Nomico Journal
E-ISSN : 3046-6318
https://nawalaeducation.com/index.php/NJ/index
Vol.2. No.11 December 2025
DOI : https://doi.org/10.62872/2ccmsh89

The Impact of Environmental Externalities on Commodity Price Stability: GARCH (Generalized Autoregressive Conditional Heteroskedasticity) Volatility Analysis

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Entered : November 03, 2025 Revised : December 02, 2025
Accepted: December 22, 2025 Published : December 30, 2025

ABSTRACT

Crude oil is a highly strategic global commodity whose price is extremely sensitive to external dynamics and economic shocks. This study aims to analyze the effect of environmental externalities on crude oil price volatility by applying the Generalized Autoregressive Conditional Heteroskedasticity (GARCH) model. Secondary data consisting of daily West Texas Intermediate (WTI) crude oil prices from January 2015 to December 2024 were examined using the ADF test, ARCH–LM test, model selection based on AIC and BIC, and parameter estimation of GARCH(1,1). The results indicate that environmental externalities have a positive and significant effect on crude oil price volatility, as evidenced by the γ coefficient of 0.227 and the α + β value of 0.905, demonstrating long-term volatility persistence. These findings show that crude oil price stability is determined not only by traditional supply and demand factors but also by global environmental regulations, emission policies, and energy transition dynamics. This study provides empirical contributions to energy economics research and practical insights for policymakers in developing energy security strategies that are adaptive to the sensitivity of global commodity prices.

Keywords: Commodity, Energy, Externalities, Price, Volatility

INTRODUCTION

Crude oil trading is one of the biggest drivers of global economic dynamics, where price volatility has a broad impact on macroeconomic stability, industrial production costs, inflation, and even state revenues. Although crude oil is a strategic commodity, world market prices often experience abnormal fluctuations that move quickly and unpredictably, causing high risk in the commodity market. In the last two decades, crude oil price trends have been characterized by extreme spikes and sharp declines that are not always caused by conventional market behavior such as supply and demand, but are increasingly influenced by external factors such as environmental degradation, climate change, carbon emissions, environmental mitigation policies, and sustainable energy regulations. Data from the International Energy Agency (IEA) shows that during 2018–2023, the acceleration phase of the global energy transition has increased the sensitivity of crude oil prices to external dynamics in the environmental sector, mainly due to carbon restriction policies and emission taxes that limit the fossil fuel energy industry production ecosystem.

Thus, environmental externalities have become a new determinant that reinforces the volatility of oil commodity prices, making analysis of their influence an urgent topic of modern research in the field of energy economics. Environmental externalities reflect

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additional costs or benefits to other parties that arise from economic activities, particularly environmental degradation, pollution, and ecological risks resulting from resource exploitation processes.

Crude oil exploitation produces negative externalities in the form of ecosystem damage, industrial waste leaks, and degradation of soil and air quality. In the context of commodity markets, the more intensive environmental regulations are applied in the oil industry, the greater the changes in production cost structures and the impact on the smoothness of the global supply chain. This triggers uncertainty that spreads to international market prices. Research by Alfin and Qomariah (2024) emphasizes that environmental externalities not only affect local socio-economic balance, but also increase price volatility through production restrictions and changes in the energy market structure. In addition, environmental protests, ecological sanctions, tighter emission limits, and changes in green energy regulations are drastically shifting global oil production and distribution patterns.

Previous studies show that commodity price fluctuations have a significant impact on economic development and stability, especially in developing countries that are highly dependent on oil exports and energy imports (Abaidoo & Agyapong, 2022). However, most of these studies focus on fundamental economic factors such as fiscal policy, geopolitics, and global energy market dynamics, while the role of environmental externalities as a trigger for price volatility has received relatively little scientific attention. The same research gap is evident in the study by Ayele et al. (2020) entitled Generalized autoregressive conditional heteroskedastic model to examine silver price volatility and its macroeconomic determinant in Ethiopia market. Although the study successfully proved the effectiveness of the GARCH model in analyzing commodity price volatility, environmental externalities were not included as a major determinant of volatility. Furthermore, the research by Osho and Oloyede (2024) on crude oil price volatility modeling also did not ignore the direct relationship between environmental externalities and price stability, but instead focused on the correlation between volatility and global supply dynamics.

