

Peer-reviewed research

Time-Frequency Impacts of Economic Growth, Urbanization, and Financial Development on Energy Intensity in Japan

Nguyen Huynh Mai Tram¹, Bui Hoang Ngoc²^a¹ Hung Vuong University of Ho Chi Minh City, Vietnam, ² The FEMRG research group, Ho Chi Minh City Open University, Vietnam

Keywords: Energy intensity, Economic growth, Wavelet tools

JEL Classifications: C32 Time-Series Models - Dynamic Quantile Regressions - Dynamic Treatment Effect Models - Diffusion Processes - State Space Models, O11 Macroeconomic Analyses of Economic Development, Q11 Aggregate Supply and Demand Analysis - Prices

<https://doi.org/10.46557/001c.162723>

Energy RESEARCH LETTERS

Vol. 7, Issue Early View, 2026

The study investigates the time-frequency interdependence between energy intensity and key economic indicators in Japan. The results reveal a consistent inverse relationship between economic growth and energy intensity, particularly over medium- to long-term periods. The connection between urbanization and energy demand has evolved from unstable to increasingly inverse and synchronized after 2008. In contrast, the effect of financial system development on energy intensity remains weak and inconsistent at all frequencies.

I. Introduction

Nowadays, the energy sector accounts for roughly 75% of greenhouse gas emissions (Ma et al., 2022). International Energy Agency (2021) emphasizes that curbing these emissions is not only essential for reaching the 2050 net-zero target but also represents one of humanity's most significant challenges. As a result, reducing energy use and improving energy intensity have consistently drawn considerable attention. Japan presents a compelling case for re-evaluating energy intensity. While the country is widely regarded as energy-efficient, recent trends reveal uneven declines in energy use - significant in industry and transport, but slower in residential and commercial sectors. These disparities, combined with ongoing urbanization and energy policy shifts following the Fukushima disaster, raise important questions about the sustainability of Japan's energy trajectory. As the country accelerates its green and digital transitions, reassessing the long-term dynamics of energy intensity becomes critical, not only to inform domestic policy, but also to offer valuable insights for other advanced, aging East Asian economies facing similar structural and environmental challenges.

Theoretically, the factors influencing energy intensity are categorized under the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model proposed by Dietz and Rosa (1997). Numerous researchers have devoted efforts to identifying the main factors influencing energy intensity and gaining deeper insights into its trends. While previous studies have provided valuable insights, they often rely on static models that fail to capture

the evolving nature of the relationships across different time scales. Economic growth, urbanization, and financial development are commonly recognized as the primary drivers behind the reduction in energy intensity during the 1990s (Deichmann et al., 2019; Marra et al., 2024). These factors often enabled the adoption of more efficient technologies and infrastructure improvements, which in turn reduced the amount of energy required to produce goods and services. In addition, energy intensity serves as a more accurate measure of a country's energy efficiency in production activities. Unlike total energy consumption, energy intensity accounts for how much economic value is derived from each unit of energy consumed, thus providing a clearer picture of energy productivity. As countries experienced economic expansion, they gradually transitioned from traditional, energy-intensive industries to more service-oriented and high-tech sectors that required less energy per unit of output. Simultaneously, urbanization facilitated more efficient energy use through improved infrastructure, compact living arrangements, and greater access to public transportation, which collectively reduced per capita energy consumption (Wang et al., 2020). Meanwhile, financial development played a crucial role by enabling investments in energy-efficient technologies and clean energy solutions, allowing both firms and households to adopt more sustainable production and consumption practices. However, despite extensive literature on the determinants of energy intensity, the empirical findings remain inconsistent across countries and time periods, especially for advanced economies like Japan, where the

a Corresponding author email: ngoc.bh@ou.edu.vn

interaction between aging population, urbanization, and capital market maturity adds layers of complexity.

