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Article

Studying the Dynamic Correlation Between Economic Growth and the Energy System Using Wavelet Analysis

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Abstract: This study investigates the dynamic relationship between economic growth and the energy system in Uzbekistan using a time–frequency analytical framework. Unlike traditional econometric approaches that focus mainly on average long-run relationships, this research applies wavelet transformation techniques to capture the evolving correlation between macroeconomic growth and key energy indicators across different time horizons. In particular, the wavelet coherence method is employed to identify short-, medium-, and long-term co-movements and lead–lag interactions between economic growth and variables such as natural gas consumption, unemployment, and foreign investment. The empirical findings reveal that the relationship between the energy sector and economic growth is not constant over time but varies significantly across different periods and frequencies. Strong correlations are observed in several medium-term cycles, highlighting the important role of energy resources in supporting economic expansion. The results provide valuable scientific insights into the structural interaction between the energy system and macroeconomic dynamics and offer practical implications for improving energy policy design, enhancing energy efficiency, and supporting sustainable economic development in Uzbekistan.

Keywords: Uzbekistan Economy, Energy Sector, Wavelet Transformation, Frequency-Domain Analysis, Time Series, Dynamic Relationship, Economic Growth, Energy Consumption, Sustainable Development.

1. Introduction

Understanding the relationship between economic growth and energy sector dynamics has become a central issue in contemporary economic and policy research. Uzbekistan, a rapidly transforming economy in Central Asia, registered around 6 % GDP growth in 2023, reflecting sustained expansion in industry, services, and investment activities [1]. Energy remains a foundational input for production, infrastructure, and technological modernization in the country [2]. In Uzbekistan's energy mix, natural gas accounts for approximately 80 % of total primary energy consumption, followed by oil, coal, and hydro sources [3]. Between 2017 and 2024, economic output increased significantly while energy intensity declined, indicating improvements in energy efficiency and structural utilization [4]. Despite this trend, the economy remains relatively energy-intensive compared with global averages. Traditional econometric approaches often focus on average or long-run linkages and may overlook transient or frequency-specific dynamics inherent in time-series data [5]. In contrast, wavelet transformation offers a powerful analytical framework capable of decomposing relationships simultaneously across time and frequency domains. This allows the identification of short-

, medium-, and long-term co-movements and lead–lag patterns between macroeconomic indicators and energy sector variables. In this context, the present study aims to analyze the frequency-domain relationship between Uzbekistan's economy and the energy sector using wavelet transformation techniques. By applying wavelet-based analysis to relevant economic and energy time-series data, the study seeks to uncover hidden dynamic patterns across different time horizons [6]. The findings are expected to contribute to a deeper understanding of the role of energy in economic growth and to inform evidence-based energy policy formulation and sustainable development strategies for Uzbekistan.

Literature Review

An important methodological guide for the practical application of wave analysis in economics was proposed by Christopher Torrence and Gilbert P. Compo. In their work, the frequency composition of time series is determined using the Continuous Wavelet Transform (CWT) [7].

Later, the wavelet coherence (WTC) method, developed by Aslak Greensted, John C. Moore, and Svetlana Jevrejeva, made it possible to determine the dynamic correlation between two time series in the time-frequency domain. This approach shows at what period and at what frequency the relationship between economic growth and energy consumption is strong or weak [8].

Works devoted to the study of energy-economic relations in Uzbekistan and the countries of Central Asia are mainly based on classical econometric methods. Local scientists Nurbek Khalimjonov, Odiljon Rikhsimbaev, and Ergash Ibadullaev analyzed the relationship between Uzbekistan's economic growth and energy consumption using ARDL and VECM models [9], [10].

2. Methodology

In this study, a quantitative research approach is used to determine the relationship between economic growth and the energy system. The research is carried out using modern wavelet econometric methods, based on the analysis of time series.

