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# Do U.S. Interest Rates, Oil Prices, Economic Growth, and Domestic Interest Rates Affect Renewable Energy in Germany? New Insights from the NARDL Approach

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**Abstract:** Germany's energy transition depends not only on domestic policy commitment but also on stable financing conditions and resilience to external monetary and commodity-market shocks. This study examines the asymmetric short- and long-run effects of U.S. interest rates, Brent oil prices, German interest rates, and economic growth on renewable energy consumption in Germany, using annual data from 1970 to 2021. To the best of the author's knowledge, this is one of the first studies to apply a nonlinear autoregressive distributed lag (NARDL) framework to the German case with this combined set of external and domestic macro-financial determinants. The bounds F-test confirms a long-run equilibrium relationship (F = 70.48, significant at the 1% level), and Wald tests reject symmetry in both the short and long run ($p < 0.01$); the error-correction term is negative and significant (−0.841), indicating that about 84% of any deviation from equilibrium is corrected within one year. Short-run economic growth is initially associated with lower renewable energy consumption (contemporaneous coefficient −0.149) but with strong positive lagged responses (up to +2.796), consistent with reliance on fossil-fuel infrastructure in the short term and renewable expansion over the long run. Oil-price shocks display clear asymmetry: positive changes reduce renewable consumption (coefficients −0.325 to −0.385), whereas negative changes raise it (0.099 to 0.395), reflecting input-cost and substitution channels. Responses to U.S. interest-rate shocks are lagged and predominantly negative (−0.283 to

−0.556), implying that global monetary tightening is transmitted to Germany’s renewable-energy sector through financing and cost channels, and German interest-rate shocks likewise have time-varying asymmetric effects. The findings show that Germany’s renewable energy sector remains vulnerable to macroeconomic and financial instability despite its strong policy framework, and they endorse counter-cyclical green investment policies, more comprehensive domestic green-finance instruments, and strategies to strengthen financing resilience against external shocks. These insights may also guide other advanced, energy-importing nations exposed to comparable fluctuations in global interest rates and commodity prices.