Therefore, this study aims to extend the discussion by addressing the above shortcomings and revisiting the time-varying impacts of economic growth (GDP), urbanization (URB), and financial development (FD) on energy intensity (ENI) in Japan from 1970 to 2022 using Wavelet tools. That means we try to answer the following questions: (1) Are GDP, URB, FD and ENI inversely or directly connected? (2) What is the lead-lag patterns between GDP, URB, FD and ENI in Japan? (3) What is the direction of causality across various frequencies? By focusing on Japan as a case study, this research not only contributes to the empirical literature on energy intensity and its drivers but also offers practical implications for energy and urban policy in other developed and rapidly urbanizing economies.

The rest of this paper is structured as follows. Section II outlines the methodology, Section III discusses the principal results, and the concluding section wraps up the discussion.

II. Methodology

To achieve the research aim, the initial model is suggested as follows: $ENI_t = f(GDP_t, URB_t, FD_t)$. ENI denotes energy intensity (unit: kWh), which is collected from the International Energy Agency database. GDP , URB and FD are economic growth, urbanization, and financial development, respectively. We use the GDP per capita (fixed 2015 prices), urbanization rate, and domestic credit to private sector by banks (% of GDP) to present GDP , URB and FD variables, respectively. All data were taken from the World Bank. The start year is 1970, and the end year is 2022.

As mentioned in part one, the existing econometric models ignored the time-varying impact of GDP , URB and FD on ENI . Thus, they cannot provide a more intuitive understanding of the connectedness between the examined variables, signifying short-, medium-, and long-run interactions and which variables are leading or lagging at specific time-frequency domains. So, in this section, the study briefly introduces the main wavelet tools to overcome these limitations. The Wavelet ($Wx(s)$) of the series $x(t)$ is defined as:

$$W_x(s) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{s}} \psi^* \left(\frac{t}{s} \right) dt \quad (1)$$

In Equation (1), $*$ denotes the complex conjugate and where the scale parameter s identifies whether the Wavelet can detect higher or lower series $x(t)$ components, possible when the admissibility condition yields. Torrence and Webster (1999) suggested that the cross-wavelet transform technique of two series $x(t)$ and $y(t)$ can be given as:

$$W_n^{XY}(u, s) = W_n^X(u, s) W_n^{Y*}(u, s) \quad (2)$$

In Equation (2), u presents the position and s denotes the scale. The equation of the squared wavelet coherence can be specified as:

$$R_n^2(u, s) = \frac{|S(s^{-1} W_n^{XY}(u, s))|^2}{S(s^{-1} |W_n^X(u, s)|^2) S(s^{-1} |W_n^Y(u, s)|^2)} \quad (3)$$

In Equation (3), S connotes the smoothing process for time and frequency simultaneously, therefore, $R_n^2(u, s)$ is in the range between zero and one. The co-movement between $x(t)$ and $y(t)$ series is stronger when $R_n^2(u, s)$ reaches one. Similarly, the series indicators are not associated or have no causal link when $R_n^2(u, s)$ approaches zero. Nevertheless, the coherence wavelet is squared; thus, it does not capture the causal association between positive or negative dependency. Torrence and Webster (1999) suggested the formula for the phase difference mechanism between $x(t)$ and $y(t)$ series as:

$$\phi_{XY}(u, s) = \tan^{-1} \left(\frac{\Im\{S(s^{-1} W_{XY}(u, s))\}}{\Re\{S(s^{-1} W_{XY}(u, s))\}} \right) \quad (4)$$

In Equation (4), $\Im$ and $\Re$ are the imaginary and real parts of the smooth power spectrum, respectively. Arrows indicate correlation: an up-right arrow shows a positive correlation with a lead of less than 90°; a down-right arrow indicates a positive correlation with a lead of 90°-180°. An up-left arrow denotes a negative correlation with a lead of less than 90°; a down-left arrow indicates a negative correlation with a lead of 90°-180°. Arrow length reflects coherence strength. Finally, the test proposed by Olayeni (2015) will be employed to check the wavelet-based Granger causality result.

