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Effects of the circular economy, environmental policy, energy transition, and geopolitical risk on sustainable electricity generation

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A R T I C L E I N F O

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A B S T R A C T

The recent global paradigm shift toward sustainable green development necessitates revealing the likely green determinants of sustainable electricity generation in order to derive key policy recommendations for dealing with the global energy crisis. As a result, the current study focuses on the drivers of global electricity generation (EG) and identifies environmental policy (EP), energy transition (ET), geopolitical risk (GPR), and circular economy (CE) as novel determinants. The study employs a battery of advanced econometric techniques, including quantile VAR, quantile slope estimate, and wavelet-based correlation methods, for empirical analysis. The quantile VAR-based connectedness confirms the modeled series' significant interconnectedness. Furthermore, the findings suggest that CE plays an important role in promoting the global EG process, as evidenced by positive effects across quantiles. When the effects of ET and EP are considered, a positive relationship between ET, EP, and EG is discovered, implying that ET and EP are important drivers of electricity generation. Furthermore, GPR has significant and negative effects on EG across most quantiles, indicating that the EG process suffers a significant loss as a result of GPR. Furthermore, the wavelet-based correlation method confirms the significant association between selected series, supporting the preceding findings. In order to achieve sustainable electricity generation, several results-based policies are proposed for local and global authorities.

1. Introduction

Economic development is over-reliant on energy, as exhibited by the correlation between rising GDP and the increased availability and affordability of electricity (Dogan et al., 2022; Chishti and Dogan, 2022; Cheng et al., 2019). For instance, in 1990, the world's electricity generation (EG) was 2244 kwh per-capita, while the world's GDP was $4304 per capita. In 2021, the per capita EG was recorded at 3610 kwh, and global per-capita GDP turned into $18604 (World Economic Forum, 2022). Putting it simply, approximately a 61% rise is recorded in world EG, and similarly, an approximate 332% upsurge is observed in world per-capita GDP during 1990–2021. Further, Fig. 1 clearly depicts the positive correlation between EG and GDP. On account of the vital role of energy in fostering economic growth, sustainable EG became an essential aim of the global nations (Park and Yun, 2022). Before the 1990s, electricity generation relied heavily on fossil fuels, which contributed to global economic growth but also resulted in environmental pollution due to the increase in greenhouse gas emissions. This issue prompted global policymakers to take action against escalating environmental pollution and called for an immediate shift to green energy sources (United Nations, 2022). This led to the establishment of various treaties, such as the Kyoto Protocol, the Paris Agreement, COP26, COP27, etc., at the global level. As a result, there has been a paradigm shift in the global energy sector, with renewable energy sources contributing 21% of global electricity generation in 2021 and expected to reach 61% by 2030.

Since electricity generation is the fundamental pillar of sustainable development (Chishti and Sinha, 2022), the paradigm shift calls for more exploration in this area to put the global economies on the path of sustainable development. Therefore, several studies have endeavored to

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explore the salient determinants of EG. Throughout the world, there has been a noticeable shift in paradigm towards prioritizing sustainable and environmentally friendly economic development instead of solely promoting GDP growth by endorsing the EG (International Energy Agency, 2022). To put it differently, the paradigm shift necessitates utilizing EG derived from environmentally friendly sources in order to facilitate green development. Given the immense importance of electricity generation (EG) and its potential role in achieving sustainable development, a recent study emphasizes the need to address economic and social variables that can assist policymakers in promoting the generation of electricity from environmentally friendly resources. Assuming this is the significant and policy-oriented gap in the existing literature, the recent study claims the circular economy process, the energy transition process, environmental policy, and geopolitical risk as the novel and less explored determinants of EG.

The circular economy, i.e., an economy in which there is almost no waste and there is as much recycling and reusing as feasible (World Economic Forum, 2022), can be a vital source for EG. The reason is that the circular economy process focuses on producing a minimal amount of waste by triggering recycling and reusing the waste to generate energy and, thus, electricity. For instance, the circular economy relies on the pyrolysis method for recycling, which generates energy while using a low temperature, resulting in electricity generation and low carbon emissions (Energy Saving Trust, 2022). Under the umbrella of the circular economy process, several global companies are reusing the local wastes that are already available, transforming them to increase their lifespan, and pooling resources. Similar to this, the automotive industry is also endeavoring to design sustainable cars using recycled and recoverable materials and reusing electric car batteries. Also, the mining industry's experts are looking into ways to boost the environmental viability of their operations by recovering commodities from waste streams and fulfilling energy demands (Atlas Renewable Energy, 2022). The above discussion unambiguously demonstrates that the circular economy may play a pivotal role in promoting the EG.

Similarly, the energy transition process—shifting from fossil fuel energy usage to green energy usage—is observed as a crucial determinant of the EG. Further, the energy transition based on renewable energy sources such as bioenergy, tides, waves, geothermal, solar, wind, and hydropower significantly contributed to enhancing the global EG process. For example, global renewable energy sources' contribution to global electricity was 2855.77 TW h in 2000, which increased to 7855.62 TW h in 2021, implying an approximate 175% rise in the EG. In a similar vein, low-income, lower-middle-income, upper-middle-income, and high-income nations were producing 36.4 TW h, 270.15 TW h, 1001.36 TW h, and 1265.15 TW h of green sources-based electricity in 2000, respectively, which is recorded at 36.4 TW h, 270.15 TW h, 1001.36 TW h, and 1265.15 TW h, correspondingly, in 2021, implying a significant rise in the green sources-based EG (Statistical Review of World Energy, 2022).

Further, Fig. 2 indicates the overall scenario of the energy transition's contribution to EG during 2000–2021. However, the experts can be categorized into two groups regarding the effects of environmental policy on electricity generation. The first bunch of experts claim that environmental policy (EP) can escalate electricity generation by encouraging green investors' investment in the electricity sector, promoting green energy programs, attracting investors to the green energy markets through green subsidies, enhancing green technologies, and improving energy efficiency use (Det Norske Veritas, 2022). On the other hand, the second bunch of experts contradicts and argues that EP—which thrives on green technologies to increase green electricity production—cannot be economical on account of the high cost of production (Acevedo et al., 2021). This significant gap in the literature prompted the recent study to re-investigate the likely nexus between EP and EG in order to divulge some interesting findings.

Additionally, the global geopolitical risk (GPR) (i.e., which computes the potential economic, political, and social risks) drew the attention of policymakers due to recent economic shocks such as COVID-19 and the Ukraine-Russia War (URW) to analyze their likely effects on the various economic variables (Islam et al., 2023). Hence, it is important to analyze the dynamic connectedness between GPR and EG, specifically in the context of COVID-19 and URW.

Based on the above discussion, the recent study claims that the aforementioned plausible drivers of EG may play a crucial role in achieving a sustainable EG. However, the available literature does not pay the considerable attention needed to assess the likely dynamic connectedness between the circular economy, environmental policy, energy transition, geopolitical risk, and sustainable electricity generation in order to draw policy recommendations. Thus, the aforementioned significant gap posits the following research question:

Research question: How do the circular economy, environmental policy, energy transition, and geopolitical risk affect global sustainable electricity generation?

To extend the prior economic literature, the study's contribution can be documented as follows: First, to the best of our humble knowledge, this is the first study that claims the circular economy process as the crucial and novel determinant of EG and assesses its plausible impacts.

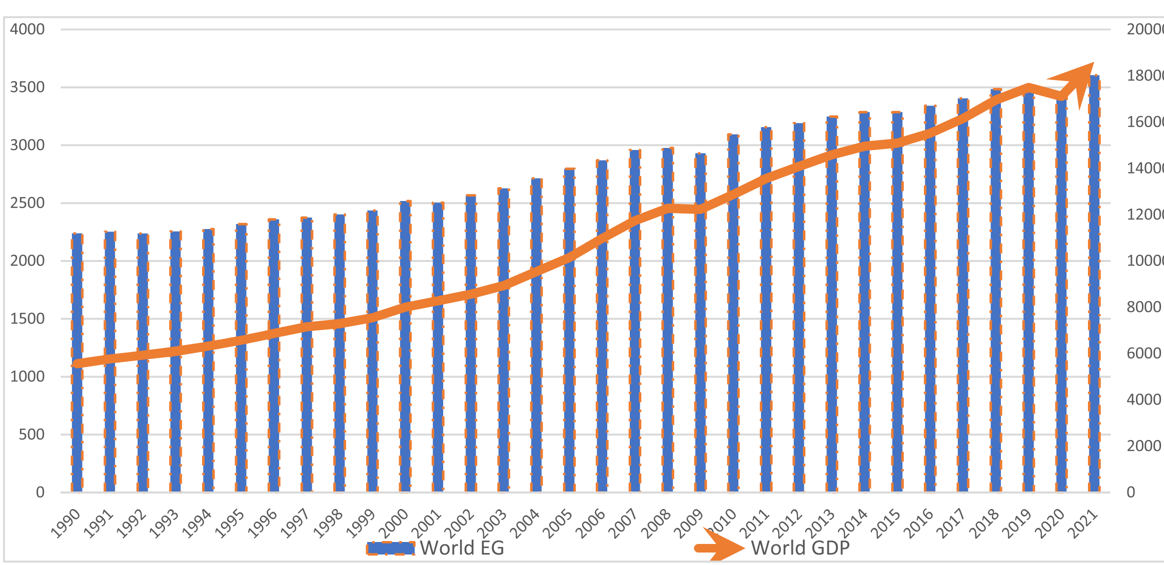

Fig. 1. Overall trends in the global electricity generation and GDP. Source: WDI (2022)

