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Unveiling the role of renewable energy in mitigating environmental degradation and energy poverty

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Abstract. This study applies wavelet coherence analysis to examine if transitioning to green energy through renewable energy consumption (RE) could reduce environmental degradation (carbon dioxide emissions, CO_2) and energy poverty by comparing high income, middle income and low income countries. The data spanned from 2000 to 2023. The results reveal strong negative correlation between RE and CO_2, verifying that RE could lead to environmental quality improvement in all groups of countries in the short term, but less effective in the long term. The correlation between RE and energy poverty (EP1 – access to electricity; EP2- access to clean fuel) varies across countries. The low income group experienced the improvement in energy poverty (EP1 and EP2) in the short term, while the impacts of RE on energy poverty is mixed in the high and middle income groups. Hence, transitioning to green energy is most beneficial to low income group.

1 Introduction

Against the backdrop of increasingly severe global climate change, energy poverty and environmental degradation have become one of the important social issues of global concern [1]. To address this challenge, the international community is constantly seeking systematic solutions. These SDGs highlight the close connection between energy poverty and environmental degradation, as insufficient energy access not only restricts people's ability to obtain clean water, sanitation conditions and basic services, but also prompts some regions to continue to rely on highly polluting traditional energy sources, exacerbating the degradation of the ecological environment [2]. However, under the multiple shocks of the pandemic, conflicts and climate change, although some of the SDGs have made progress, many key issues such as poverty eradication and climate change are still lagging behind. The overall global progress is far from reaching the 2030 vision.

As one of the new types of poverty, energy poverty is mainly manifested in the deprivation of aspects such as the affordability of living energy use, the availability of energy services, the cleanliness of energy use [3]. According to World Bank data, from 1990 to 2020, the proportion of renewable energy consumption in high income countries rose from 5.97%

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to 12.78%, in middle income countries it remained within the range of 22% to 33%, and in low income countries it has consistently stayed above 50%, reflecting significant differences among various economies in their green energy transition paths [4]. Although low income countries have a relatively high proportion of renewable energy, this is mainly due to their reliance on traditional bioenergy sources such as charcoal. These energy sources are often accompanied by high pollution and low efficiency, further exacerbating environmental degradation. It can be seen from this that this energy structure more reflects the reality of limited resource access and energy poverty rather than a true green energy transition.

Although the development of energy poverty and environmental degradation has received widespread global attention, its severity and impact may vary from country to country. At the same time, it remains unclear how the effectiveness of the transition to green energy demonstrates its achievements across different economies. In existing research, studies on green energy, environmental degradation and energy poverty are increasing [5]. However, most scholars often discuss environmental degradation and energy poverty as independent themes, lacking effective analysis of green energy on the two, especially in different levels of economic development. Therefore, this study attempts to explore the role of renewable energy in addressing the dual challenges of environmental degradation and energy poverty at different income levels. The main contributions of this study are reflected in the following aspects: Firstly, this research enriches the study on the role of renewable energy in environmental degradation and energy poverty. Secondly, starting from economies of different incomes, the effectiveness of green energy in playing a role in countries at different stages of development has been expanded. Finally, this study employs Wavelet analysis to better capture the long-term and short-term dynamic relationships among variables, providing more targeted policy implications for achieving the SDGs.

1.1 Background study

The concept of energy poverty has long received extensive attention in the academic community and in policy formulation. There is no unified definition of energy poverty. [6] demonstrated a nonlinear relationship between energy consumption and income levels. This phenomenon reveals a special form of poverty. Therefore, scholars have proposed the concept of “fuel poverty” to specifically refer to those families that encounter difficulties due to their inability to afford basic energy expenses, especially in terms of heating and maintaining a suitable living temperature. Subsequently, [7] started from the perspective of energy consumption and proposed the “10% rule” as the criterion for judgment. However, [8] proposed a definition different from Boardman, namely the Low Income High Cost (LIHC) indicator. Subsequently, IEA proposed that the situation of energy poverty is characterized by households being severely constrained by modern energy supplies and being forced to mainly rely on solid fuels such as firewood and coal to meet basic cooking and heating needs. Due to significant differences in economic and social development levels, many scholars have successively proposed the concept of energy poverty applicable to both developed and developing countries. Although there are differences in definitions, the academic community has gradually reached a consensus: Energy poverty, as a common governance challenge in the global green energy transition process, is essentially the obstacle to the accessibility of clean energy faced by vulnerable groups, thereby exacerbating social inequality.