III. Empirical Results

The wavelet analysis results presented in Figures 1, 2, and 3 show a stable negative correlation between GDP and ENI , with a coherence coefficient greater than 0.5, indicating significance (see Panel E of Figure 1). The XWT confirms a strong interaction at medium- and high-frequency bands (8-16 years) and a weak one at low frequencies. The scale-averaged phase shift plot reveals that GDP leads ENI by 0-2 years (see Panel C of Figure 1). Additionally, Panel D of Figure 1 shows a medium lag (4-8 years), with GDP controlling ENI . These findings suggest that GDP growth in Japan leads to reduced ENI , reflecting efforts to decrease energy consumption and waste.

Likewise, Panel A of Figure 2 shows that the interaction between URB and ENI was erratic from 1980 to 2008, but became strongly correlated afterward, with a coherence coefficient of 0.9 during 2008-2022 (see Panel E of Figure 2). The down-left arrows indicate a negative correlation, with ENI lagging. Panel C of Figure 2 reveals minimal lag in shorter cycles (0-2 years), and from 1970-2001, URB dominated, while ENI became the leading variable from 2002 onward. Panel D of Figure 2 shows synchronized behavior between ENI and URB across all time scales. These findings suggest that a growing urban population reduces energy intensity in Japan.

Similarly, the co-movement between ENI and FD is documented in Figure 3. Accordingly, Panel A of Figure 3 shows a light negative correlation between ENI and FD in the short run. In the long run, the relation is insignificant (coherence < 0.5) (see Panel E of Figure 3). The dynamic relationship between ENI and FD is highlighted by varying lag patterns, notably during significant periods from 1993 to 2016. Panel C of Figure 3 indicates that ENI lags behind FD in the cy-