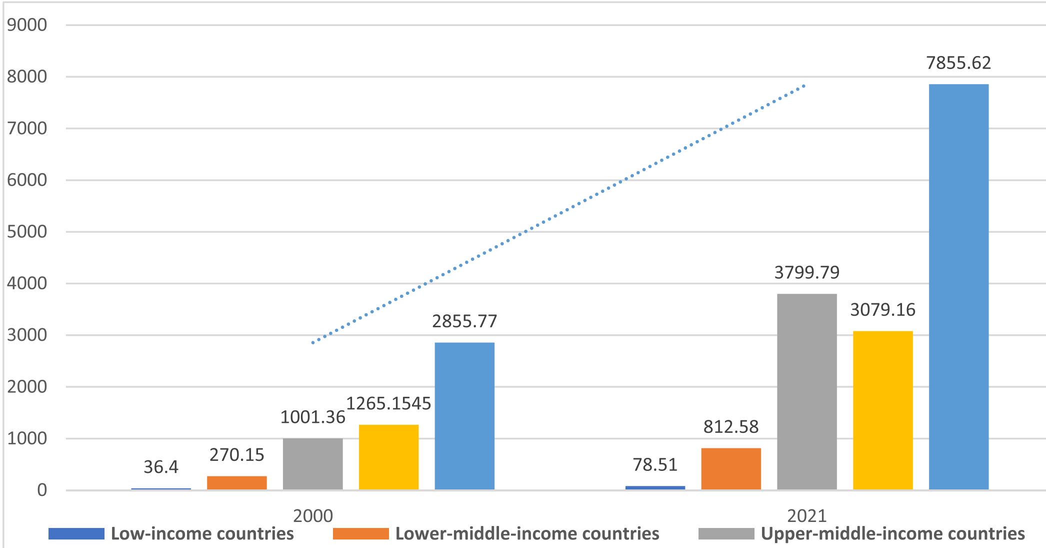

Fig. 2. Overall scenario of the energy transition's contribution in EG. Source: Statistical Review of World Atlas Renewable Energy (2022).

Second, this is again the first study that categorically analyzes the effects of energy transition and environmental policy on the EG. Third, to measure the impacts of recent economic shocks such as COVID-19 and URW, the study extends the literature by analyzing the effects of geopolitical risk on the EG. Fourth, the majority of the previous studies deployed econometric methods that compute the average effects of the independent series while neglecting the likely asymmetric information in the series. To tackle the biasness and obtain more detailed results, the recent article relies on the three advanced econometric methods, i.e., the QVAR method, the quantile-slope estimate method, and Rau's wavelet-based correlation method.

The rest of the paper is organized as follows: The second section reviews the pertinent literature to support the contribution of the study by identifying the literature gap. The third section presents the data sources, then Section 4's documented methods and methodology. Section 5 reports the results and discussion. The last section concludes the study and suggests some salient policy recommendations.

2. Literature review

To identify the significance of the literature gap, the current section is categorized into the following subsections: (i) determinants of electricity generation (EG), (ii) modeled series and EG nexus, (iii) literature gap, and (iv) theoretical bridge.

2.1. Determinants of electricity generation (EG)

So far, several studies have explored the many determinants of electricity, including, but not limited to, income, new housing, aging, household size, taxes, construction, population, innovation, oil prices, economic uncertainty, urbanization, trade, industrialization, FDI, human capital, energy prices, exports, natural resources, financial development, and exchange rate (Abbas et al., 2023; Lorente et al., 2022; Aldieri et al., 2022). For instance, Park and Yun (2022) utilize the data for 225 Korean municipalities to explore the determinants of electricity production. The results confirm that income, new housing, aging, household size, taxes, and construction play a significant role in determining the EG. Similarly, Azam et al. (2022) assess the effects of GDP, trade, carbon emissions, FDI, and urbanization on the EG, while deploying the data from 1972 to 2015 for selected 79 nations. The study relies on the OLS method for empirical analysis. The study relies on the OLS method for empirical analysis. The findings confirm that the selected variables influence the production process of electricity significantly.

In a similar vein, a study by Shafiullah et al. (2021) investigates the response of EG to economic uncertainty, oil prices, economic growth, and technological innovation in the USA. The results infer that oil prices and uncertainty tend to curtail the EG process. On the other hand, economic growth and innovation processes encourage the EG. Another study by Canh et al. (2021) uses a large sample of 115 nations in order to analyze the effects of FDI, trade, and industrialization on the EG. The GMM results assert that FDI, trade, and industrialization play a vital role in fostering the EG market. In a similar vein, Adetola and Sunday (2021) examine the determinants of EG for Egypt while utilizing the ARDL method. The results indicate that imports and urbanization significantly trigger the production of electricity in Egypt.

Additionally, Fernandes and Reddy (2021) check the influence of financial development, trade openness, and exchange rate on the EG for the selected Asian economies. For analysis, the study deploys the VECM. The results affirm that trade and financial development significantly ameliorate the EG industry. However, the exchange rate' variations tend to discourage the EG process in the selected nations. Similarly, Li et al. (2020) for OECD nations, Nawaz et al. (2020) for Pakistan, Nathaniel and Bekun (2020) for Nigeria, Zaharia et al. (2019) for EU nations, Sarkodie and Adom (2018) for Kenya, and Dalei (2016) for China, India, and Japan analyze the effects of various economic and social series on the EG. The findings suggest that climate change, carbon emissions, economic growth, inflation, population, renewable energy, economic complexity, and FDI inflows are crucial drivers of the EG.

2.2. Modeled series and EG nexus

The primary aim of the study is to analyze the connectedness between the circular economy, environmental policy, energy transition, geopolitical risk, and global sustainable electricity generation. However, the existing literature does not support the empirical studies on the aforementioned side. Furthermore, the available data supports the construction of the theoretical literature between selected variables. For instance, the circular economy possesses a significant literary nexus with the EG. According to the Energy Saving Trust (2022), the circular economy focuses on producing a minimal amount of waste by triggering recycling and reusing the waste to generate energy and, thus, electricity. For instance, the circular economy relies on the pyrolysis method for recycling, which generates energy while using a low temperature, resulting in electricity generation and low carbon emissions. Under the umbrella of the circular economy process, several global companies are reusing the local wastes that are already available, transforming them to increase their lifespan, and pooling resources. Similar to this, the automotive industry is also endeavoring to design sustainable cars using recycled and recoverable materials and reusing electric car batteries. Also, the mining industry' experts are looking into ways to boost the environmental viability of their operations by recovering commodities from waste streams and fulfilling energy demands (Atlas Renewable Energy, 2022). The aforementioned theoretical literature explicitly induces the empirical nexus between the circular economy and EG.

Similarly, the energy transition process, based on the theoretical literature, seems to encourage EG. For example, a report by the Statistical Review of World Atlas Renewable Energy (2022) documents that global renewable energy sources' contribution to global electricity was 2855.77 TW h in 2000, which increased to 7855.62 TW h in 2021, implying an approximate 175% rise in the EG. Likewise, the theoretical literature argues that experts can be categorized into two groups regarding the effects of environmental policy on electricity generation. The first bunch of experts claim that environmental policy (EP) can escalate electricity generation by encouraging green investors' investment in the electricity sector, promoting green energy programs, attracting investors to the green energy markets through green subsidies, enhancing green technologies, and improving energy efficiency use (Det Norske Veritas, 2022). On the other hand, the second bunch of experts contradicts the first and argues that EP — which thrives on green technologies to increase green electricity production — cannot be economical on account of the high cost of production (Acevedo et al., 2021). This significant gap in the literature prompts the recent study to re-investigate the likely nexus between EP and EG in order to divulge some interesting findings. Also, the global geopolitical risk (GPR) due to recent economic shocks such as COVID-19 and the Ukraine-Russia War (URW) necessitates analyzing its likely effects on EG for important policy implications.

2.3. Literature gap

Based on the above critical literature review, the current study claims the following significant gaps in the literature: Firstly, as the global economies are shifting their economic structure from a linear economy to a circular economy, not a single study is available to assess the response of EG to the paradigm shift of the circular economy. Secondly, to achieve SDGs 7 and 8, global economies are endeavoring to practice energy transition processes and green environmental policies. However, not much attention is paid to checking the empirical effects of the energy transition and environmental policy on the EG. Finally, recent economic shocks such as COVID-19 and URW have drawn the attention of global policymakers in the context of their impacts on various economic variables. But still, not a single study investigates their plausible effects on EG. Considering the aforementioned arguments, it is worth investigating the dynamic connectedness between the circular economy, environmental policy, energy transition, geopolitical risk, and global sustainable electricity generation to derive the local and global policy implications.