Energy poverty and environmental degradation are the two key challenges currently faced by global sustainable development. Energy poverty reflects that there are still huge gaps in access to modern energy in many regions, especially among low income groups and remote areas [9]. Environmental degradation stems from the excessive consumption of resources and ecosystem imbalance caused by the long-term reliance on non-renewable energy sources. The two are closely related, not only reflecting the contradiction between development and the environment, but also becoming an important driving force for promoting the transformation of green energy.

1.2 Literature review

The academic community generally believes that renewable energy has a positive impact on alleviating energy poverty and improving environmental degradation. Renewable energy offers low income and resource poor regions the possibility of accessing electricity and clean energy, which helps to enhance energy accessibility. And the promotion of clean energy also helps to reduce carbon emissions and environmental pollution and promotes the achievement of the goal of sustainable development [10]. Meanwhile, the use of renewable energy may be hindered by poverty and income.

At present, research on the influencing factors of energy poverty mainly focuses on three aspects: family characteristics, socio-economic and environmental factors. Studies by [11] and [12] have both found that income poverty is the main factor affecting energy poverty. Social factors can also alleviate energy poverty. For instance, [13] holds that education effectively reduces the risk of energy poverty by enhancing human capital and easing borrowing constraints. In terms of environmental impact, in the Indian context, the development of renewable energy and the construction of a sustainable energy system have effectively alleviated energy poverty and improved environmental quality [14]. In addition, many scholars have also analyzed other influencing factors of energy poverty. [15] holds that green finance will help alleviate energy poverty. Renewable energy is the key to alleviating energy poverty and the fundamental way to improve environmental conditions. The influencing factors of CO_2 emissions have always been one of the hot topics in the field of global climate change research. Many scholars have conducted research from several influencing aspects such as energy, population, economy, technological innovation, and natural environment [16]. Among the numerous influencing factors, economic factors have received the most extensive discussion. In the context of COP-26, [17] employed Mean Group regression and found that economic growth in low and middle income countries was positively correlated with carbon emissions, while economic growth in high income countries was negatively correlated with carbon emissions. Similarly, [18] found that GDP has a significant impact on GHG emissions in both low income countries.

Existing studies have also gradually realized that renewable energy plays an important role in addressing energy poverty and environmental degradation [19]. [20] focused on the EU and found that when renewable energy becomes the main source of energy supply, it ultimately helps to reduce energy poverty. [21] also mentioned that changing the current energy structure is a necessary condition for reducing CO_2 emissions. That is to say, the shift from traditional fossil fuels to clean and renewable energy is the key to achieving the SDGs. Research on the relationship between energy poverty, CO_2 emissions and renewable energy has also begun to make some scholars gradually realize that their relationship is not isolated. This is to some extent due to the fact that the process of renewable energy replacing traditional energy is gradual rather than sudden. Consumption of fossil fuels has exacerbated environmental hazards both in the short term and the long term, and increasing the use of renewable energy can improve environmental quality.

2 Data

In this study, we collected data from high, middle and low selected countries during the period from 2000 to 2023. The selected countries were classified based on the World Bank's

2024 Atlas per Capita Gross national income (GNI). All data are collected from the World Bank, namely renewable energy consumption (as % of total final energy consumption, RE), access to electricity (% of population, EP1), access to clean fuels and technologies for cooking (% of population, EP2) and carbon dioxide emissions per capita (t CO_2 e/capita). World Bank provides aggregated data for these three groups of countries directly. As the time series are quite short and in annual frequency, upscaling to quarterly frequency through cubic interpolated method is performed, this enables more detail and more accurate analysis, especially in the wavelet coherence trend and correlation analyses. This allows for a finer-grained view of trends and patterns that might be missed when looking at data collected at longer intervals. This method assigns each value in the low frequency series to the first or last high frequency observation associated with the low frequency period, then places all intermediate points on a natural cubic spline connecting all the points. The converted data spanning from 2000Q1 to 2023Q4.