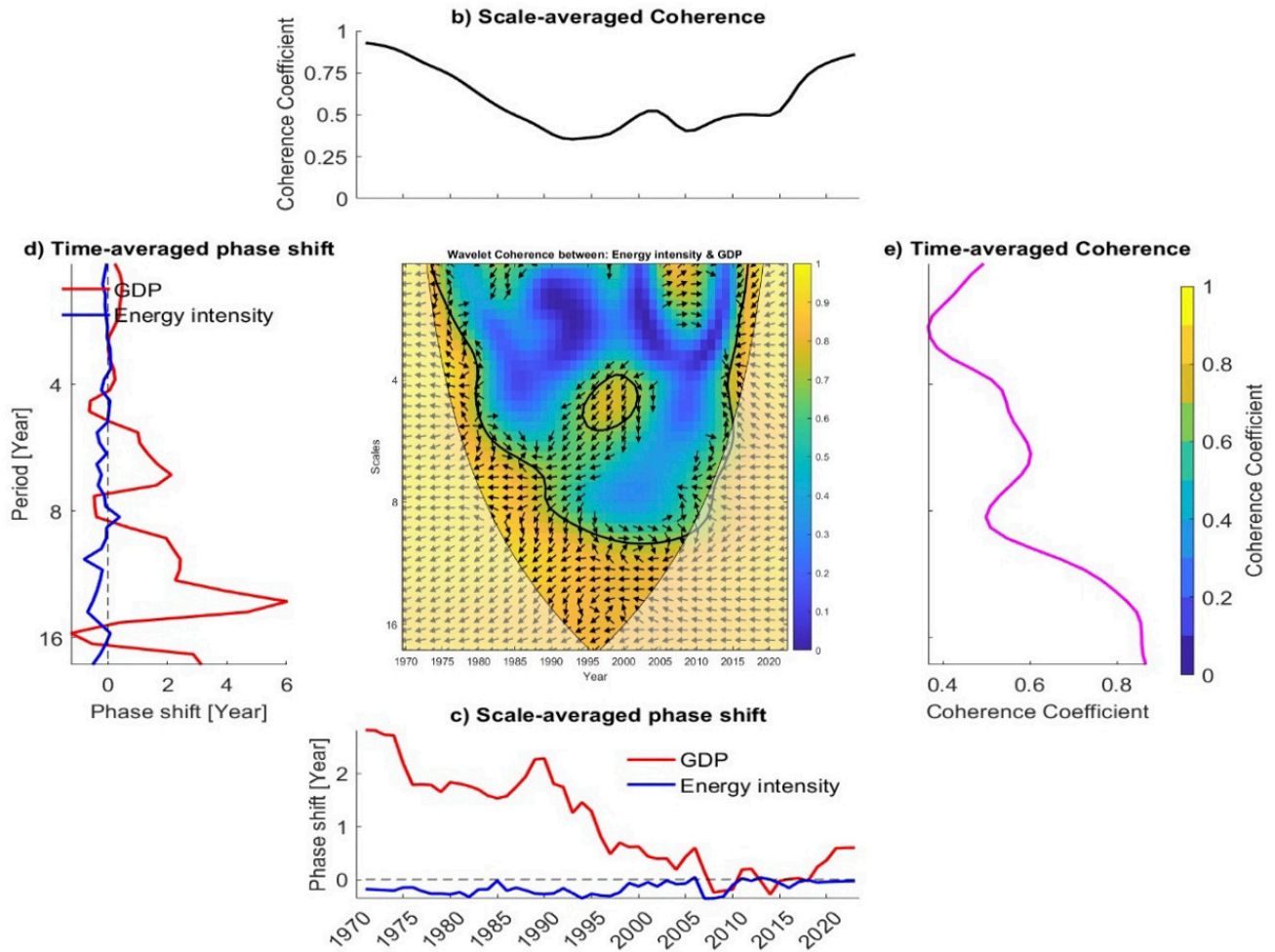


Figure 1. The Wavelet coherence between energy intensity and GDP

Note: The vertical axis is the frequency element, whereas the horizontal axis is the time element. The colour code shows the power range.

cle shorter than one year throughout the entire period. The co-movement of *ENI* and *FD* is confirmed in the short run (0-8 year scales), and there appears to be no significant impact in the medium to long term. Notably, the *ENI* exhibits a stronger correlation with *GDP* and *URB* than with *FD*. All the above outcomes reveal that *FD* has contributed less to improving energy efficiency in Japan.

In the next step, the study carried out the wavelet-based Granger causality test introduced by Olayeni (2015) to inspect the causal dependency. The findings (see Table 1) show that there is a bi-directional association between *ENI* and *GDP* at all frequencies, except at the 4-8 year scales. Likewise, there is a uni-directional causality running from *ENI* to *URB* at medium and high frequencies (> 4-year scales). Table 1 also indicates that the causal relationship between *ENI* and *FD* is significant at the low frequency (0-2 year scales).

IV. Conclusion

Using wavelet tools and wavelet-based Granger causality, this study examines the time-frequency links between Japan's energy intensity and GDP, urbanization, and financial development. Results show a persistent inverse GDP–energy intensity relationship, strongest at 8–16-year

scales, with GDP typically leading energy intensity by 0–2 years; evidence of continued decoupling driven by efficiency gains. The urbanization–energy intensity link is initially unstable but turns strongly negative and coherent after 2008.

These patterns suggest that energy-efficient urban infrastructure increasingly reinforces urban growth, consistent with Japan's smart-city transition. By contrast, financial development is weakly and inconsistently related to energy intensity, implying that finance has played a limited role in decarbonization to date, potentially reflecting cautious investment behavior and the slow scale-up of green finance.

Policy implications: (1) Sustaining the growth–energy decoupling requires continued investment in low-carbon technologies (renewables, high-efficiency equipment, and digital optimization), supported by industrial policy and targeted incentives, especially for SMEs, to speed diffusion of energy-saving innovation. (2) Urbanization can further reduce energy intensity if guided by compact, mixed-use planning and high-quality public transport, which lowers commuting needs, curbs private vehicle reliance, and reduces fossil-fuel use and emissions. (3) Financial development should be repositioned as a driver of the green transition by expanding green finance (e.g., green banks and

