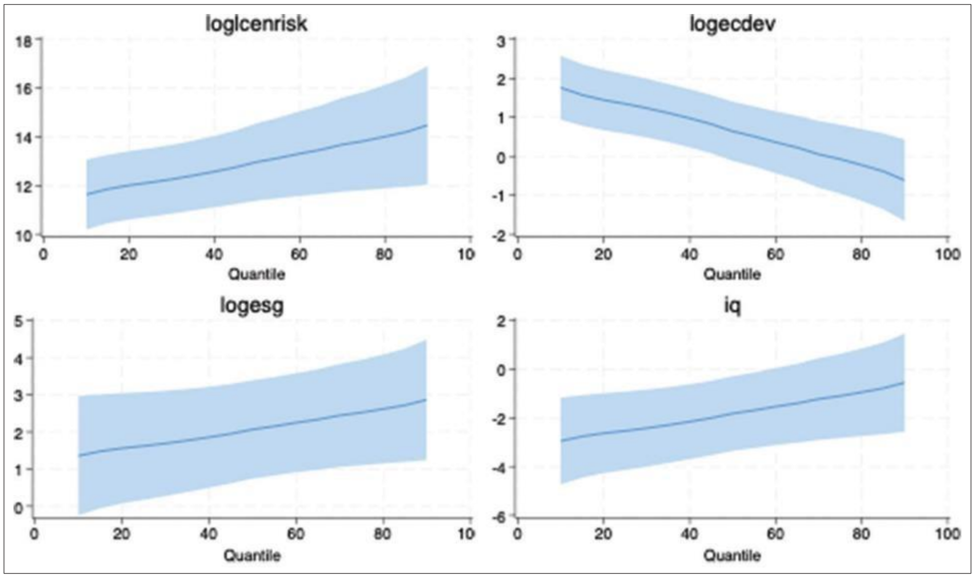

Table 7: MMQR results of developed economies

Quantiles	10%	25%	50%	75%	90%
Dependent variable: RENERGY					
LOGLCENRISK	14.392***	14.875***	15.533***	16.575***	17.236***
LOGECDEV	9.774***	8.903***	7.716***	5.838***	4.645**
LOGESG	−0.474	6.349	15.639***	30.340***	39.675***
IQ	−0.680	−2.100	−4.034**	−7.094***	−9.037***
Constant	−122.628***	−139.850***	−163.297***	−200.404***	−223.964***

** and *** denote statistical significance at 5% and 1% levels, respectively

The marginal impact of low-carbon energy risk (LOGLCENRISK) on renewable energy (RENERGY) in developed economies is also consistent with the hypothesis, as Figure 2 illustrates. More specifically, renewable energy is also improved by a decline in the additional unit of low-carbon energy risk and the marginal effect of environmental quality (LOGESG) has a positive impact as well. While the marginal effects of institutional quality (IQ) and economic development (LOGECDEV) have a negative impact on renewable energy (RENERGY).

Context of developing countries in Table 8 shows that RENERGY is impacted by LOGLCENRISK positively and significantly throughout the considered quantiles. This result is consistent with research that takes into account composites of the primary explanatory variable. For example, Ivanovski and Marinucci (2021) in a study including 8 developing economies show a negative long-term relationship between economic policy uncertainty and the use of renewable energy. But the analysis of geopolitical risks and renewable energy innovation by Zhang et al. (2024) reveals that they former positively impacts the latter at a significant level.

Regarding LOGECDEV, RENERGY is significantly negatively influenced by it at middle and higher quantiles (between 50% and 90%). It does not align with number of studies with the context of developing countries. Particularly, with Sadorsky (2009) runs panel cointegration estimations revealing that per capita use of renewable energy is positively and statistically significantly impacted by increases in real per capita income, and with Apergis and Payne (2014) who analyse seven Central American nations to discover a positive and statistically significant effect of real per capita GDP on per capita renewable energy consumption according to the FMOLS output.