2.4. Theoretical bridge

Electricity is an essential driver of economic growth and plays a significant role in every sector of an economy. Before the 1990s, the electricity generation process was heavily dependent on fossil fuels. This process triggered global economic growth on the one hand, while on the other, it caused environmental pollution on account of the rise in greenhouse gases. The global policymakers showed serious concern about the escalating environmental pollution, calling for an immediate shift of the electricity generation process from fossil fuels to green energy sources (United Nations, 2022). To do so, several treaties, such as the Kyoto Protocol, the Paris Agreement, COP26, COP27, etc., are organized at the global level. These steps caused a paradigm shift in the global energy sector, and consequently, renewable energy sources contributed to global electricity generation by 21% in 2021, which is expected to increase to 61% in 2030. The paradigm shift requires exploring some new plausible drivers of sustainable electricity generation to boost this process and improve the global environment. In this context, the recent study claims that the circular economy, energy transition, environmental policy, and geopolitical risk are the most likely crucial drivers of electricity generation.

Where the role of the circular economy is concerned, it is expected that it can foster sustainable electricity generation. The reason being, the circular economy process focuses on producing a minimal amount of waste by triggering recycling and reusing the waste to generate energy and, thus, electricity. For instance, the circular economy relies on the pyrolysis method for recycling, which generates energy while using a low temperature, resulting in electricity generation and low carbon emissions (Energy Saving Trust, 2022). Under the umbrella of the circular economy process, several global companies are reusing the local wastes that are already available, transforming them to increase their lifespan, and pooling resources. Similar to this, the automotive industry is also endeavoring to design sustainable cars using recycled and recoverable materials and reusing electric car batteries. Also, the mining industry' experts are looking into ways to boost the environmental viability of their operations by recovering commodities from waste streams and fulfilling energy demands (Atlas Renewable Energy, 2022). The above discussion unambiguously demonstrates that the circular economy may play a pivotal role in promoting the EG.

Similarly, the energy transition process is also expected to be a crucial determinant of the EG. The reason being that the energy transition based on renewable energy sources such as bioenergy, tides, waves, geothermal, solar, wind, and hydropower significantly contributed to enhancing the global EG process. (Statistical Review of World Energy, 2022). As for the environmental policy's effects on electricity generation, the experts can be categorized into two groups based on their opinions. The first bunch of experts claim that environmental policy may escalate electricity generation by encouraging green investors' investment in the electricity sector, promoting green energy programs, attracting investors to the green energy markets through green subsidies, enhancing green technologies, and improving energy efficiency use (Det Norske Veritas, 2022). On the other hand, the second bunch of experts contradicts and argues that EP—which thrives on green technologies to increase green electricity production—cannot be economical on account of the high cost of production (Acevedo et al., 2021). This significant gap in the literature prompted the recent study to re-investigate the likely nexus between EP and EG in order to divulge some interesting findings.

Finally, the global geopolitical risk (GPR) drew the attention of policymakers due to recent economic shocks such as COVID-19 and the Ukraine-Russia War (URW) to analyze its likely effects on various economic variables (Islam et al., 2023). Hence, it is important to analyze the dynamic connectedness between GPR and EG, specifically in the context of COVID-19 and URW. Based on the above discussion, the study formulates the following expected nexus between circular economy (CE), environmental policy (EP), energy transition (ET), geopolitical risk (GPR), and sustainable electricity generation (EG).

$$\text{Marginal Effect of circular economy}: \frac{\Delta EG}{\Delta CE} > 0$$

$$\text{Marginal Effect of environmental policy}: \frac{\Delta EG}{\Delta EP} > 0$$

$$\text{Marginal Effect of energy transition}: \frac{\Delta EG}{\Delta ET} > 0$$

$$\text{Marginal Effect of GPR}: \frac{\Delta EG}{\Delta GPR} < 0$$

3. Data

To perform the empirical analysis, daily data for all selected series are retrieved from: https://www.spglobal.com/spdji/en/regional-exposure/global/#overview, and the study covers the time period from May 1, 2017 to December 31, 2022 (viz., 1799 observations). Except for the data for geopolitical risk, which is retrieved from a source provided by Caldara and Matteo (2022). The study retrieves the data for the renewable energy index (a proxy for energy transition), the carbon efficient index (a proxy for environmental policy), the circular economy index (a proxy for the circular economy), the geopolitical risk index (a proxy for geopolitical risk), and the electricity transmission and distribution index (a proxy for electricity generation). All the indices are measured in US dollars except the geopolitical risk index. All the opted series are in logarithmic form. Since the raw series possess the unit root according to Elliot et al. (1996), the difference is taken, and all the series turn into stationary processes, as Table 1 reports.

Table 1 implies that the application of the proposed econometric methods to the modeled series would not be spurious and the results would be meaningful. Also, it can be noticed that EG has the highest average value, followed by CE, while GPR possesses the lowest average value. Since all the mean values are positive, it implies that all the economic variables are, on average, growing and thriving. However, the positive mean values of GPR indicate that there is, on average, a higher level of perceived risk. Some more pre-estimation tests are applied in order to analyze the characteristics of the modeled series. For instance, the significance of skewness and kurtosis in the series reveal the tail dependence, implying that all modeled series are asymmetrically distributed and quantile analysis is suitable to tackle such asymmetries. Further, the variances and the Jarque-Bera test confirm the non-linear distribution of the series.

Fig. 3 shows the ups and downs in the modeled series, which backs up the results of the pre-estimation tests. For example, a quick decline can be observed after 2020 in the series of CE, CEI, ET, and EG, implying the adverse effects of COVID-19, which significantly disrupted the all-economic variables. Further, the quick rises in the series GPR after 2020 and 2022 demonstrate economic shocks such as COVID-19 and the Ukraine-Russia War.

4. Methodology

The recent study deployed the daily data for analysis. The pre-estimation tests such as JB, Kurtosis, and skewness tests assert that all modeled series are asymmetric and non-normally distributed. For instance, the significance of skewness and kurtosis in the series reveal tail dependence, implying that all modeled series are asymmetrically distributed. Also, high variances also affirm the asymmetric distribution of the selected variables. Thus, Chishti et al. (2023a,b) argue that the application of mean-based econometric techniques while dealing with the asymmetric series may produce biased and inconsistent results. Hence, the econometricians (Hu et al., 2022; Liu et al., 2022; Saqib et al., 2023; Su et al., 2023) suggest that it is suitable to perform quantile analysis in order to handle the asymmetries in the series and to obtain robust and detailed results. Hence, the study tends to deploy the QVAR method, the Quantile-Quantile (QQ) method, and Rua's (2013) wavelet-based correlation method for empirical analysis.

4.1. QVAR method

Firstly, the study uses the novel QVAR method extended by Ando et al. (2022) that captures the dynamic connectedness among the modeled series by generating the quantile-wise heatmaps. The notable feature of the method is that it predicts the h-step ahead error variance decomposition. Following the Ando et al. (2022), we firstly compute the QVAR model in order to estimate the total connectedness among the selected variables. The mathematical form can be written as:

$$y_t = \alpha + \sum_{j=1}^{p} \theta_j y_{t-j} + u_t \tag{1}$$

where y_t, α, θ_j, and u_t are the vectors of the variable, intercept, matrix of parameters, and error term. For estimating h-step forward generalized forecast error variance decomposition, Ando et al. (2022) suggest the following expression:

$$\omega_{ij}^{g}(H) = \frac{\sigma(\tau)_{ii}^{-1} \sum_{h=0}^{H-1} \left(e_j A_j(\tau)\sigma(\tau)e_j\right)^2}{\sum_{h=0}^{H-1} \left(e_j A_j(\tau)\sigma(\tau)e_j\right)} \tag{2}$$

The above equation exhibits that $\omega_{ij}^{g}(H)$ is the response stemming from ith series' forecasted error variance at H horizon to the jth series. Further, σ represents error's variance vector. Next, to normalize the variance decomposition matrix, Ando et al. (2022) suggest:

$$\widehat{\omega_{ij}^{g}}(H) = \frac{\omega_{ij}^{g}(H)}{\sum_{j=1}^{k} \omega_{ij}^{g}(H)} \tag{3}$$

Based on the above mathematical expressions, we can compute the total dynamic connectedness and net total directional connectedness with the help of the following expressions.[1]

$$TRSI = \frac{\sum_{i=1}^{k} \sum_{j=1, i\neq j}^{k} \widehat{\omega_{ij}^{g}}(\tau)}{\sum_{i=1}^{k} \sum_{j=1}^{k} \widehat{\omega_{ij}^{g}}(\tau)} \times 100 \tag{4}$$

$$NSI_i(\tau) = TO_i(\tau) - FROM_i(\tau) \tag{5}$$

where equations (4) and (5) assist in computing the total dynamic and net directional connectedness among the modeled series. Besides, it is important to note that total dynamic connectedness, as reported by Khalfaoui et al. (2022), indicates the network interconnectedness degree, implying that higher the total connectedness leads to higher the degree of interconnectedness.