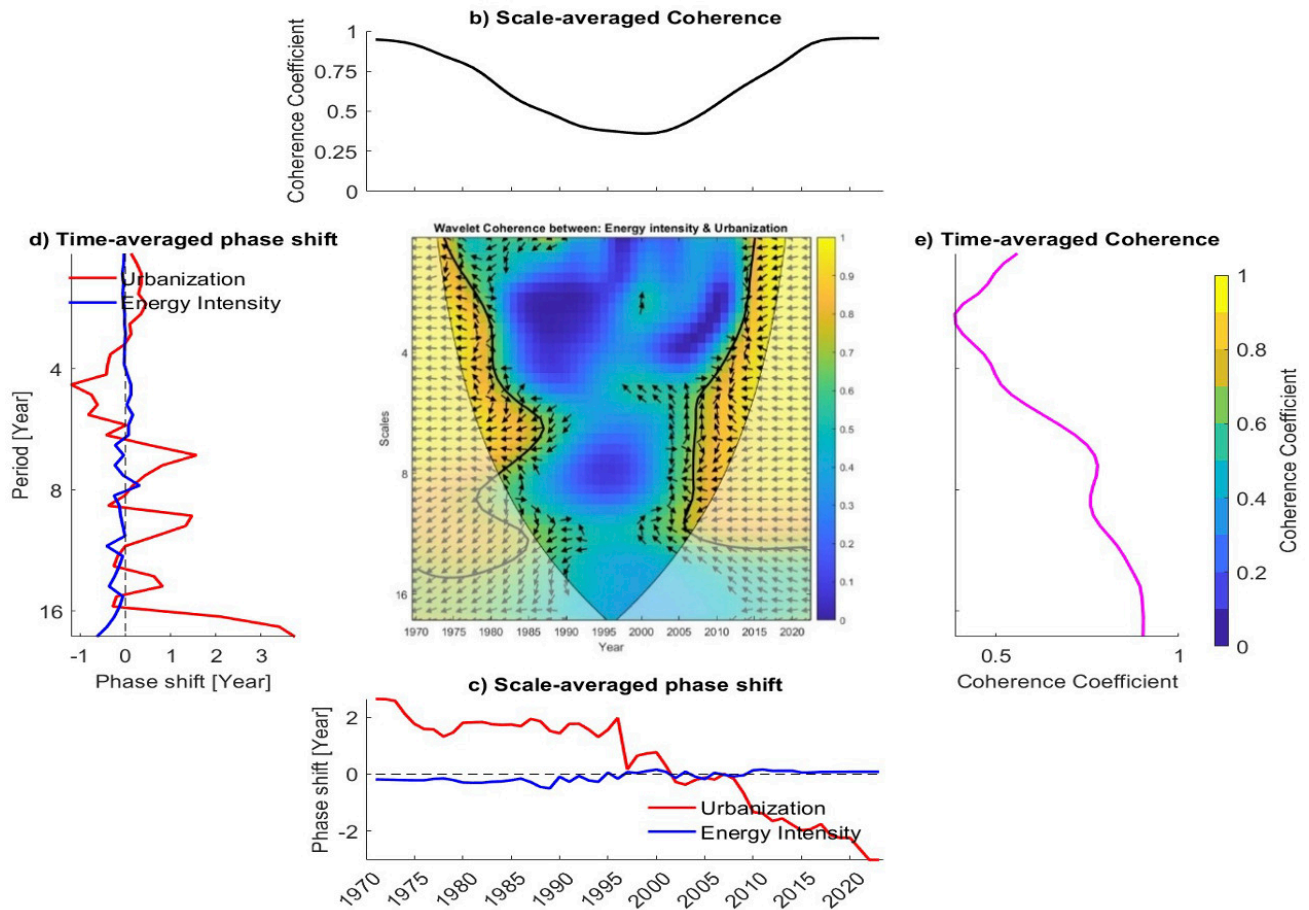


Figure 2. The Wavelet coherence between energy intensity and urbanization

Note: The vertical axis is the frequency element, whereas the horizontal axis is the time element. The colour code shows the power range.

tax incentives) and strengthening climate-related disclosure to improve transparency and direct private capital toward low-carbon technologies and infrastructure.