3. Results and Discussion

In this study, the wavelet coherence methodology is used to study the time-varying dynamic relationship between the energy uncertainty index (EUI) and the stability uncertainty index. The main advantage of wave analysis is that, unlike traditional correlation or Granger tests [11], it shows multi-frequency relationships and phase differences between two time series together on short-, medium-, and long-term scales. This approach is particularly effective in analyzing the relationship between energy uncertainty and stability uncertainty, as it effectively distinguishes between non-stationary series, structural changes, and cyclic oscillations.

At the initial stage of the dependence analysis, the time series is decomposed using the method of continuous wavelet transform using Morlet waves developed by Grossmann and Morlet [12] as follows:

$$W_{x;\psi}(\tau, s) = \int_{-\infty}^{\infty} x(t) \frac{1}{\sqrt{s}} \psi^* \left(\frac{t-\tau}{s}\right) dt \qquad (1)$$

In the formula τ represents the time shift parameter, s the wave scale, and ψ the complex conjugation of the wave function. In the second stage, according to the method developed by Torrence & Compo [13] and Greensted et al. [14], wave coherence is calculated as a local correlation (local dependence) between two time series x (t) and y (t) in the time-frequency domain:

$$R_{xy}^2(\tau, s) = \frac{\left|S(s^{-1}W_{xy}(\tau,s)\right|^2}{S(s^{-1}|W_x(\tau,s)|^2 S(s^{-1}\left|W_y(\tau,s)\right|^2} \qquad (2)$$

In the above equation, W_{xy} represents the transverse wave transform (cross-wavelet transform), which is calculated using the smoothing operator S. The value of the wave coherence (dependence) varies from 0 (no linear correlation) to 1 (perfect linear correlation).

The phase difference obtained from the cross-wavelet transform provides additional important information about the lead-lagging relationship between two time series, i.e., the characteristics of one series being ahead or behind the other, and the direction of the overall correlation:

$$\phi_{xy}(\tau, s) = \arctan\left(\frac{\Im(W_{xy}(\tau,s))}{\Re(W_{xy}(\tau,s))}\right) \quad (3)$$

Here, τ and s represent the imaginary and real parts, respectively. The direction of the indicators on the relationship diagram visually reflects the phase difference (Torrence & Compo; Greensted et al.). Indicators directed to the right indicate that time series are synchronously or positively correlated, i.e., they are moving together. The left-directed arrows indicate an opposite phase or negative relationship, indicating that time series move in opposite directions. On the dependence diagram, arrows pointing upwards (↑) indicate that the first time series (x (t)) is leading relative to the second series (y (t)) and thereby influences in the direction x (t) → y (t). The downward arrows (↓) represent leadership and influence in the direction y (t) → x (t). Diagonal arrows (e.g., β or β) indicate a combined combination of lead-lag ratios with a phase difference (positive or negative correlation). The statistical significance of wave coherence is determined by Monte Carlo simulations. In simulations, the null hypothesis with a red noise model based on the AR (1) process is used against it. As a result, the contours on the diagram are usually drawn at a 5% significance level ($p < 0.05$), which indicates the statistical reliability of the high-dependence zones [15].

In this study, the variable relationship between economic growth and natural gas consumption was deeply analyzed in time-frequency space based on the wave coherence methodology. In a graphical representation, the intensity of colors indicates the degree of coherence between two indicators: red indicates a high degree of correlation, and blue indicates a low degree of correlation. Areas bounded by a black contour are considered statistically reliable zones with a significance level of 5% based on Monte Carlo simulations.