4.2. Quantile-Quantile (QQ) approach

After confirming the network interconnectedness among the selected series through total connectedness index, QQ method by Sim and Zhou (2015 is applied to assess the dynamic effects of independent series on electricity generation. To formulate the QQ model, study utilizes the following nonparametric framework:

$$V_t = b^{\theta}(indvar_t) + u_t^{\theta} \tag{8}$$

In the above equation, V_t and $indvar_t$ indicate the total connectedness (viz, total market volatility of electricity generation) and independent indices, correspondingly, in period t. Further, θ signifies the quantiles, and u_t^{θ} show the quantile-wise errors. Besides, b^{θ} indicate the unknown functional form which is need to be estimated. In order to transform equation (8) into linear form, 1st order Tylor expansion of $b^{\tau}(,)$, around the OP_t that can be written as:

$$b^{\theta} indvar_t \approx b^{\theta} indvar^{\tau} + b^{\theta}(indvar^{\tau})(indvar_t - indvar^{\tau}) \tag{9}$$

[1] To compute the NSI, we deploy the following equations of TO and FROM as given equation 6 and 7, respectively. $TO = \frac{\sum_{i=1,i\neq j}^{k} \widehat{\omega_{ij}^{g}}(\tau)}{\sum_{i=1,}^{k} \widehat{\omega_{ij}^{g}}(\tau)} \times 100$ $FROM = \frac{\sum_{i=1,i\neq j}^{k} \widehat{\omega_{ij}^{g}}(\tau)}{\sum_{i=1,}^{k} \widehat{\omega_{ij}^{g}}(\tau)} \times 100.$

Table 1
Statistical description.

	CE	CEI	GPR	ET	EG
Mean	2003.442	331.657	101.593	203.512	4325.139
Variance	526291.588	7105.944	3284.31	4838.802	187262.547
Skewness	0.718***	0.626***	2.100***	1.106***	0.681***
	0.000	0.000	−0.003	0.000	0.000
Ex.Kurtosis	−0.461***	−0.792***	8.875***	0.528***	0.016
	0.000	0.000	0.000	0.000	0.000
JB	213.454***	206.145***	9049.727***	485.590***	173.929***
	0.000	0.000	0.000	0.000	0.000
ERS	−19.061***	−6.364***	−5.154***	−18.773***	−17.746***
	0.000	0.000	0.000	0.000	0.000
Q(10)	17.691***	37.716***	265.180***	11.530**	42.249***
	−0.001	0.000	0.000	−0.034	0.000
Q2(10)	602.171***	979.810***	311.546***	0.012	1722.016***
	0.000	0.000	0.000	−1	0.000

Equation (9) demonstrates the double indexing of $b^{\theta}\boldsymbol{indvar}^{\theta}$ and $b^{\theta}(\boldsymbol{indvar}^{\theta})$ in τ and θ. It indicates that $b^{\theta}\boldsymbol{indvar}^{\theta}$ and $b^{\theta}(\boldsymbol{indvar}^{\theta})$ are the functions of τ and θ. Thus, the equation can be expressed as:

$$b^{\theta}(indvar_t) \approx b_0(\tau,\theta) + b_1(\tau,\theta)\left(indvar_t - indvar^{\theta}\right) \tag{10}$$

To obtain the final version of the equation, we put the Equation 7 into Equation (5) as:

$$EG_t = \underbrace{b_0(\tau,\theta) + b_1(\tau,\theta)\left(indvar_t - indvar^{\theta}\right)} + u_t^{\theta} \tag{11}$$

In Equation (11), the part in $\underbrace{\quad}$ indicates the θ th conditional quantile of EG_t. Moreover, the part $\underbrace{\quad}$ expresses that how global electricity generation responds to the independent series, considering the whole distribution of both series. Besides, τ, and θ represent the quantiles of each independent series, while, unlike the standard quantile regression, b_0 and b_1 are indexed in τ, and θ.

4.3. Wavelet correlation method

Finally, the study tends to deploy the Rua's (2013) wavelet correlation technique for robustness check of the QQ's findings. The notable benefit to use the wavelet-based correlation method is it can capture the asymmetric association during the sampled period while considering the likely economic shocks (Chishti et al., 2023a,b; Rua, 2013). The mathematical expression to measure the correlation, as suggested by Rua (2013) can be presented as:

$$\rho_{XY}(s,\tau) = \frac{\gamma\left\{s^{-1}\left|\beth\left(W_{XY}^{m}(s,\tau)\right)\right|\right\}}{\gamma\left\{s^{-1}\sqrt{\left|W_X^{m}(s,\tau)\right|^2}\right\}.\gamma\left\{s^{-1}\sqrt{\left|W_Y^{m}(s,\tau)\right|^2}\right\}} \tag{12}$$

The above equation calculates the wavelet-based correlation, while the values of $\rho_{XY}(s,\tau)$ ranges between −1 and +1.

5. Results and discussion

In this section, the study performs the three advanced econometric methods (i.e., QVAR method, Quantile-slope estimate (QSE) method, and Rau's wavelet-based correlation (RWC) method to obtain the detailed and robust results. Firstly, the QVAR technique is deployed in order to confirm the dynamic connectedness among the selected series. Next to this, the study opts to apply QSE technique to analyze the bivariate effects. In the end, the study relies on RWC method and QVAR based network plot analysis in order to affirm the robustness of the results.

5.1. Dynamic connectedness analysis

The QVAR method by Chatziantoniou et al. (2021), which is based on the 10-step forecast horizon and 200-day rolling window, is used in the study to look at the total dynamic and net total dynamic connectedness among the chosen series. As for the total dynamic connectedness, it is reported in Fig. 4, which is based on the QVAR's heatmap for EG and other opted series. The hot and cold colors on the color bar next to Fig. 4 show a high level of connectedness and a low level of connectedness, respectively. Where the total dynamic connectedness is concerned, as Fig. 4 depicts, it can be divided into two sub-time periods: before 2020 and after 2020. Before 2020, it can be noticed that the hot shadow covers the area below the 30% quantile and above the 70% quantile. It implies that all the selected series are highly connected to each other during the aforementioned quantiles on account of the likely high-level oscillations and uncertainty. Interestingly, the period after 2020 demonstrates a higher level of dynamic connectedness. For instance, the time between 2020 and 2021 and after 2022 shows the hot shadow that covers approximately 0–100% quantile. It indicates the high ratio of connectedness during 2020–21 and after 2022 is likely due to recent economic shocks such as COVID-19 and URW. Further, the in between time of 2021 & 2022 also exhibits a high ratio of connectedness while covering the area below the 40% quantile and above the 60%. To recapitulate, a high ratio of total dynamic connectedness is witnessed among the all-modeled variables.

Next, the net total connectedness for EG, CEI, GPR, ET, and CE are reported in Figs. 5–9, respectively. Again, for the analysis, the QVAR model based on 200 rolling window periods along with the 10-day forecast is deployed. Further, each heatmap possesses a warmer red and warmer blue color (also, as shown in the color bar given with the left-side of each heatmap), indicating the net receipt and net transmitting indexes, respectively. For instance, Fig. 5 depicts the case of EG. It can be seen that before 2020, red as well as blue but not deep colors exhibit the mixed behavior of the EG to the other selected series during the various quantiles. Simply, the series of EG is net receipt as well as transmitting index before 2020. After 2020, the dominant blue color shade can be observed until the end of 2022 over the various quantiles. It implies that the EG series becomes the net receipt index, likely due to the COVID-19 and URW. Additionally, the CEI (in Fig. 6) and ET (in Fig. 8) also show overall the behavior of the net receipt index, as the dominant blue color shade over time and across the various quantiles can be observed. Intriguingly, the circular economy affects the other series, as red shades can be observed in Fig. 9. Besides, GPR plays the role of net contributor specifically after 2020 and 2022, as the deep red shades can be noticed in Fig. 7 across the various quantiles, implying the notable effects of COVID-19 and URW.

5.2. QQ method's results

After confirming the dynamic connectedness among the selected series, it is worth estimating the sensitivity of the CE, ET, CEI, and GPR towards the EG. The QQ method is used to figure out the slopes of the

Fig. 3. Overall trends in the opted series.