The research gap is further reinforced by the study by Syahril et al. (2022) entitled Palm Oil (Perspectives on Price Volatility, Marketing Margins, and the Environment), which emphasizes the close relationship between the environment and the dynamics of plantation commodity prices. However, this study did not use a GARCH-based quantitative volatility approach, so it did not describe the pattern of price instability dynamically. Thus, to date, there has been no research that empirically examines how environmental externalities contribute to crude oil price volatility using the Generalized Autoregressive Conditional Heteroskedasticity (GARCH) approach. Therefore, this study fills the theoretical gap by formulating the relationship between external environmental pressures and oil price changes within the volatility model framework.

The academic and empirical urgency of this research is also driven by the fact that the global energy market is undergoing a transformation towards a low-carbon economy, which increasingly places the environment as a key variable in the movement of energy commodity prices. Green energy policies, sustainable production standards, and tightening industrial waste regulations have changed the cost structure of oil while triggering uncertainty in the energy supply chain. In other words, environmental externalities create price volatility risks through the mechanism of reducing traditional oil supplies and accelerating the penetration of alternative energy. Environmental

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externalities do not only function as disruptive variables in free market theory, but as catalysts for price volatility that are increasingly dominant in modern energy markets.

This study is novel in its integration of two major concepts: environmental externalities and energy commodity volatility within the GARCH analysis framework, an approach that, as far as the literature review shows, has not been explicitly implemented in previous empirical studies on crude oil prices. Thus, this study aims to analyze how environmental externalities affect crude oil price stability by testing volatility based on Generalized Autoregressive Conditional Heteroskedasticity (GARCH) as a model for predicting price instability. The findings of this study are expected to contribute theoretically to the development of energy economics and practically to policymakers in formulating energy and environmental regulations that are adaptive to global commodity price sensitivity.

METHODS

This study uses a quantitative method based on time series analysis with a Generalized Autoregressive Conditional Heteroskedasticity (GARCH) model to predict and test crude oil price volatility. Secondary data was obtained from the daily prices of West Texas Intermediate (WTI) crude oil from January 2015 to December 2024. The main variables consist of oil price volatility as the dependent variable and environmental externalities as the independent variable, represented by indicators of the global carbon emission regulation index and the international environmental policy index. The selection of the GARCH model is based on the nature of oil price data, which tends to experience heteroskedasticity and volatility clustering, making this model more accurate than traditional linear regression models in detecting price instability spikes.

The estimation process began with an Augmented Dickey-Fuller (ADF) stationarity test to ensure data stability at the first difference level. This was followed by ARCH modeling to detect the presence of heteroscedasticity effects, then continued with the selection of the best GARCH model based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values.

Parameter significance testing is performed using the Z-statistic and P-value with a significance level of 5%. The estimation results are used to assess the strength of the influence of environmental externalities on oil price volatility and to assess short-term and long-term sensitivity. This study uses EViews 12 software for statistical data processing due to its ability to estimate complex volatility models such as ARCH/GARCH and their derivatives.

The accuracy of the model is measured through the evaluation of residual diagnostic tests such as ARCH-LM, normality tests, and forecast evaluation tests to assess the quality of crude oil price volatility predictions. With this methodological approach, the study is expected to provide a comprehensive analysis of the impact of environmental externalities on extreme fluctuations in crude oil prices in the global market.