3 Methodology

In this study, wavelet coherence analysis is applied in examining the correlation and dynamic interactions between renewable energy and indicators (carbon dioxide emissions and energy poverty – EP1 and EP2). The analysis is on pairs of variables where, x is RE and y could be CO_2, EP1 and EP2. Wavelet coherence analysis is based on the continuous wavelet transform (CWT), in charactering cross-correlations between pairs of variables. CWT is a tool used in analyzing time-frequency domain of time series data applies to stationary and non-stationary data [22].

Wavelet coherence is defined as:

$$R_{xy}^2 = \frac{\left|S(W_{xy})\right|^2}{\left[S\left(\left|W_x\right|^2\right)S\left(\left|W_y\right|^2\right)\right]} \text{ where } 0 \le R_{xy}^2 \le 1. \tag{1}$$

where S is a smoothing operator; W_x and W_y are continuous wavelet transforms of the time series x and y respectively at position τ and scale s; W_{xy} denotes the cross-wavelet transform, i.e. $W_{xy} = \frac{1}{s} W_x \cdot W_y$. The value of 0 indicates no coherence while 1 indicates perfect coherence between the two series at a specific time and scale. The wavelet coherence graph shows the time-frequency plots between two series, where the x-axis represents time, while the y-axis represents the scale or frequency. Coherence values are shown using color gradients, with higher coherence typically indicated by warmer colors like red, and lower coherence shown by cooler colors like blue. The wavelet coherence provides interpretations of analysis based on phase differences (phase x - phase y), displayed as arrows in the plot of cross-wavelet power. The phase difference:

$$\phi_{xy} = \tan^{-1}\left(\frac{\Im\left(S\left(W_{xy}\right)\right)}{\Re\left(S\left(W_{xy}\right)\right)}\right),\ \phi_{xy} \in \left[-\pi, \pi\right] \tag{2}$$

The interpretations can be as summarized as below (Table 1) [23]:

Table 1. Phase differences and interpretations.

Phase difference, ϕ_{xy}	Arrow	Remark
$\left(0, \frac{\pi}{2}\right)$	↗	Positive correlation, x leads y

$\left(-\frac{\pi}{2},0\right)$	↘	Positive correlation, y leads x
$\left(-\pi,-\frac{\pi}{2}\right)$ $\left(\frac{\pi}{2},\pi\right)$	↙ ↖	Negative correlation; x leads y Negative correlation; y leads x
π , $-\pi$ 0	← →	Negative correlation; x and y move opposite Positive correlation; x and y move together

4 Results

Wavelet coherence provides the phase difference plots, where the y-axis scale or frequency 4, 8, 16 and 32 quarters, enabling interpretations of results according to short, medium and long-run correlations. The x-axis is the time or date in quarters, representing the sample date started 2000Q1, such that quarter 1 represents this starting date, quarter 2 represents 2000Q2 and so on. The darker and hotter color indicate stronger correlations. These darker and hotter areas are indicated by arrows to further show the directions of correlations. The brighter and cooler colors are without any arrow as they represent weak correlations.

4.1 Impact of RE on CO_2

Figure 1 shows the wavelet coherence plots of RE on CO_2. The transition to green energy with higher renewable energy consumption leads to positive outcome in terms of greener environmental quality (lower CO_2). However, the impacts might differ across groups of countries.

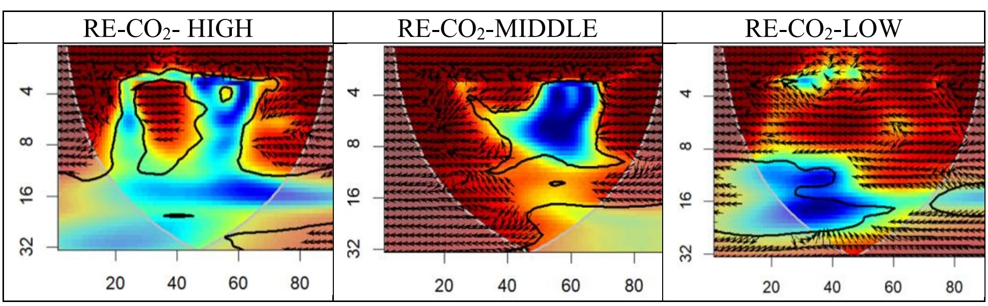

Fig. 1. Wavelet coherence plots of RE on CO_2.