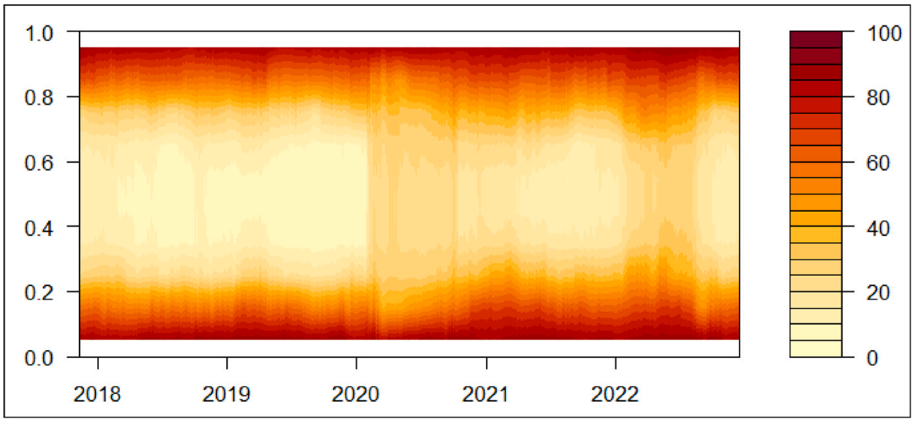

Fig. 4. Dynamic total connectedness based on EG. (Note: The heatmap is measured based on a 200-days rolling window QVAR (1) and 10-variate-ahead forecast.).

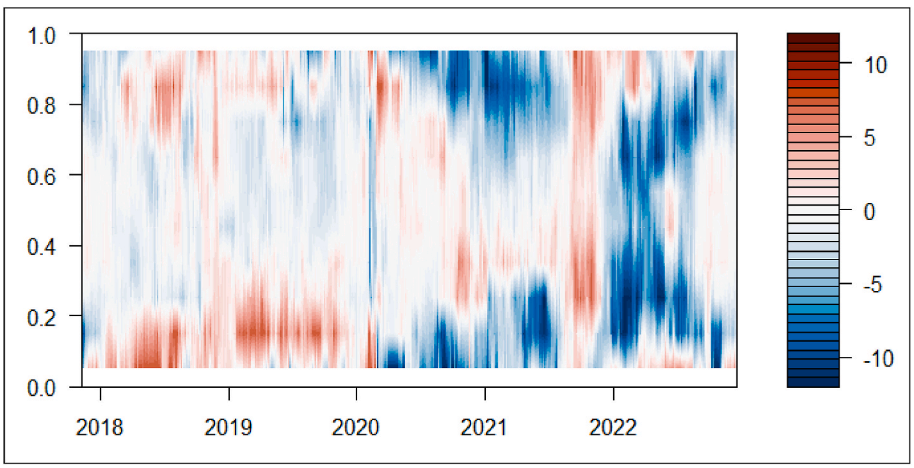

Fig. 5. Net total directional connectedness for EG (Note: See Fig. 4 for more details).

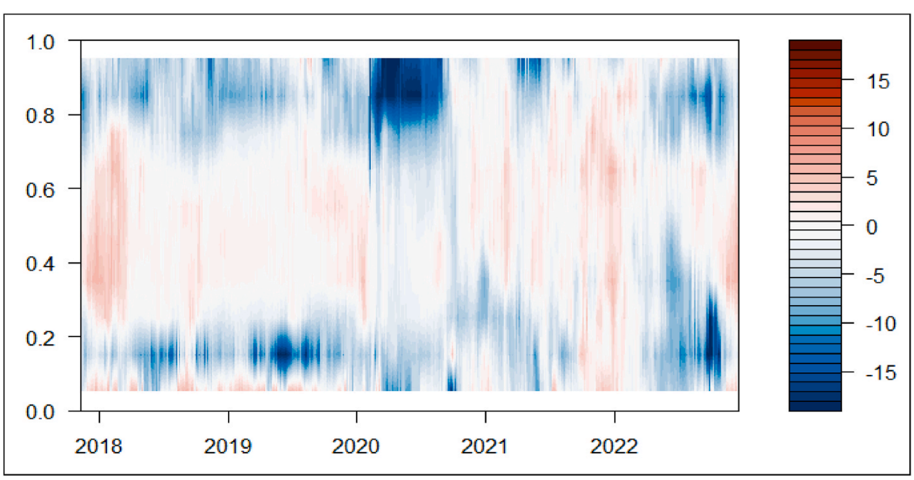

Fig. 6. Net total directional connectedness for CEI (Note: See Fig. 4 for more details).

modeled series in the study. In each QQ heapmat, quantiles from 0 to 0.4 show lower quantiles, quantiles from 0.4 to 0.6 show medium quantiles, and quantiles from 0.6 and up show higher quantiles. Further, the color bar along with each heatmap helps in deciding the direction of the nexus, whether it is positive or negative. As for the GPR-EG nexus reported in Fig. 10, the results suggest a significant but negative sensitivity of GPR to EG across the various quantiles. For instance, the lower quantiles of GPR show the significant negative effects on the lower to higher quantiles of the EG. The same negative sensitivity can be witnessed when noticing the response of all qunatiles of EG to the medium qunatiles of GPR. Notably, the GPR's higher qunatiles indicate the extreme negative sensitivity to the EG's lower to higher qunatiles, implying the significantly negative association between the GPR and EG. Whereas the nexus between CEI and EG is concerned, overall significant

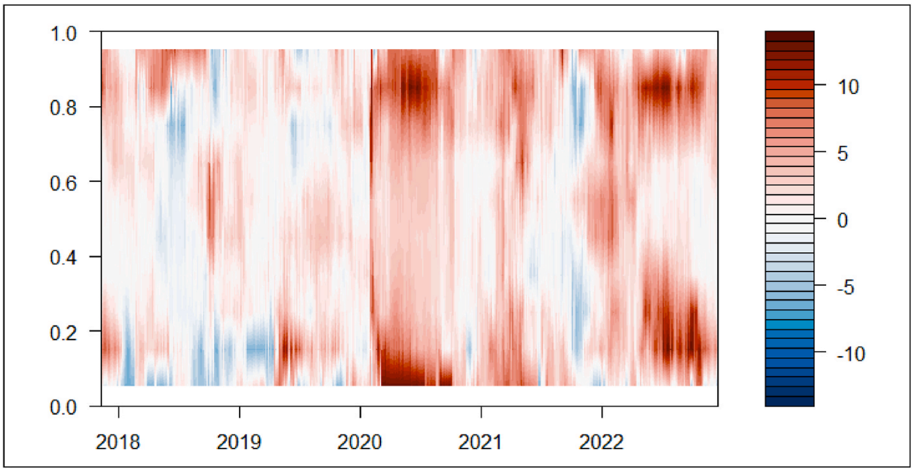

Fig. 7. Net total directional connectedness for GPR (Note: See Fig. 4 for more details).

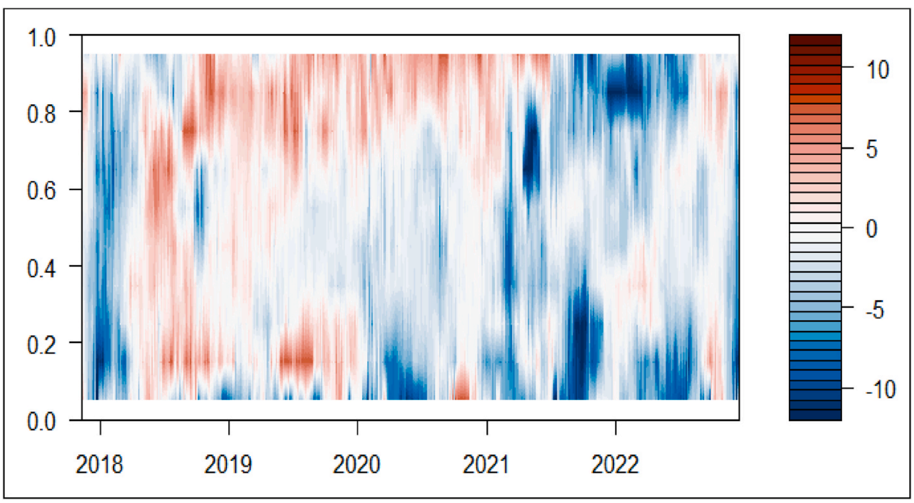

Fig. 8. Net total directional connectedness for ET (Note: See Fig. 4 for more details).