Submitted: April 14, 2025 AEDT. Accepted: January 05, 2026

AEDT. Published: July 20, 2026 AEDT.

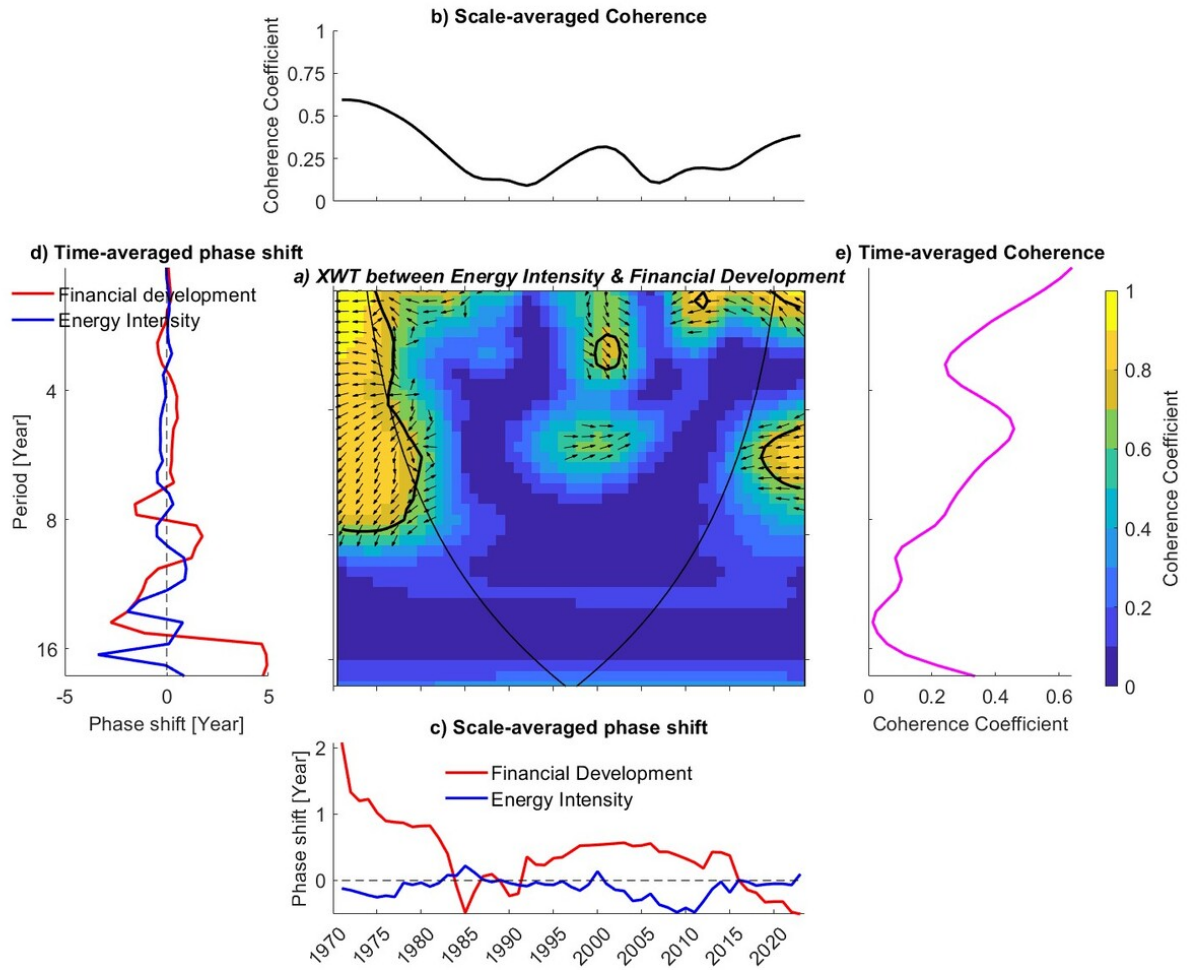


Figure 3. The Wavelet coherence between energy intensity and financial development

Note: The vertical axis is the frequency element, whereas the horizontal axis is the time element. The colour code shows the power range.