**Keywords:** Renewable energy, interest rate, oil price, economic growth, NARDL, Germany.

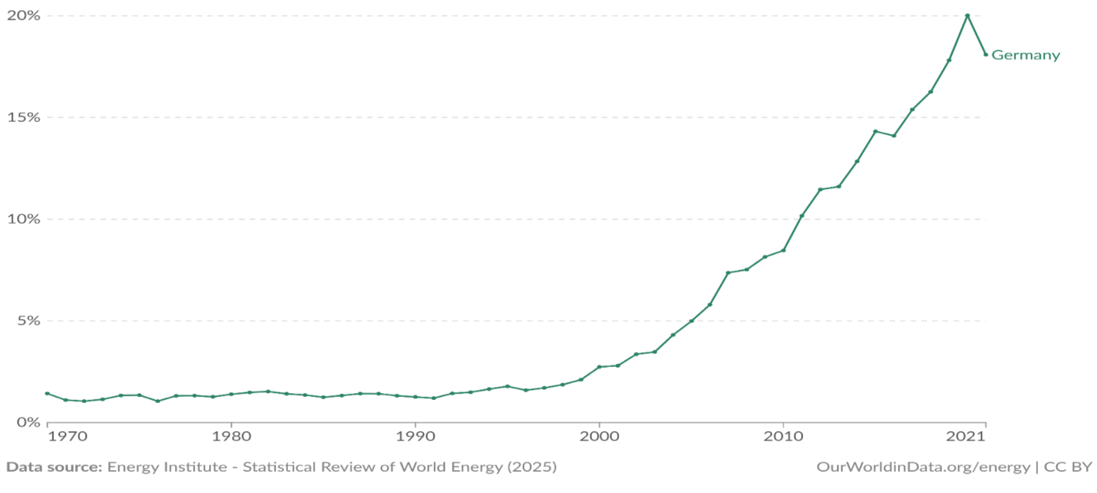
## Introduction

Germany is an advanced economy and, by nominal GDP, the fourth-largest in the world; by purchasing power parity (PPP), it ranks sixth. However, due to its economic system and high energy consumption, the country is highly dependent on energy imports, with around 77% of its energy imported and around 20% supplied by renewable sources (Bundeswirtschaftsministerium, 2022). This heavy reliance on fossil fuels also causes environmental problems due to high $CO_2$ emissions (Paraschiv & Paraschiv, 2020). In the future, Germany will see increased energy demand from both industry and households. Germany has thus declared a bold climate policy to become carbon neutral by 2045. To meet growing demand and reduce GHG emissions by 65% compared to current levels, Germany expects renewables to account for 75% of the total energy mix by 2030. In this context, Germany has expedited the development of renewable energy infrastructure, particularly within the industrial, transportation, and heating sectors.

As a result, the share of renewable energy has grown by nearly 429% between 2000 and 2022. However, fossil fuels remain a significant part of the nation’s energy mix, declining by about 14% between 2000 and 2024. Figure 1 illustrates the relatively modest growth in renewable energy sources between 1970 and 2010. However, since 2010, the share of renewables has resumed an upward trajectory, driven by new policy measures and investment. Various internal and external factors within Germany's energy system may be contributing to these observed trends.

**Figure 1**

*Evolution of renewable energy’s share in total energy consumption*




German renewable energy projects are affected by fluctuations in U.S. interest rates, as higher rates can tighten global financing conditions. Moreover, Germany’s continued dependence on fossil fuels, particularly oil, may make energy investment sensitive to oil-price volatility. Accordingly, this study examines the associations of U.S. interest rates, oil prices, economic growth, and German interest rates with renewable energy consumption in Germany.

Germany imports roughly 97% of its crude oil. Accordingly, oil-price volatility may significantly affect energy use (Rokicki & Perkowska, 2021). Oil prices also strongly influence consumer choices. Rising oil prices may prompt consumers to delay purchasing fossil-fuel-powered appliances (coal, oil, and gas). As a result, consumer choices will shift toward clean energy sources such as wave, wind, and solar power. Accordingly, renewable energy consumption will grow as it replaces fossil energy. Oil is a key input in production, and its price volatility can affect economic growth. In light of this, Adeniyi et al. (2022) have shown that oil prices affect economic performance in advanced economies. This impact is transmitted through inflationary forces and subsequent changes in the industrial sector's structure (Su et al., 2021). From a theoretical perspective, a positive oil-price shock boosts revenue for petroleum-exporting countries. For petroleum-importing economies, the direct consequence of rising oil prices is higher production costs. In addition, high oil prices reduce private investment in renewable energy (Adeniyi et al., 2022; Samour & Pata, 2022). For this reason, this study examines the relationship between oil-price fluctuations and renewable energy use in Germany. U.S. economic shocks transmit to the global economy through multiple channels, particularly via interest rates and the real effective exchange rate (Feldkircher & Huber, 2015). The international effects of higher U.S. interest rates are significant: a 1% increase in the U.S. rate reduces GDP in advanced economies by 0.5% and in emerging economies by 0.8% (Iacoviello & Navarro, 2019). Therefore, rising interest rates in Germany would directly affect renewable energy costs, thereby weakening the competitiveness of renewable energy sources (Schmidt et al., 2019). Based on these arguments, this paper examines the potential impact of U.S. interest rates, oil prices, gross domestic product per capita, and German interest rates on renewable energy consumption in Germany.

### *Research Problem*

Germany is increasingly relying on renewable energy, but its energy system remains vulnerable to fossil-fuel dependence, oil-price volatility, international financial market conditions, and domestic monetary policy. External financial conditions could be affected by changes in US interest rates, and energy costs and the relative attractiveness of renewable energy sources could be affected by changes in oil prices. Simultaneously, interest rates in Germany and the state of domestic economic activity may affect investment in and consumption of renewable energy via capital costs, income effects, and long-term energy demand. The linkages among renewable energy use, economic growth, oil prices, financial conditions, and institutions have been previously studied. However, the combined asymmetric effects of U.S. interest rates, oil prices, growth and German interest rates on German renewable energy use have not been sufficiently studied. An empirical framework is needed to separate positive and negative shocks and to assess their short- and long-run effects on renewable energy consumption.