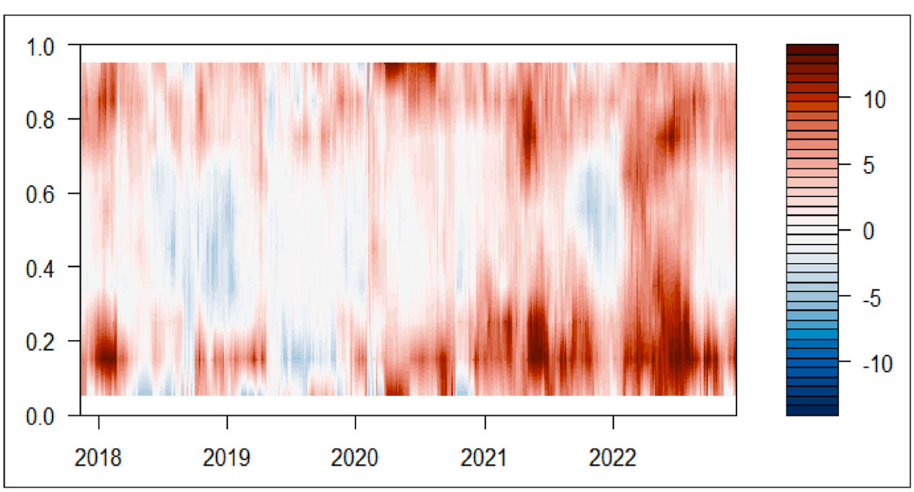

Fig. 9. Net total directional connectedness for CE (Note: See Fig. 4 for more details).

and positive association is observed across the various qunatiles as reported in Fig. 11. For example, CEI's lower qunatiles demonstrate the positive link with the EG's lower to higher quatiles, implying the encouraging effects of CEI on the EG. The same effects of CEI on EG are noticed during the response of medium qunatiles of CEI to the EG's lower to higher qunatiles. In the same way, the higher quantiles of the CEI have a strong and positive relationship with both the lower and higher quantiles. Except the lower quantiles of EG, which exhibit the

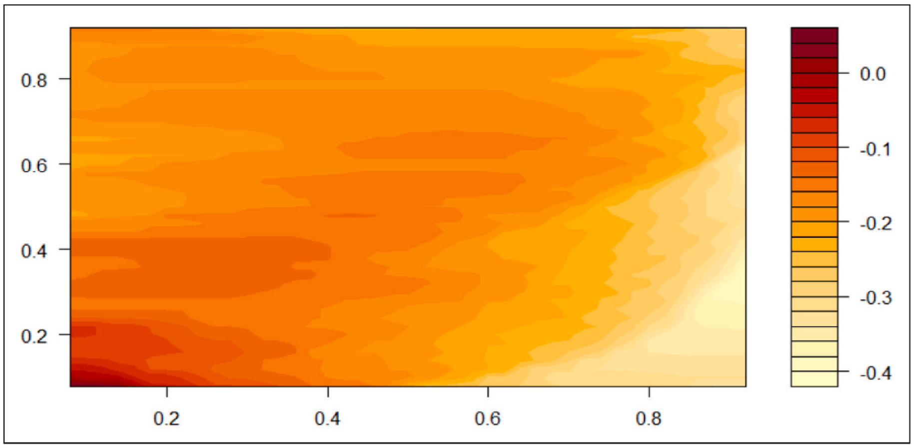

Fig. 10. Quantile slope computation of GPR's effects on EG.

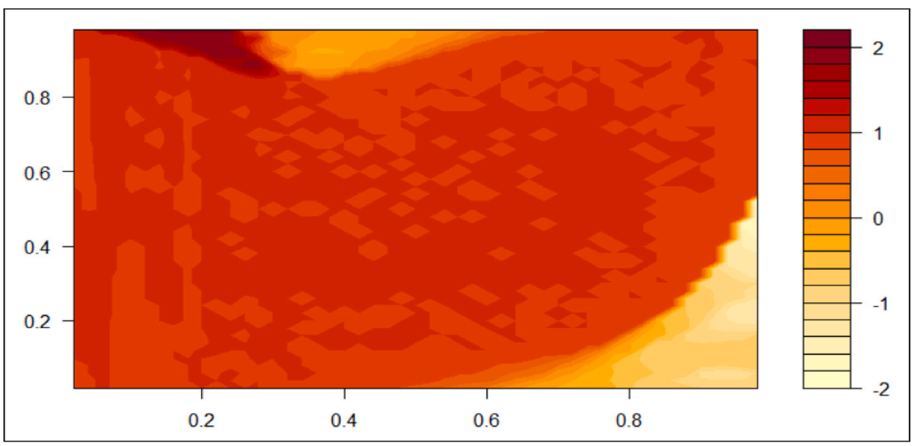

Fig. 11. Quantile slope computation of CEI's effects on EG.

negative response to the extreme quantiles of CEI. In the case of the ET-EG nexus, as presented in Fig. 12, mixed but predominantly positive effects are observed. For instance, the lower qunatiles of the ET possess significant and positive effects on the lower qunatiles of the EG. However, ET's lower qunatiles impact on the medium and higher qunatiles of the EG becomes mixed, such that ET shows positive, negative, and no effects on the EG across the aforementioned qunatiles. Further, the ET's medium quantiles have a positive link with the same quantiles of the EG. In addition, the higher qunatiles of ET show positive as well as negative effects, as these qunatiles affect the EG's lower qunatiles negatively and the higher qunatiles positively. Summing up, ET predominantly encourages the EG process.

In terms of the CE-EG link, Fig. 13 shows that there are overall positive effects across all quantiles. For instance, the lower to middle quantiles of CE have a big and positive effect on the same quantiles of EG. However, the positive link becomes weak while observing the CE's

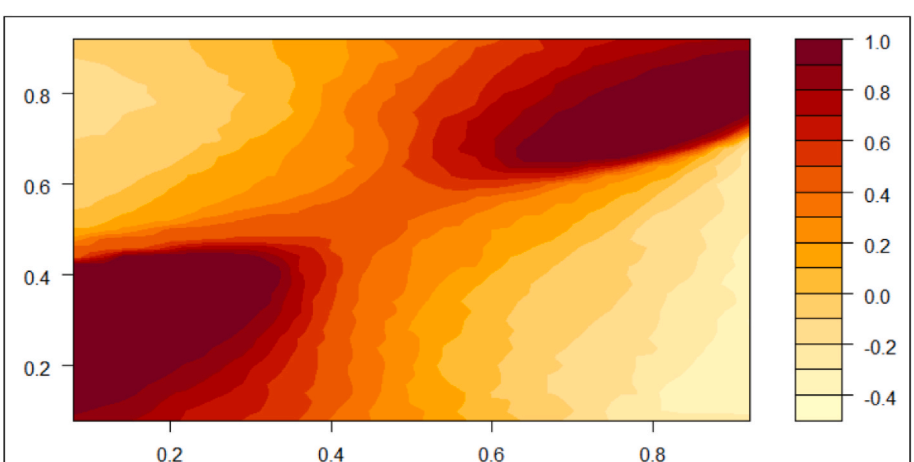

Fig. 12. Quantile slope computation of ET's effects on EG.

higher quantiles effects on the lower-higher quantiles of EG. Further, a significant and positive association is observed when looking at the response of EG's higher qunatiles to the CE's extreme qunatiles. In sum, all the independent series significantly and positively affect the EG across most of the quantiles, except in the case of GPR, which adversely affects the EG process across the various quantiles.

5.3. Robustness check

To assess the reliability of the above results, the study relies on two robustness checks: network directional connectedness based on the QVAR method (NDC) and Rua's wavelet-based correlation method (RWC). As for the NDC's outcome, the network plot elaborates on the net directional connectedness among the modeled series, as Fig. 14 shows. From the nodes on the network, it can be inferred that GPR is a major transmitter of spillover effects, while EG is the major recipient. Further, CEI, ET, and CE are the transmitters as well as the recipients of the spillover effects. Notably, all the independent series have significant spillover effects on the EG, supporting the main results of the QVAR and QQ methods. It implies that GPR, ET, CEI, and CE are the significant determinants of the global EG.

The second method that is applied for robustness checking is the RWC method. The notable characteristic of the method is that it measures the wavelet-based correlation between the series across the whole time period, while indicating the significance level of the associations. Besides, it is assumed that the periods given on the left side of each graph represent the various time periods. For instance, 0–8 signifies the short run (SR), 8–32 signifies the medium run (MR), 3–128 signifies the long run (LR), and 128–256 signifies the very long run (VLR). Fig. 15 shows the wavelet-based association between ET and EG. The outcome demonstrates that ET has a mixed association level with the EG in the SR to MR across the whole sample period. In the LR and VRL, the association tends to be positively significant across the whole sample period, supporting the previous results.

Where the correlation between CE and EG is concerned, Fig. 16 indicates that CE possesses a mixed association with the EG in the SR and MR. However, in the LR and VLR, the CE predominantly exhibits a significant and positive link with the EG. The same findings are witnessed in the case of CEI, as Fig. 17 reports. However, in the VLR, the CEI shows the significant adverse effects on EG during 2020 and 2021. In the case of GPR, as Fig. 18 reports, it is noticed that GPR shows a mixed association with the EG during the SR and MR across the whole sample period, but the adverse impacts remain dominant. While the LR and VLR periods suggest a significant adverse association between GPR and EG, specifically after 2020, It may be on account of COVID-19 and URW, which occurred after 2020. Summing up, the outcomes of the NDC and RWC categorically support the core results of the study.