The wavelet coherence plots show that the low income group exhibits a much larger red color area than the high income group. The phase difference plots show that RE- CO_2 is stronger in low income group. Next, compare the frequency of correlation, it is observed that the strong relationship is prevalent for <4 quarters (1 year) or in the short term for all groups of countries. While in the medium term (4 to 12 months), there are certain periods that the correlation is weak in high income (20th to 30th quarter or late 2004 to early 2007; and 50th to 65th quarter or mid-2012 to early 2016) and middle income (40th to 70th quarter or around 2010 to 2017) groups; while the low income group remains strong correlation across all periods in the medium term (4-12 quarters). Then, for the longer term (above 12 quarters or above 3 years), the correlation of RE-CO_2 is weak in the high income group along all years. However, the correlation is strong in the middle income group along the years except 50th to 65th quarters. In the low income group, the correlation is weak prior to the 50th quarter but it is getting stronger after that. In terms of direction of correlation, majority areas show (←) or negative relationship, in certain areas with ↙ (RE leads CO_2) and ↖ (CO_2 leads RE).

4.2 Impact of RE on energy poverty (EP1 and EP2)

Figure 2 shows the wavelet coherence plots of RE on EP1 and EP2. Transitioning to green energy consumption (RE) could improve energy poverty in terms of access to electricity, with stronger correlations found in middle and low income groups.