On the other hand, LOGESG affects RENERGY positively with a high significance level through the each regarded quantiles in developing nations. The finding has an alignment with studies regarding CO_2 emissions, which is a component of ESG environmental performance, and renewables showing positive significant relation (Apergis and Payne, 2014; Omri and Nguyen, 2014; Mukhtarov et al., 2023).

Despite, Rahman and Sultana (2022) show that impact of IQ on RENERGY is significantly positive in 19 emerging economies via panel PMG-ARDL method, our outputs suggest no significance within this sample.

In developing nations, the marginal impact of low-carbon energy risk (LOGLCENRISK) on renewable energy (RENERGY) is likewise consistent with the theoretical concept, as Figure 3 indicates. More specifically, renewable energy is also boosted by a fall in the additional unit of low-carbon energy risk. Additionally beneficial are the marginal effects of institutional quality (IQ) and environmental quality (LOGESG). Renewable energy (RENERGY) is negatively impacted by the marginal effects of economic development (LOGECDEV).

Figure 2: The marginal effect of LOGLCENRISK, LOGECDEV, LOGESG and IQ on RENERGY in developed economies

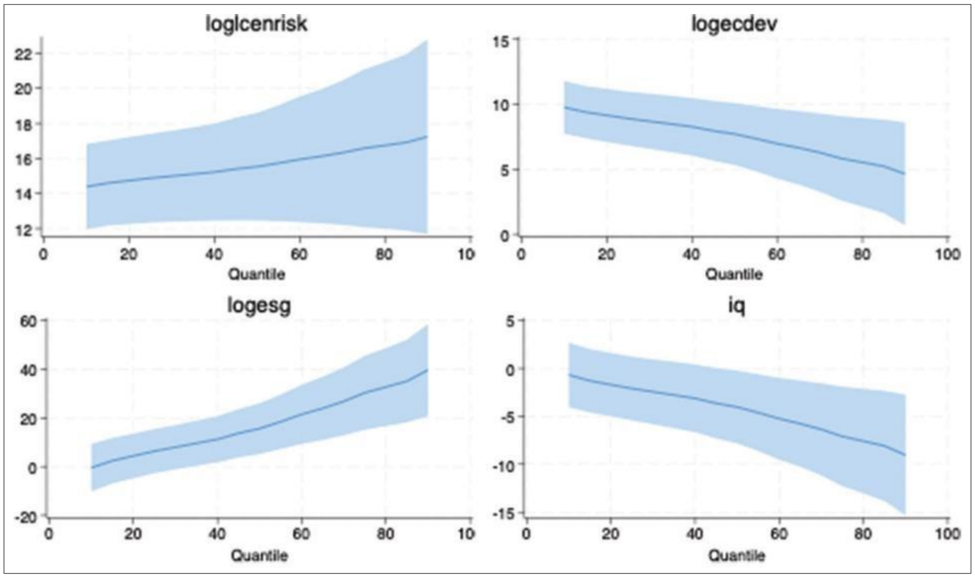

Figure 3: The marginal effect of LOGLCENRISK, LOGECDEV, LOGESG and IQ on RENERGY in developing economies