### *Research Aim*

This study examines the asymmetric short-run and long-run effects of U.S. interest rates, Brent oil prices, economic growth, and German interest rates on renewable energy consumption in Germany from 1970 to 2021. To this end, the study applies the nonlinear autoregressive distributed lag (NARDL) approach. The NARDL framework allows positive and negative changes in the explanatory variables to have distinct effects on renewable energy consumption, making it suitable for analysing asymmetric macro-financial and energy-market relationships.

### *Research Questions*

The following research questions guide this study:

1. Do U.S. interest rate shocks have asymmetric short-run and long-run effects on renewable energy consumption in Germany?
2. Do positive and negative oil-price shocks affect Germany's renewable energy consumption differently?
3. Does economic growth have asymmetric effects on renewable energy consumption in the short run and long run?
4. Do German domestic interest rate shocks influence renewable energy consumption asymmetrically?

The remainder of this paper is organised as follows. Section 2 presents a brief literature review of relevant studies. Section 3 introduces the methodology and the data sources. Section 4 discusses the empirical results, and Section 5 concludes the paper.

**Literature Review**

The relationship among US interest rates, oil prices, and renewable energy has been extensively studied in macroeconomics (Alam & Murad, 2020; Cihat et al., 2021; Fazioli & Pantaleone, 2021; Shah et al., 2018; Uzar, 2020). A considerable body of literature exists on the effects of U.S. interest rates on the global economy. Vicondoa (2019) studied the impact of U.S. interest rates on declines in economic indicators. The author estimated a quarterly vector autoregressive (VAR) model for nine emerging economies from 1995–2017. The results suggest a 0.5% decline in GDP for a 25-basis-point increase in U.S. interest rates. The author finds that U.S. interest rates account for about 14% of the variation in these economies. Samour et al. (2020) also investigated the effect of the U.S. interest rate on Turkey's equity market. The study employed an Autoregressive Distributed Lag (ARDL) model and found that the U.S. interest rate had a considerable negative impact on the Turkish equity market through external sovereign debt channels.

Son and Park (2019) similarly examined the effect of US interest rates on household debt sustainability in South Korea. Their empirical analysis suggests that an increase in U.S. interest rates raises domestic interest rates e and, consequently, increases households' debt vulnerability. Another study by Wu and Deng (2021) investigated the impact of U.S. macroeconomic conditions on foreign direct investment from Japan (1970–1990) and China (2000–2018). Their data suggest that Chinese FDI is more sensitive to reductions in US real interest rates than Japanese FDI during the previous period. Considering both advanced and emerging economies, Iacoviello and Navarro (2019) analysed the spillovers of U.S. interest rates across a large panel of 50 economies. The authors found substantial heterogeneity in responses to US interest rates. In advanced economies, US interest rates depreciate the exchange rates of most countries with flexible exchange rate regimes. For countries that peg to the dollar, an increase in interest rates causes a drop in GDP. According to the same authors, US interest rates increase the real exchange rate and policy rates in these economies much more than they do in the US. Focusing on the spillover effects of US interest rates, Alba and Wang (2021) found that countries with free capital mobility and flexible exchange rates respond to decreases in short-term US interest rates but not to increases.

In contrast, countries with low volatility in exchange regimes react more to increases than to decreases in short-term US interest rates. Other strands of the literature examined the relationship between oil prices and renewable energy. For instance, Lee and Baek (2018) used the Non-Linear Autoregressive Distributed Lag (NARDL) to examine the impact of oil prices on renewable energy prices for 97 companies across 22 countries from January to December 2016. The results revealed that variations in oil prices have an asymmetric effect on renewable energy prices. Using cross-country data (1990-2018) from South Asian countries, Murshed and Tanha (2021) constructed a model of the nonlinear association between crude oil prices and renewable electricity. The authors largely found a nonlinear relationship between oil prices and renewable electricity, but they did not find any impact of rising oil prices on renewable electricity shares. The study also revealed that movements in oil prices lead these countries to transition to renewable energy.