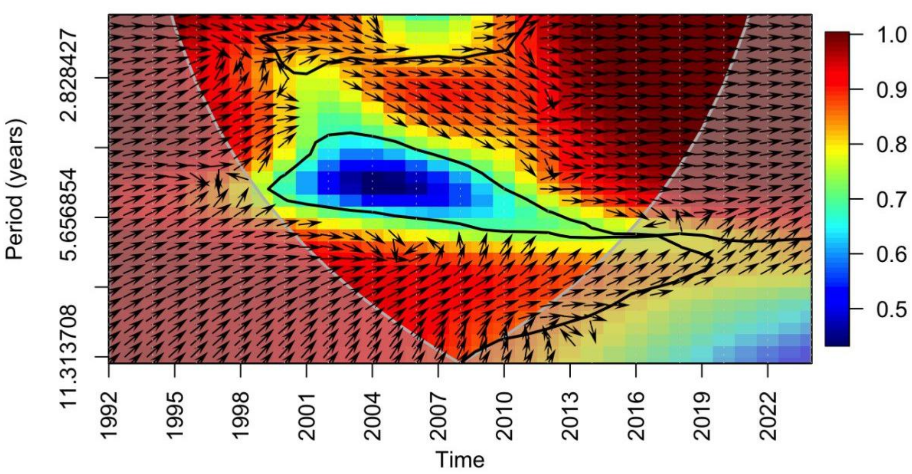

Figure 1. The wave relationship between economic growth and natural gas consumption.

The conducted analyses show that the relationship between economic growth and natural gas consumption does not have a constant character over time, on the contrary, it has changed significantly in different periods. In particular, a strong correlation was revealed between these indicators between 1995-2000 and 2010-2018, especially in 3-7 year periodic sections. This situation means that during these periods there was a strong and stable relationship between the natural gas consumption sector and economic growth.

On the contrary, in the period from 2000 to 2010, a decrease in the degree of dependence (the predominance of blue) is observed, especially in periodic sections of 4-7 years. This situation shows that economic growth during this period was formed mainly under the influence of institutional reforms, investment activity, technological innovations, and external economic conditions. Also, in the medium term, an increase in energy efficiency and diversification of the production structure may have led to a relative weakening of the relationship between natural gas consumption and economic growth.

Although the blue areas in the central part of the wave relationship map reflect a low degree of correlation, the intensification of color intensity and the formation of statistical significance contours at the upper (short-term) and lower (long-term) boundaries of this territory indicate a strong and meaningful correlation between economic growth and natural gas consumption. This situation is explained as follows.

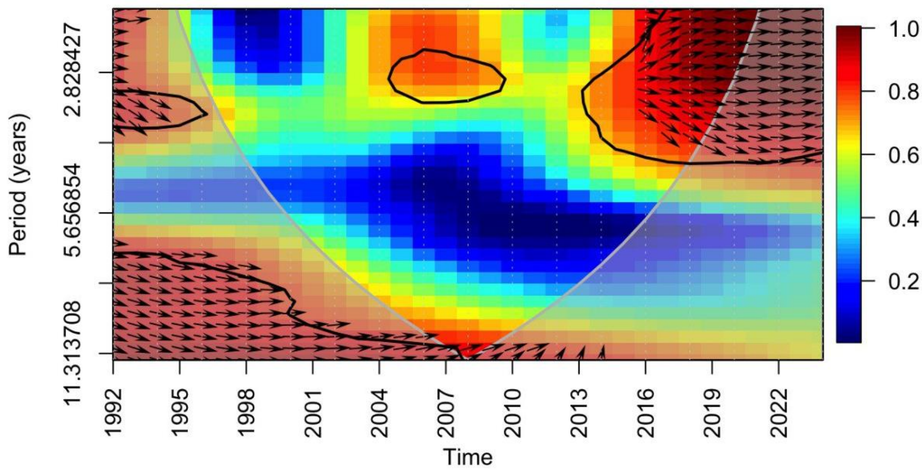

Figure 2. The wave link between economic growth and unemployment.