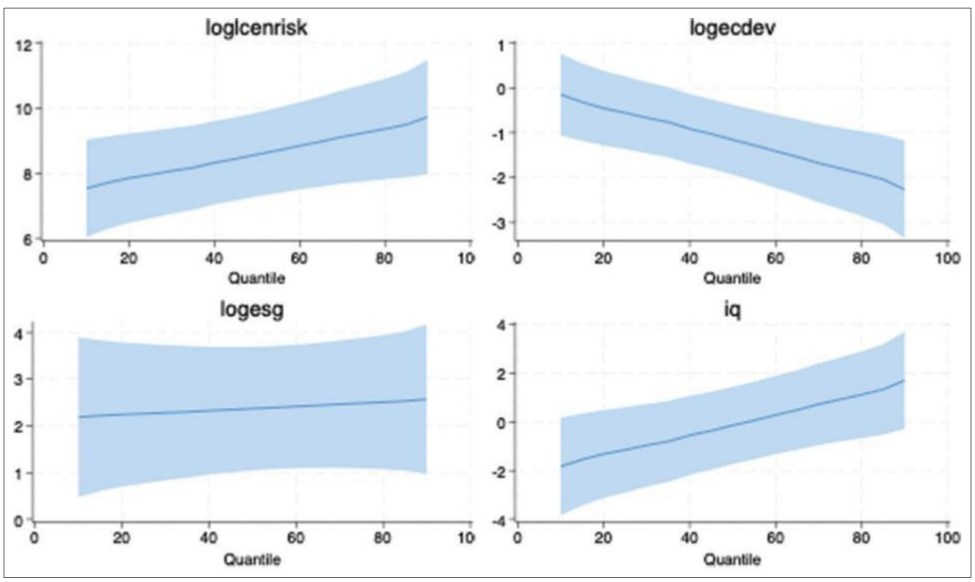

Table 8: MMQR results of developing economies

Quantiles	10%	25%	50%	75%	90%
Dependent variable: RENERGY					
LOGLCENRISK	7.532***	7.954***	8.578***	9.242***	9.729***
LOGECDEV	−0.147	−0.555	−1.159***	−1.801***	−2.273***
LOGESG	2.188**	2.261***	2.370***	2.486***	2.571***
IQ	−1.826*	−1.148	−0.143	0.924	1.708*
Constant	1.765	6.829	14.328***	22.299***	28.150***

*, **, and *** denote statistical significance at 10%, 5%, and 1% levels, respectively

5. CONCLUSION

The work assesses the impact of low-carbon energy risk on renewable energy for the first time. To this end, MMQR method is employed which is robust to heterogeneity. The empirical findings shed lights into the current literature. More specifically, the decline of low-carbon energy risk promotes renewable energy, validating the theoretical relation. The results are robust since the impact is negative and significant across all the quantiles of all the nations regarding the economic development stage. As control variables, economic development, environmental quality and institutional quality are used in the system of the relation between low-carbon energy risk and renewable energy. The risks associated with low-carbon energy are the main determinants in the development of renewable energy. The composite index of low-carbon energy risk applied in the study covers all the risks, and its positive effect on renewable energy represents mitigating effect since high values mean less risk.

Admittedly, coping with economic risks help to promote renewable energy since the costs associated with renewable energy transition are considered high. More precisely, boosting investment expenditures in renewable energy sector is vital. Effective monetary and fiscal policies also important to influence business and consumers to be encouraged to manufacture and choose renewable energy related products.

Apart from economic risks, technological risks should be also considered. Technological advancement allows to renewable energy transition. Contrary, technological dependence on the import slows down renewable energy transition because of import costs and utilization issues. In this context, technological development in the local markets are key issues.

Climate change risks also effect on renewable energy development. Renewable energy development requires suitable conditions in the nature in order to generate electricity. Therefore, any damages done to environment will adversely effect on renewable energy development in the long-run. Climate actions should be fostered to keep renewable energy development stable.

Achieving high level of institutional quality serves to enhance renewable energy. Because, risks in institutional quality increase corruption, causes ineffective government and violence of laws. Consequently, all these adversely effect on renewable energy development. Therefore, institutional quality should be well considered in renewable energy policy.

The results of the research are valuable guide for the policymakers in the field of renewable energy. Particularly, the role of low-carbon energy risk in the renewable energy development must be highlighted in decision-making process. The components of low-carbon energy risk score are not negligible in shaping renewable energy development. The findings of this study can be used, especially, to achieve Goal 7 and Goal 13 since renewable energy development not only promotes affordable and clean energy, but also helps to cope with climate change.

Even though the study addresses one of the key topics in literature, there are also some limitations. More specifically, it would be interesting to robust the results with the additional estimates incorporated by the components of low-carbon energy risk score. However, on the one hand those components are well-studied in the literature in the context of renewable energy. On the other hand, the length of the manuscript would be overloaded with additional estimations.

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