5.4. Discussions

To analyze the dynamic connectedness between energy transition, environmental policy (CEI), circular economy, geopolitical risk, and electricity generation (EG) at the global level, the recent study relies on several advanced econometric methods such as the QVAR method, the QQ approach, and the wavelet-based correlation method. Where the dynamic effects of environmental policy are concerned, the heatmap based on QVAR in Fig. 6 determines that environmental policy series are a significant recipient. Similarly, QQ method-based Fig. 11 confirms the significant positive effects of environmental policy on the EG level. The network plot based on the QVAR model in Fig. 14 confirms the aforementioned results by confirming the significant environmental policy spillover effects on the EG ratio. Also, wavelet-based correlation's outcome in Fig. 17 endorses the significantly positive effects of environmental policy, supporting the above outcomes. In a similar vein, the results suggest that the energy transition significantly contributes to enhancing the electricity generation process, as reported in Figs. 8, 12, 14 and 15. Economically, there are several likely reasons to support the positive nexus between environmental policy and global EG. Firstly, the global economies have taken significant measures to practice environmental policies by supporting green investment to escalate the green energy ratio. This process eventually triggers global electricity generation. For instance, the Green Climate Fund (2022) has reported that 209 green energy projects have been initiated with the collaboration of 194 nations. The organization has set aside $11.4 billion for this purpose. Secondly, the global authorities support green electricity generation by providing subsidies to the green energy markets. For example, the EU collected approximately $321.5 billion in environmental taxes in 2020 to support the green energy level (Eurostatistics, 2022). Also, global nations are endeavoring to enhance green technologies to foster green energy markets. All the aforementioned steps ultimately contribute to increasing global electricity generation.

Like environmental policy and the energy transition process, the circular economy process also significantly assists in boosting electricity generation, as the results in Figs. 9, 13, 14 and 16 suggest. Logically, the circular economy process, unlike the linear economy, focuses on minimal waste, recycling, and reusing. This process minimizes the cost of production, including the production cost of electricity generation. For instance, the circular economy relies on the pyrolysis method for recycling, which generates energy while using a low temperature, resulting in the generation of electricity. Hence, several global companies are reusing the local wastes that are already available, transforming them to increase their lifespan, and pooling resources. Similar to this, the automotive industry is also endeavoring to design sustainable cars using recycled and recoverable materials and reusing electric car batteries. Also, the mining industry' experts are looking into ways to boost the

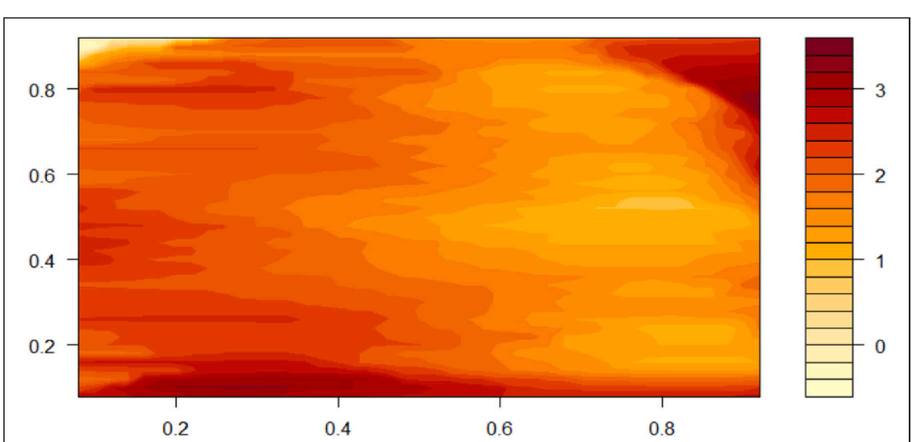

Fig. 13. Quantile slope computation of CE's effects on EG.

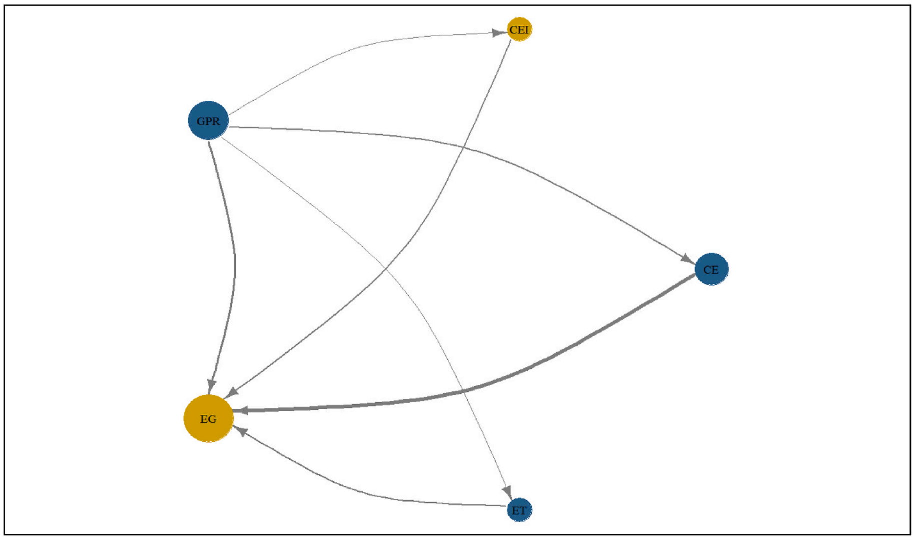

Fig. 14. QVAR based network plot for spillover effects. Lag = 6 (SIC criteria); forecast horizon = 100 days.

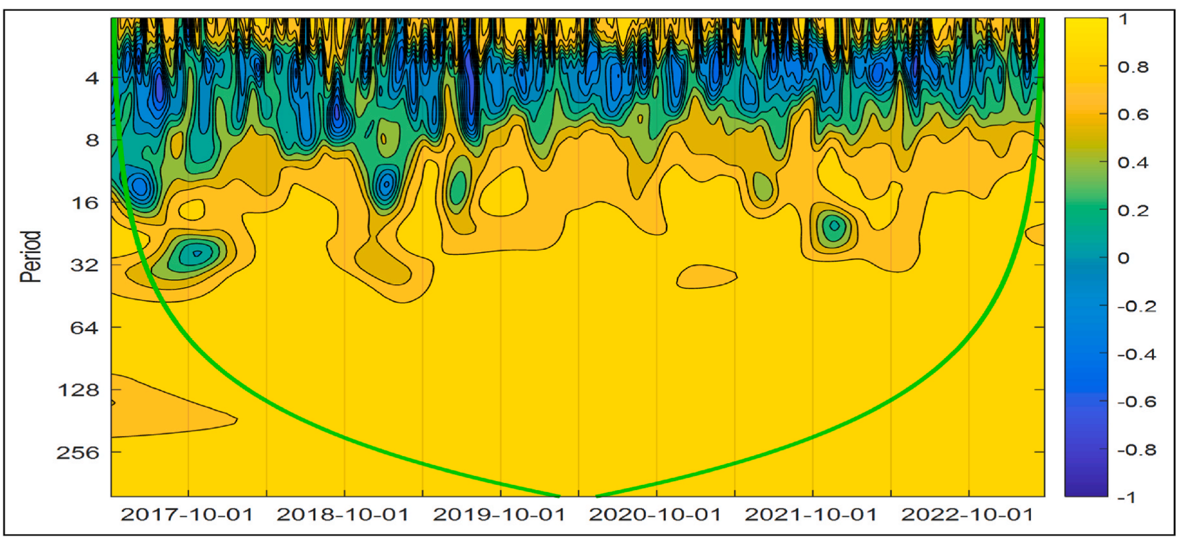

Fig. 15. Wavelet-based correlation between ET and EG.

environmental viability of their operations by recovering commodities from waste streams through fulfilling energy demands (Atlas Renewable Energy, 2022).

Finally, the results determine the detrimental effects of geopolitical risk (GPR) on the electricity generation process, as Figs. 7, 10, 14 and 18 report. There are several likely reasons for this outcome. Firstly, GPR causes economic uncertainty on account of the various economic shocks such as the financial crisis, COVID-19, and UKW. The uncertainty tends to disrupt the investment and production processes, which ultimately decrease the global outcome, including the global generation of electricity. Secondly, GPR tends to cause high inflation, which makes the production process costly. This process eventually curtails the generation of electricity. The study's results are of remarkable importance for recommending the policy recommendations that should enhance local and global electricity generation.

6. Conclusions

By far, the study reveals that the circular economy is the crucial factor that considerably encourages global electricity generation. Similarly, energy transition and environmental policy also significantly support the production of global electricity. However, geopolitical risk plays a critical role and significantly deteriorates the production ratio of global electricity. Summing up, the study's findings explicitly support the research question by affirming the circular economy, energy transition, environmental policy, and geopolitical risk as the vital determinants of global electricity generation.