Another study by Wang et al. (2020) assessed the impact of five factors, including the oil price, on a panel of 20 economies. Findings suggest that oil prices play a crucial role in promoting renewable energy. Similarly, using panel data for 30 OECD economies spanning the period 1970-2015, Gozgor et al. (2020) found a positive impact of oil prices on renewable energy prices. Another study in the United States, covering July 1989 to July 2016, by Troster et al. (2018) also assessed the effect of oil prices on renewable energy consumption. The authors tested the impact using quantile Granger causality and found no evidence of Granger causality between oil prices and renewable energy consumption. However, the results revealed unidirectional causality from changes in oil prices and reported that high oil prices are not sufficient incentives to affect renewable energy consumption. An analysis by Bamati and Raoofi (2020) covered 25 countries in two panels of developing and developed economies for the period from 1990 to 2015. The study suggested that oil prices have a weak impact on renewable energy production in both panels. Alkathery and Chaudhuri (2021) analysed the co-movement among oil price, CO2, and clean energy in the context of the Gulf Cooperation Council (GCC) energy stock market. The results revealed co-movement and volatility spillover effects among clean energy production, CO2, and crude oil prices.

Among the aforementioned studies, the impact of US interest rates, Oil prices, economic growth, and German interest rates on renewable energy use has not been extensively investigated, and, to the best of the author's knowledge, no empirical study has examined the case of Germany. Assessing this impact offers a better understanding of several shocks related to the development of the renewable energy sector. This research further fills an important gap in the literature by assessing the asymmetric impacts of US interest rates, Oil prices, economic growth, and German interest rates on renewable energy. In this perspective, the study employs the approach of Shin et al. (2014) to provide a more nuanced understanding of the short-run and long-run positive and negative effects of US interest rates, Oil prices, economic growth, and German interest rates on renewable energy consumption. Unlike the ARDL method used by Samour and Pata (2022) to investigate the impact of US interest rates, Oil prices, economic growth, and German interest rates on renewable energy consumption, the NARDL approach of Shin et al. (2014) demonstrates strong capability to capture both positive and negative impacts. The results of this analysis can help the German government to develop a strategy to protect the country's renewable energy industry. The results can be generalised to other nations with similar structural features.

## Research Methodology

### *Data*

This study focuses on Germany because it is a major renewable-energy producer that remains exposed to both global and domestic shocks. The sample comprises 52 annual observations covering 1970–2021. Table 1 summarises the variables, sources, and units of measurement.

**Table 1**

*Variable Descriptions*

| Variable (notation) | Source | Unit of measurement |
|---|---|---|
| Renewable energy ($re_t$) | International Energy Agency | Renewable energy consumption as a share of total energy (%) |
| U.S. interest rate ($r_t^*$) | OECD | Percentage points |
| German interest rate ($r_t$) | OECD | Percentage points |
| Brent oil price ($P_t^{\text{oil}}$) | OECD | Brent crude oil prices (US dollars/barrel) |

| | | |
|---|---|---|
| GDP per capita ($y_t$) | World Bank | GDP (constant 2010 in US$ per capita) |

*Source:* Author's work

Renewable energy consumption, GDP per capita, and Brent oil prices are included in the model in natural logarithms. Throughout the manuscript, $re_t \equiv \ln(\mathrm{RE}_t)$, $y_t \equiv \ln(\mathrm{GDP}_t^{\mathrm{pc}})$, and $\ln P_t^{\mathrm{oil}}$ denote the logged series. The unstarred and starred interest-rate variables denote the German domestic rate and U.S. foreign rate, respectively, and are expressed in percentage points. The oil-price log change is $\pi_t^{\mathrm{oil}} \equiv \Delta \ln P_t^{\mathrm{oil}}$.

### *Methodology*

Building on Samour and Pata (2022), who study renewable energy in Turkey, this paper adapts the framework to Germany. The NARDL model assesses asymmetric associations between renewable energy consumption and U.S. interest rates, oil prices, German interest rates, and economic growth. Compared with a standard ARDL model, Shin *et al.* (2014) estimate separate positive and negative effects in both the short and long run. Related dynamic ARDL methods also emphasise transparent simulation and interpretation of nonlinear adjustment paths (Sarkodie & Owusu, 2020).