RESULTS AND DISCUSSION

1. **Stationarity Test : Augmented Dickey-Fuller (ADF)**

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Variable	Level	First Difference	Decision
Crude Oil Price (WTI)	p-value = 0.128	p-value = 0.000	Stationary after first difference

Interpretation:

Crude oil prices (WTI) are not stationary at the data level ($p > 0.05$), but become stationary at the first difference level ($p < 0.05$). This means that the data is suitable for further modeling into GARCH because its volatility is reflected after the differencing process.

2. ARCH Effect Test : ARCH-LM

Statistic	Value	p-value	Decision
F-Statistic	21.437	0.000	ARCH effect detected

Interpretation:

A P-value of 0.000 < 0.05 indicates the presence of ARCH effects in the residual series. Thus, the GARCH model is an appropriate method for modeling crude oil price volatility.

3. Best Model Selection : AIC and BIC

Model Candidate	AIC	BIC	Decision
ARCH(1)	5.749	5.912	-
GARCH(1,1)	**5.103**	**5.309**	Best Fit
EGARCH(1,1)	5.188	5.426	-
TGARCH(1,1)	5.241	5.452	-

Interpretation:

The GARCH(1,1) model has the lowest AIC and BIC values, so it is selected as the best model for estimating crude oil price volatility.

4. Parameter Estimation : GARCH (1,1)

Parameter	Coefficient	Z-Statistic	p-value	Decision
Mean μ	0.00321	2.931	0.003	Significant
Externality Impact Coefficient (γ)	0.227	3.884	0.000	Significant
α (ARCH term)	0.294	4.627	0.000	Significant
β (GARCH term)	0.611	8.044	0.000	Significant

Interpretation:

The environmental externality variable has a coefficient of $\gamma = 0.227$ with a p-value of 0.000, indicating that the dynamics of environmental externalities significantly increase the volatility of crude oil prices. The values $\alpha = 0.294$ and $\beta = 0.611 > 0$ indicate the occurrence of volatility clustering, where external shocks cause prolonged volatility. The value $\alpha + \beta = 0.905$ is close to 1, so that volatility is persistent, meaning that oil price shocks have a long-term effect on future price instability.

5. Forecast Error Evaluation Test

Statistic	Value

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RMSE	1.604
MAE	1.283
MAPE	2.96%

Interpretation:
Low RMSE and MAE values, while MAPE < 10%, indicate that the GARCH(1,1) model has high predictive power in projecting crude oil price volatility.

6. Volatility Forecasting Summary

Period	Forecast Volatility Level	Trend
Q1 2025	High	Uptrend
Q2 2025	High	Uptrend
Q3 2025	Medium	Downtrend
Q4 2025	Medium	Stabilizing

Interpretation:
Volatility projections indicate that crude oil price volatility will remain high in the first half of 2025 and begin to decline gradually in the second half, in line with the increase in green energy policies and market adjustment mechanisms.

Volatility projections indicate that crude oil price volatility will remain high in the first half of 2025 and begin to decline gradually in the second half, in line with the increase in green energy policies and market adjustment mechanisms.The results of the GARCH(1,1) model estimation show that environmental externalities have a positive and significant effect on crude oil price volatility, meaning that global environmental pressures increase the instability of energy commodity prices. The $\alpha + \beta$ value of 0.905 indicates that volatility is persistent, meaning that price shocks due to environmental factors have a long-term effect on price movements. Meanwhile, model performance evaluation using RMSE, MAE, and MAPE indicates that GARCH(1,1) is capable of predicting volatility with a high degree of accuracy. Thus, environmental externalities are proven to be an important determinant in determining the dynamics of crude oil prices in the international market.

The Impact of Environmental Externalities on Crude Oil Price Volatility

The GARCH(1,1) estimation results show that environmental externalities have a positive and significant effect on crude oil price volatility, as indicated by the γ coefficient of 0.227 with a p-value of 0.000. This finding confirms that changes in environmental regulations, tighter emissions, and global pressure to reduce fossil fuel-based industrial activities increase the instability of oil prices in the international market. When environmental policies are tightened, oil producers must bear additional costs to meet these standards, thereby affecting production structures, supply volumes, and market prices. Consequently, the market responds volatilely to environmental information such as carbon tax increases, production limits, and exploration restrictions. This pattern shows that environmental factors are no longer passive external variables but determinants that reinforce the sensitivity of global energy prices (Alfin & Qomariah, 2024).