Based on the findings, the study recommends the following policies to enhance the global electricity generation level: Firstly, the results reveal the circular economy process as the crucial determinant of sustainable electricity generation. The following policies are recommended to enhance the adoption of the circular economy: Global economies that are practicing the circular economy policy, such as China, Chile, Japan, and other leading countries, should share their experiences and best practices on international forums to motivate other nations. International forums such as the United Nations (UN), World Economic Forum (WEF), World Trade Organization (WTO), etc. should organize events, workshops, and seminars to promote the adoption of circular economy practices among all nations. In addition, governments should offer incentives and assistance to enterprises and industries that implement circular economy methods. Tax breaks, subsidies, and other financial incentives can be used to encourage businesses to invest in sustainable

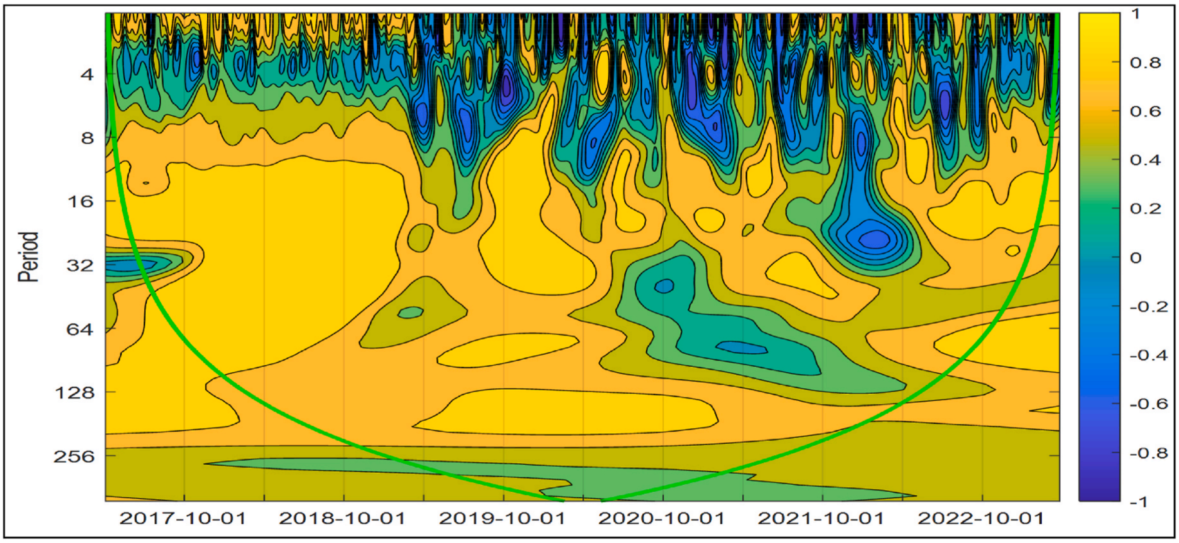

Fig. 16. Wavelet-based correlation between CE and EG.

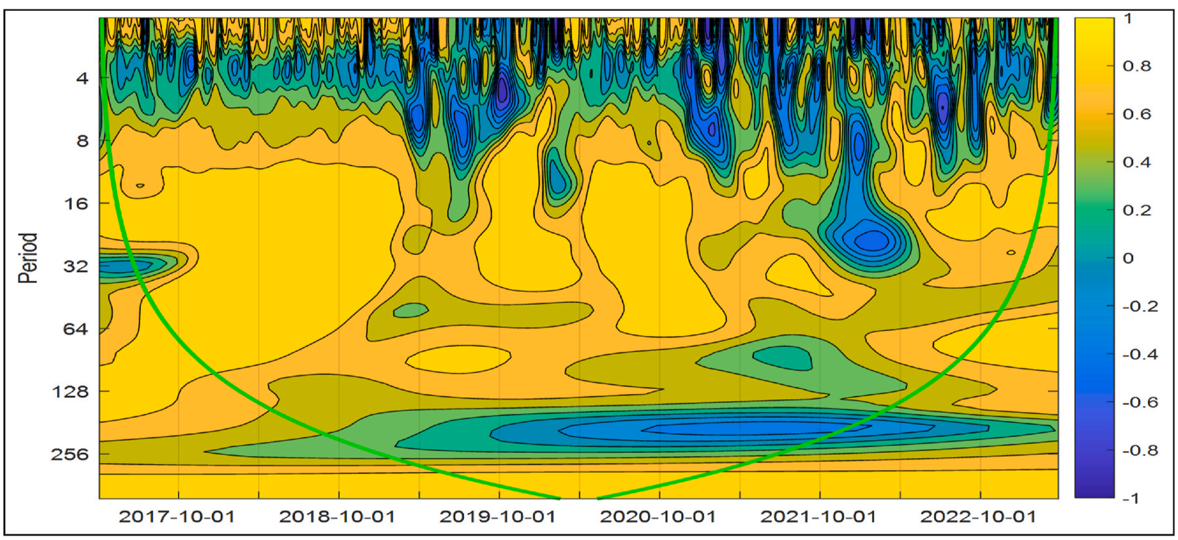

Fig. 17. Wavelet-based correlation between CEI and EG.

practices. Governments should also implement rules that stimulate the use of recycled materials, reduce waste, and support the development of environmentally friendly products. Besides, coordination among governments, industries, and other stakeholders is crucial to developing circular economy practices. Governments should collaborate with businesses, industry groups, and other relevant stakeholders to create policies, rules, and guidelines that encourage the use of circular economy methods.

Secondly, the results assert that geopolitical risk disrupts global electricity generation. The global authorities should focus on erecting international collaboration via economic and political ties to bridge the political and economic distances between developing and developed nations. This step may help in reducing the detrimental repercussions of geopolitical risk by minimizing the uncertainty stemming from the various regions. Further, international integration may assist in curtailing local and regional conflicts such as the Ukraine-Russia War, resulting in a decreased risk. Besides, the global international forum can also help in preparing the proper policies in order to deal with global shocks such as COVID-19. By following the aforementioned steps, it is expected to increase the stability of global markets, including sustainable electricity generation, while reducing global geopolitical risk.

Thirdly, the results show that environmental policy and energy transition are considerable determinants of electricity generation. In this context, the following steps may play an effective role in boosting sustainable electricity generation: The global authorities should welcome the global paradigm shift towards sustainable green development by following the footsteps of global treaties such as the Kyoto Protocol, the Paris Agreement, COP26, and COP27. Further, developed nations should promote green energy investment in developing nations by increasing green FDI. Additionally, the local authorities should impose gradual green taxes to support the green subsidies.

Finally, the recent study also suffers from some limitations that may assist in opening new vistas for future scholars. For instance, the recent article deploys global level indices to provide global-level evidence. Future scholars can testify to the same model for various regions and economies for more interesting and policy-oriented findings. Also, the recent study deployed linear methods for analysis. The researchers can use asymmetric methods for more detailed results. Finally, the recent article confirms the circular economy, energy transition, environmental policy, and geopolitical risk as the new drivers of electricity generation. For more interesting findings, future studies can enrich the model by including some other economic series such as blockchain technology,

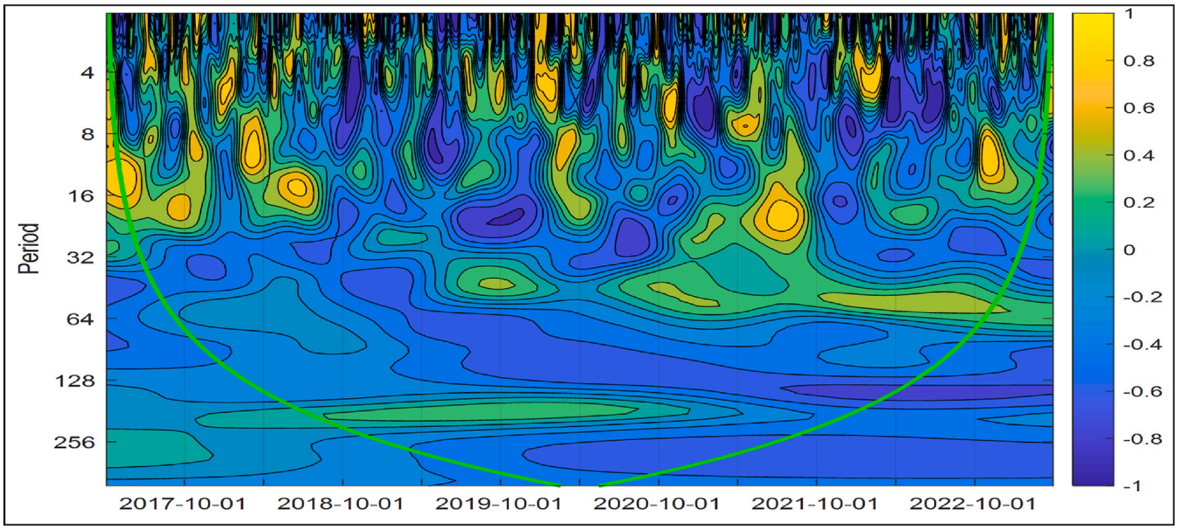

Fig. 18. Wavelet-based correlation between GPR and EG.

information and communication technology, the Ukraine-Russia War Index, terrorism, business freedom, and tourism.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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