The baseline econometric relationship is specified as follows:$re_t = \beta_0 + \beta_1 y_t + \beta_2 r_t^* + \beta_3 r_t + \beta_4 \ln P_t^{\mathrm{oil}} + \varepsilon_t \quad (1)$

Here, $\beta_0$ is the intercept and $\varepsilon_t$ is the error term. The starred rate $r_t^*$is foreign to Germany (the U.S. rate), whereas the unstarred rate $r_t$ is the domestic German rate.

### *Nardl Model*

In the NARDL model, $P_t^{\mathrm{oil}}$ denotes the Brent oil price level and $\pi_t^{\mathrm{oil}} \equiv \Delta \ln P_t^{\mathrm{oil}}$ denotes its log change. The positive and negative are defined as follows:

$$z_t^+ = \sum_{j=1}^{t} \max(\Delta z_j, 0), \; z_t^- = \sum_{j=1}^{t} \min(\Delta z_j, 0)$$

$$(\ln P_t^{\mathrm{oil}})^+ = \sum_{j=1}^{t} \max(\pi_j^{\mathrm{oil}}, 0), \; (\ln P_t^{\mathrm{oil}})^- = \sum_{j=1}^{t} \min(\pi_j^{\mathrm{oil}}, 0) \qquad (2)$$

In equation (2), $Z = \{y, r^*, r\}$. Superscripts + and − denote cumulative positive and negative changes, not powers. Let $S = \{+, -\}$ index the two signs. Substituting these partial sums into the error-correction ARDL form yields equation (3).

$$\Delta re_t = \alpha_0 + \rho\, re_{t-1} + \sum_{z \in Z} \sum_{s \in S} \theta_z^s z_{t-1}^s + \sum_{s \in S} \theta_P^s (\ln P_{t-1}^{\mathrm{oil}})^s$$
$$+ \sum_{i=1}^{p} \varphi_i \Delta re_{t-i} + \sum_{z \in Z} \sum_{s \in S} \sum_{i=0}^{q_z^s} \gamma_{z,i}^s \Delta z_{t-i}^s$$
$$+ \sum_{s \in S} \sum_{i=0}^{q_P^s} \gamma_{P,i}^s \pi_{t-i}^{\mathrm{oil},s} + \varepsilon_t. \qquad (3)$$

Here, $\rho$ is the error-correction coefficient. The $\theta$ terms are coefficients on lagged levels; the corresponding normalised long-run coefficients are $-\theta_z{}^s/\rho$ and $-\theta_P{}^s/\rho$. The $\varphi_i$ and$\gamma_{z,i}{}^s, \gamma_{P,i}{}^s$ terms capture short-run dynamics. The lag orders $p$, $q_z{}^s$, and $q_P{}^s$ may vary by variable and sign.

## Results

### *Descriptive Statistics*

Table 2 reports descriptive statistics for the study variables. The standard deviations are below 1, indicating relatively limited dispersion in the reported series; this descriptive evidence does not, by itself, rule out structural breaks. All variables are negatively skewed, and their kurtosis values exceed 3. The reported Jarque–Bera p-values are below 0.05 for every variable; therefore, the null hypothesis of normality is rejected at the 5% level. These distributional features motivate formal unit-root and diagnostic testing.

**Table 2**

*Descriptive Statistics*

| | $y_t$ | $r_t$ | $\ln P_t^{\text{oil}}$ | $r_t^*$ | $re_t$ |
|---|---|---|---|---|---|
| Mean | 9.905 | 1.169 | 3.286 | 1.100 | 1.147 |
| Median | 10.164 | 1.451 | 3.262 | 1.661 | 0.571 |
| Maximum | 10.835 | 2.496 | 4.720 | 2.767000 | 3.050 |
| Minimum | 7.923 | -1.560 | 1.085 | -2.170096 | 0.114 |
| Std. Dev. | 0.804 | 0.967 | 0.889 | 0.995503 | 0.988 |
| Skewness | -0.790 | -0.964 | -0.540 | -1.122745 | -0.698 |
| Kurtosis | 3.566 | 3.457 | 3.291 | 3.091554 | 3.871 |
| Jarque-Bera | 5.825 | 8.510 | 2.718 | 10.94299 | 6.985 |
| Probability | 0.044 | 0.014 | 0.025 | 0.004205 | 0.030 |
| Observations | 52 | 52 | 52 | 52 | 52 |