Table 1. The wavelet-based Granger causality results

Time scales	Findings	ENI does not cause independent variables		Independent variables do not cause ENI	
		F-test	p-value	F-test	p-value
Energy intensity & Economic growth					
0-2 years	ENI ⇔ GDP	3.796	0.029	4.385	0.018
2-4 years	ENI ⇔ GDP	7.206	0.002	7.668	0.001
4-8 years	No causality	0.853	0.432	1.702	0.194
8-16 years	ENI ⇔ GDP	6.068	0.005	15.01	0.000
> 16 years	ENI ⇔ GDP	77.83	0.000	146.70	0.000
Energy intensity & Urbanization					
0-2 years	No causality	0.768	0.469	1.083	0.347
2-4 years	No causality	1.727	0.189	1.088	0.345
4-8 years	URB => ENI	3.903	0.027	5.772	0.006
8-16 years	ENI => URB	4.881	0.012	2.368	0.105
> 16 years	ENI ⇔ URB	96.29	0.000	182.13	0.000
Energy intensity & Financial development					
0-2 years	FD ENI	78.18	0.000	136.14	0.000
2-4 years	FD => ENI	2.447	0.098	7.683	0.001
4-8 years	No causality	0.596	0.555	0.411	0.665
8-16 years	No causality	0.477	0.623	0.344	0.710
> 16 years	No causality	0.773	0.467	0.0047	0.954

Note: $\Rightarrow$ denotes unidirectional causality and $\Leftrightarrow$ denotes bi-directional causality



This is an open-access article distributed under the terms of the Creative Commons Attribution-ShareAlike 4.0 International License (CCBY-SA-4.0). View this license's legal deed at <https://creativecommons.org/licenses/by-sa/4.0> and legal code at <https://creativecommons.org/licenses/by-sa/4.0/legalcode> for more information.

References

- Deichmann, U., Reuter, A., Vollmer, S., & Zhang, F. (2019). The relationship between energy intensity and economic growth: New evidence from a multi-country multi-sectorial dataset. *World Development*, 124, 104664. <https://doi.org/10.1016/j.worlddev.2019.104664>
- Dietz, T., & Rosa, E. A. (1997). Effects of population and affluence on CO₂ emissions. *Proceedings of the National Academy of Sciences*, 94(1), 175–179. <https://doi.org/10.1073/pnas.94.1.175>
- International Energy Agency. (2021). *Net Zero by 2050: A Roadmap for the Global Energy Sector*. International Energy Agency. <https://www.iea.org/reports/net-zero-by-2050>
- Ma, Y., Zhao, Y., Jia, R., Wang, W., & Zhang, B. (2022). Impact of financial development on the energy intensity of developing countries. *Heliyon*, 8(8), e09904. <https://doi.org/10.1016/j.heliyon.2022.e09904>
- Marra, A., Colantonio, E., Cucculelli, M., & Nissi, E. (2024). The “complex” transition: Energy intensity and CO₂ emissions amidst technological and structural shifts. Evidence from OECD countries. *Energy Economics*, 136, 107702.
- Olayeni, O. R. (2015). Causality in Continuous Wavelet Transform Without Spectral Matrix Factorization: Theory and Application. *Computational Economics*, 47(3), 321–340. <https://doi.org/10.1007/s10614-015-9489-4>
- Torrence, C., & Webster, P. J. (1999). Interdecadal Changes in the ENSO–Monsoon System. *Journal of Climate*, 12(8), 2679–2690. [https://doi.org/10.1175/1520-0442\(1999\)012](https://doi.org/10.1175/1520-0442(1999)012)
- Wang, Q., Lin, J., Zhou, K., Fan, J., & Kwan, M.-P. (2020). Does urbanization lead to less residential energy consumption? A comparative study of 136 countries. *Energy*, 202, 117765. <https://doi.org/10.1016/j.energy.2020.117765>