The analysis results show that the relationship between economic growth and the unemployment rate is significantly variable over time. In particular, at the end of the 1990s and the beginning of the 2000s, a moderate and high degree of harmony is observed in the cross-section of short-term periods, i.e., approximately 2-3-year fluctuations. This situation means that there was a certain degree of correlation between economic activity and labor market indicators during these periods. At the same time, due to the relatively low reliability of the results obtained in remote areas bounded by the action cone, the analysis is mainly carried out within the zones within the cone. Overall, the analysis of the wave relationship shows that the relationship between economic growth and the unemployment rate is relatively stronger in the short and medium term and weaker in the long term, and confirms the complex and time-dependent relationship between the labor market and economic growth. The relationship between economic growth and foreign investment was analyzed in time and oscillation sections using the wave relationship method. In the graph, color intensity represents the degree of harmony: red represents a high correlation, and blue represents a relatively low correlation. Areas separated by black contours show statistically significant harmony zones, i.e., identified at a level of 5 percent.

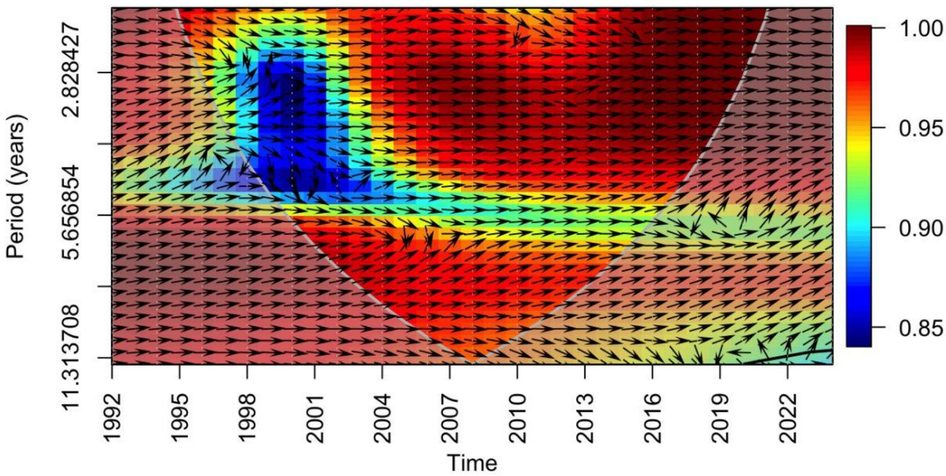

Figure 3. The wave link between economic growth and foreign investment.

The results of the analysis show that the relationship between economic growth and foreign investment is formed at a high level in most periods. In particular, the predominance of red in the context of 3-7 year periods between 2003-2015 confirms the presence of a strong and stable correlation between these indicators. This means that foreign investments have emerged as an important factor supporting economic growth. Between 1997 and 2001, a relatively low degree of harmony, i.e., the predominance of blue, is observed in some short-term and medium-term periods. This period can be interpreted as a stage in which the inflow of foreign investments was unstable or their impact on economic growth temporarily weakened.

Analysis of the spatial indicators reflected in the graph shows that in most periods, the indicators are directed to the right or right-up. This means that there is a predominantly positive relationship between economic growth and foreign investment, and in many cases, foreign investment plays a leading role in economic growth. At the same time, in some periods, economic growth manifested itself as a factor stimulating the inflow of foreign investments. Since the reliability of the results obtained in remote areas bounded by the influence cone is relatively low, conclusions are mainly formed based on areas within the cone. In general, the analysis of the wave relationship confirms that the relationship between economic growth and foreign investment is strong in the short, medium, and long term and empirically substantiates the important role of investment factors in economic development.

4. Conclusion

In conclusion, it can be said that the use of wave analysis in the study of the energy impact on the country’s economy creates a basis for the efficient use of energy resources and the development of renewable energy sources while reducing the consumption of extracted resources. In addition, in our study, the relationship between the unemployment rate and the economy was studied, and an increase in the unemployment rate affects a decrease in economic growth. We can also say that due to the attention paid by our government over the past decade, the unemployment rate has decreased, and on the contrary, economic growth has accelerated. At the same time, there is an opportunity to increase resource efficiency by attracting foreign direct investment.

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