*Source:* Author's calculation

***Stationarity Test***

Table 3 reports the Augmented Dickey–Fuller (ADF) and Phillips–Perron (PP) unit-root tests, following Dickey and Fuller (1979) and the PP implementation considerations discussed by Cheung and Lai (1997). The reported specifications include an intercept and, where indicated, a deterministic trend. Across tests, the series show a mix of level and first-difference stationarity. Because nonlinear regressions with nonstationary variables can be spurious (Lee *et al.*, 2005), the absence of I(2) variables should be verified before estimating the NARDL bounds model. Subject to that condition, a mixture of I(0) and I(1) series supports the use of NARDL.

**Table 3**

*Unit Root Results*

| Variables | ADF: Intercept | ADF: Intercept and Trend | PP: Intercept | PP: Intercept and Trend |
|---|---|---|---|---|
| **Level** | | | | |
| $y_t$ | -3.301(0.0199) | -2.515(0.319) | -3.098(0.032) | -2.534(0.310) |
| $r_t$ | -1.599(0.475) | -3.658(0.034) | -1.141(0.567) | -2.915(0.166) |
| $\ln P_t^{\text{oil}}$ | -2.346(0.161) | -2.537(0.309) | -2.355(0.159) | -2.568(0.296) |
| $r_t^*$ | -0.693(0.838) | -4.782(0.001) | -0.783(0.815) | -2.332(0.409) |
| $re_t$ | 1.544(0.999) | -2.0884(0.539) | 1.547(0.999) | -2.088(0.539) |
| **First Differences** | | | | |
| $\Delta y_t$ | -4.959(0.000) | -5.291(0.000) | -4.848(0.000) | -5.144(0.000) |
| $\Delta r_t$ | -6.529(0.000) | -6.770(0.000) | -7.524(0.000) | -7.660(0.000) |
| $\pi_t^{\text{oil}}$ | -6.166(0.000) | -6.211(0.000) | -6.104(0.000) | -6.125(0.000) |
| $\Delta r_t^*$ | -5.424(0.000) | -5.437(0.000) | -2.327(0.167) | -2.399(0.375) |
| $\Delta re_t$ | -6.932(0.000) | -7.349(0.000) | -6.924(0.000) | -7.360(0.000) |

*Source:* Author's calculation

### ***Nonlinearity Test***

The BDS test developed by Broock *et al.* (1996) assesses whether a series is independently and identically distributed. As Table 4 shows, all reported BDS statistics are significant at the 1% level, so the null hypothesis is rejected for every variable. This result provides evidence of nonlinear dependence, although it does not, by itself, identify the correct functional form; it supports examining a nonlinear specification, such as NARDL.

**Table 4**

***BDS Test Results for Nonlinearity***

| Series | Dimension 2 | Dimension 3 | Dimension 4 | Dimension 5 | Dimension 6 |
|---|---|---|---|---|---|
| $re_t$ | 0.182(0.000) | 0.299(0.000) | 0.374(0.000) | 0.422(0.000) | 0.449(0.000) |
| $r_t^*$ | 0.126(0.000) | 0.194(0.000) | 0.263(0.000) | 0.317(0.000) | 0.354(0.000) |
| $\ln P_t^{\text{oil}}$ | 0.156(0.000) | 0.272(0.000) | 0.342(0.000) | 0.382(0.000) | 0.408(0.000) |
| $r_t$ | 0.125(0.000) | 0.215(0.000) | 0.264(0.000) | 0.296(0.000) | 0.317(0.000) |
| $y_t$ | 0.195(0.000) | 0.333(0.000) | 0.429(0.000) | 0.494(0.000) | 0.538(0.000) |