The dynamics of crude oil price volatility are also related to high market expectations for climate policy changes. When oil-producing or consuming countries announce new energy transition targets or environmental standards, energy market participants respond quickly because these changes significantly affect the balance of supply and demand. In the context of energy financial markets, environmental information

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can create structural shocks that result in short-term volatility spikes as well as long-term uncertainty effects. Oil prices reflect not only physical market conditions, but also investor expectations of potential ecological disruptions and future regulations that affect the global oil supply chain (Abaidoo & Agyapong, 2022). Therefore, the oil market is highly reactive to global environmental signals, especially since price movements are now more based on climate policy sentiment than conventional commodity fundamentals.

The findings of this study are also in line with the international commodity volatility theory pattern, which emphasizes that the stronger the external pressure on the natural resource industry, the higher the price uncertainty reflected through volatility clustering. The $\alpha + \beta$ value in the model of 0.905 confirms that external shocks due to environmental issues produce a persistent volatility effect. This means that price shocks do not recover quickly, but continue over a long period. This condition can be explained by the disturbance transmission approach, namely that industrial disturbances due to environmental policies create repeated chain uncertainties in the scale of production, distribution, and international oil trade (Osho & Oloyede, 2024). The more often environmental pressures arise, the higher the volatility in oil prices, and the impact is prolonged in the market structure.

In addition to policy pressures, environmental externalities can also affect price volatility through physical production shocks triggered by ecological disasters. Environmental damage caused by major storms in oil fields, offshore drilling accidents, industrial waste leaks, or the closure of exploration areas for conservation reasons can suddenly reduce supply capacity. Such production shocks cause oil prices to fluctuate sharply in a short period of time. Several studies show that environmental shocks not only affect prices temporarily, but also shape the narrative of long-term risk in the global energy market (Nchege & Aduku, 2022). Thus, environmental externalities are not only seen as local economic impacts, but also part of a global risk system that drives the volatility of energy commodity prices.

The findings of this study are further reinforced by the study of environmental externalities in the context of global energy sustainability. The new economic framing in the energy sector places the environment as a determinant of long-term energy price structures, as reducing dependence on oil has become an international policy goal. Advanced economies are targeting emissions reductions in line with the Paris Agreement, which in practice limits the expansion of the oil industry and shifts the energy investment structure towards renewable sources. This shift affects oil prices through speculative demand mechanisms and supply constrained by climate policy (Corona et al., 2016). Therefore, oil price volatility cannot be explained solely by energy market dynamics, but also by the structure of international environmental policy, which acts as a policy shock to global oil price stability.

In an academic context, this study reinforces the idea that analyzing commodity price instability requires a multidimensional approach that does not rely solely on pure economic variables. Previous research's dependence on traditional economic factors has led to an incomplete understanding of the modern energy market structure. Through the GARCH approach, this study empirically proves that environmental externalities are a significant variable in the formation of crude oil price volatility. These results directly expand the scope of commodity volatility research and provide a conceptual basis for shifting the focus of energy price analysis from mere supply and demand to analysis based on environmental externalities and global sustainability policies. Thus, the research hypothesis stating that environmental externalities have a positive and significant effect on oil price volatility is statistically and theoretically proven.

Implications of Oil Price Volatility for Commodity Stability and Energy Policy

High crude oil price volatility due to environmental externalities has broad implications for the price stability of other commodities and global energy policy. When oil prices fluctuate extremely, almost the entire global production chain is affected, especially industrial sectors that use oil as primary energy or manufacturing raw materials. This condition causes an increase in production costs, profit margin adjustments, and an overall increase in the selling price of goods, so that oil volatility triggers aggregate commodity price instability. PURBA's (2025) research shows that energy price fluctuations are significantly correlated with the stability of agricultural commodity prices, particularly through changes in distribution costs, production inputs, and logistics. Thus, oil price volatility influenced by environmental externalities not only affects the energy market but also produces a spillover effect on the global commodity sector.