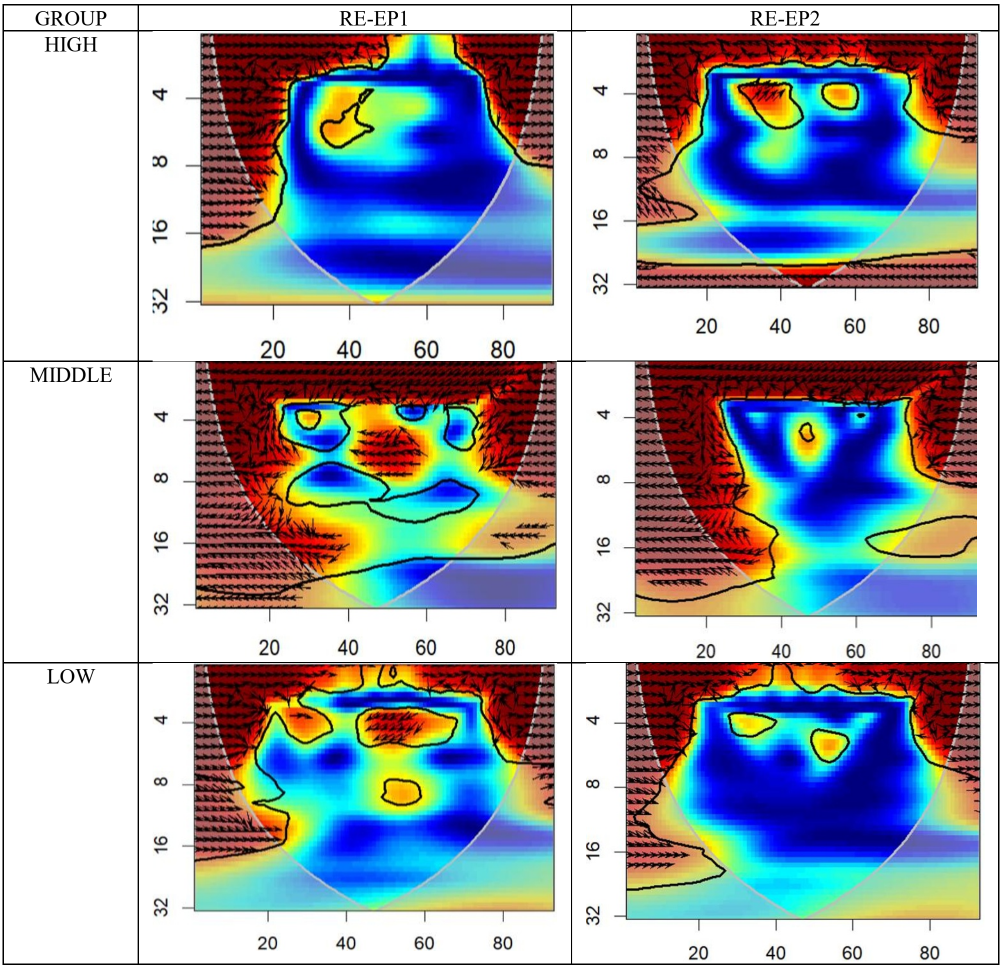

Fig. 2. Wavelet coherence plots of RE on EP1 and EP2.

Strong correlations of RE-EP1 and RE-EP2 indicated in areas with red color are detected in the high-income group mainly before the 20th quarter (2004Q4). The strong correlations exist in all frequencies (<4 quarters or short term, 8-12 quarters or medium term, and >12 quarters or long term). Strong correlation is also found after 65th quarter (2016Q1) in the median run (<8 quarters). Blue color (weak relationship) is found mostly in the medium to long terms (>4 quarters) between 20th to 70th quarters or 2004Q4 to 2017Q2. In middle income group, the strong correlation is found in the short term (<4 quarters) along all years. In the medium term (4-12 quarters), strong correlation exists mostly before 25th quarter (2006Q1) and after 70th quarter (2017Q2); while in the long term (>12 quarters), strong correlation mainly distributed before 40th quarter (2009Q4). This condition also holds in the low income group, with strong correlations exist in the short term. However, for the medium and long terms (>4 quarters), strong correlations exist before the 20th quarter or 2004Q4 and after the 70th quarter or 2017Q2. However, for the direction of correlation, positive correlation (mostly →) is found in the high income and low income groups but negative correlation (mostly ← and ↙ RE leads EP1) is found in the middle income group. The results reveal that increasing renewable energy consumption (RE) is associated with higher percent of households' access to electricity in high and low income groups (energy poverty is improved) but the negative outcome with higher energy poverty is reported for middle income group.

RE also exhibits correlations with EP2 (percent access to clean fuel and technology for cooking). The correlation is strong in the short term (<4 quarters) along all years in three groups of countries. Both high and low income groups show strong correlation before 70th quarter or 2017Q2 in medium and long terms. In the medium term (4-12 quarters), dark blue or weak correlation is found between 20th to 70th quarter in high and low income groups. Then in the long term (>12 quarters), weak correlation is detected after 20th quarter in these groups of countries. While for the middle income group, strong correlation is detected before 30th quarter or 2007Q2 in the medium term (4-12 quarters) and before 40th quarter or 2009Q4 in the long term (>12 quarters). In terms of direction of correlation, negative correlations (←, ↖, ↙) are found in the high income group, where increasing RE is associated with lower EP2 (higher energy poverty). In the middle income group, negative correlations (↙, ←) are found in the short term (<4 quarters), while in the medium 4-12 quarters), there are mixed correlations negative correlations, where positive correlations exist around 20th to 30th quarter (2004Q4 – 2007Q2) and after 70th quarter (2017Q2); while in the long term, the correlations mainly negative (←, ↙, ↖). In the low income group, the correlations are mainly positive (→, ↗, ↘) in all frequencies. Hence, low income group is mostly benefitted by RE in terms of improving energy poverty (EP2).

5 Conclusion

Wavelet coherence analysis reveals that RE could be influential on CO_2 and energy poverty, where results are varied across countries. Low income group is most benefited in terms of environmental improvement and energy poverty improvement, with more prominent effects in the short term (<1 year). High and middle income groups also experienced reduction in CO_2 in the short term, but with mixed results regarding energy poverty. The possible reason could be energy poverty is very mild in high and middle income groups, hence they have limited rooms for improvement. Also, although the quantity of renewable energy consumption in these groups are high, but the ratio to the total energy consumed is relatively low compared to the low income group. Hence, the effectiveness of RE on energy poverty is limited in high and middle income groups. Transitioning to green energy is a long and challenging effort. The government should implement green policy to support the goals of SDGs for the welfare and benefit of all nations.

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