In addition to affecting other commodity prices, oil volatility has a direct impact on the energy security system and the availability of national energy supplies. Oil-importing countries face greater risks because oil price instability will burden the state budget through energy subsidies and increased import costs. When volatility persists over the long term, governments tend to intervene with policies such as domestic price adjustments, expanded renewable energy incentives, and increased strategic reserves (Rozci & Inti, 2024). On the one hand, such interventions can alleviate price pressures on consumers in the short term, but on the other hand, they have the potential to increase the fiscal burden if volatility persists. This confirms that global oil volatility triggered by environmental externalities has become a structural challenge for many countries in designing stable and sustainable energy policies.

The next implication arises in the context of global energy transition. High oil price volatility accelerates countries' shift to alternative energy because price uncertainty increases the economic and long-term investment risks of fossil fuels. Oil-exporting countries have also begun to develop production diversification strategies to reduce their dependence on oil as their main source of income. This condition shows that oil volatility has contributed to the acceleration of the energy transition, not merely as an ideological push for environmental sustainability, but also due to considerations of long-term economic efficiency (Corona et al., 2016).

This finding is in line with international energy policy directions that increasingly place price stability as an indicator that cannot be separated from the sustainability of the global energy market. From a commodity financial market perspective, persistent oil price volatility increases speculative activity as investors seek to profit from price instability. This phenomenon can amplify the amplitude of volatility as increased speculative trading volume increases price sensitivity to changes in energy market information.

The impact of volatility on financial markets is also evident in the research by Nazlioglu et al. (2016), which found a link between energy volatility and the property investment market through cross-sector risk transmission. This reinforces the notion that energy price instability is a systemic risk that can affect economic stability at large. Thus, oil volatility has become a crucial part of macroeconomic risk dynamics in the modern era. The policy implications of these research findings emphasize the importance of developing energy strategies that are adaptive to the dynamics of environmental externalities. Oil-importing countries need to increase energy security by accelerating the penetration of renewable energy, diversifying supply, improving industrial energy efficiency, and implementing market-based price control policies so that volatility does not spill over into domestic commodity inflation. Meanwhile, oil-exporting countries need to adjust long-term investments to maintain the stability of national revenues in an increasingly uncertain energy market. Therefore, this study reinforces the significance of the environment as a determinant of modern energy price volatility and directs policymakers to be more responsive to the sensitivity of energy markets to environmental externalities. In other words, the research results are not only relevant for academic analysis, but also for designing energy and commodity trade policies in the context of increasing global uncertainty.

CONCLUSIONS

This study shows that environmental externalities are an important determinant in explaining crude oil price volatility in global markets. The GARCH(1,1) model estimation results found that changes in environmental regulations, emissions policies, and energy transition dynamics have a positive and significant effect on oil price instability. The parameter value of γ at 0.227 and the accumulation of $\alpha + \beta$ at 0.905 confirm that shocks triggered by environmental factors not only affect prices in the short term but also create persistent volatility effects. In other words, oil price fluctuations are no longer entirely controlled by traditional supply and demand interactions, but are substantially triggered by external environmental pressures that create structural uncertainty in the energy market.

The implications are far-reaching, both for global commodity price stability and energy policy formulation. Prolonged and intense oil price volatility affects production costs across various sectors, accelerates the energy transition, and requires governments to develop more adaptive energy security strategies. These conditions underscore the importance of integrating environmental perspectives into energy market analysis and public policy. Thus, this study provides empirical and conceptual contributions that the dynamics of environmental externalities cannot be ignored in studies of commodity price volatility, and need to be used as a reference in energy risk management and the formulation of economic sustainability strategies in the future.

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