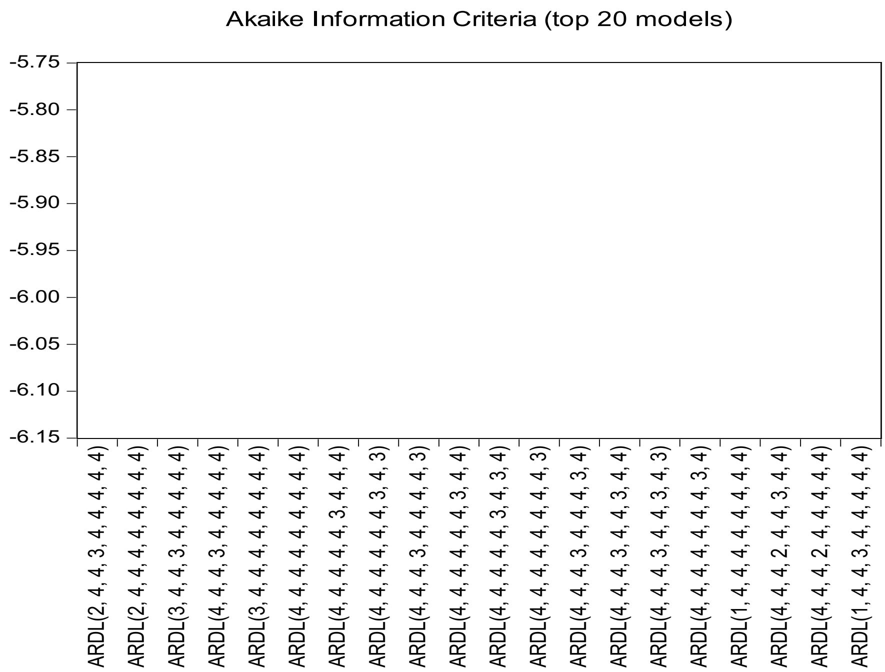
*Source:* Author's calculation

### ***Nardl Model Estimates***

#### ***Optimal Lag***

**Figure 2**

*Akaike Information Criterion*




*Source:* Author's calculation

The optimal NARDL specification was selected using the Akaike information criterion (AIC). Among the estimated candidates in Figure 2, NARDL (2, 4, 4, 3, 4, 4, 4, 4) has the lowest AIC and was retained. Given the 52 annual observations and the large number of lagged terms, this specification is parameter-intensive and warrants caution in small-sample inference.

***Cointegration Test***

The next step is to assess whether a long-run equilibrium association exists among the variables. To do so, we applied the bounds F-test. Table 5 presents the cointegration test results obtained from the nonlinear estimation.

**Table 5**

*Cointegration Results*

| Model | F-statistic | Lower bound (I(0)) | Upper bound (I(1)) |
|---|---|---|---|
| $re_t: \{y_t^{\pm}, r_t^{*,\pm}, r_t^{\pm}, (\ln P_t^{\text{oil}})^{\pm}\}$ | 70.482 | | |
| Critical values | | | |
| 10% | | 2.26 | 3.34 |
| 5% | | 2.55 | 3.68 |
| 2.5% | | 2.82 | 4.02 |
| 1% | | 3.15 | 4.43 |

*Source:* Author's calculation

Following Pesaran *et al.* (2001), the F-statistic is compared with the I(0) lower bound and I(1) upper bound. The reported F-statistic of 70.48 exceeds the upper critical bound at the 10%, 5%, 2.5%, and 1% significance levels, supporting a long-run equilibrium association among the variables. The Wald tests in Table 6 also reject the null of equality between the positive and negative coefficients in both the short and long run. These tests provide evidence of asymmetry within the specified model; they do not establish causality.

**Table 6**

*Wald Test*

| | Long-run | Short-run |
|---|---|---|
| F-statistic | 79.012 | 56.117 |
| Probability | 0.000 | 0.001 |

*Source:* Author's calculation

***Diagnostic Tests***

To assess model adequacy, the analysis applies the Breusch–Godfrey LM test for serial correlation, the Breusch–Pagan–Godfrey test for heteroskedasticity, the Jarque–Bera test for residual normality, and the Ramsey RESET specification test. As Table 7 shows, the reported p-values exceed 0.05, so we do not reject the null hypotheses. The CUSUM and CUSUMQ tests follow Brown et al. (1975) and Pesaran and Pesaran (2010). Figure 3 shows both statistics within the 5% bounds, supporting in-sample parameter stability. These diagnostics do not establish causal identification or rule out omitted-variable bias.

**Table 7**

*Diagnostic Tests for the NARDL (2, 4, 4, 3, 4, 4, 4, 4) Model*

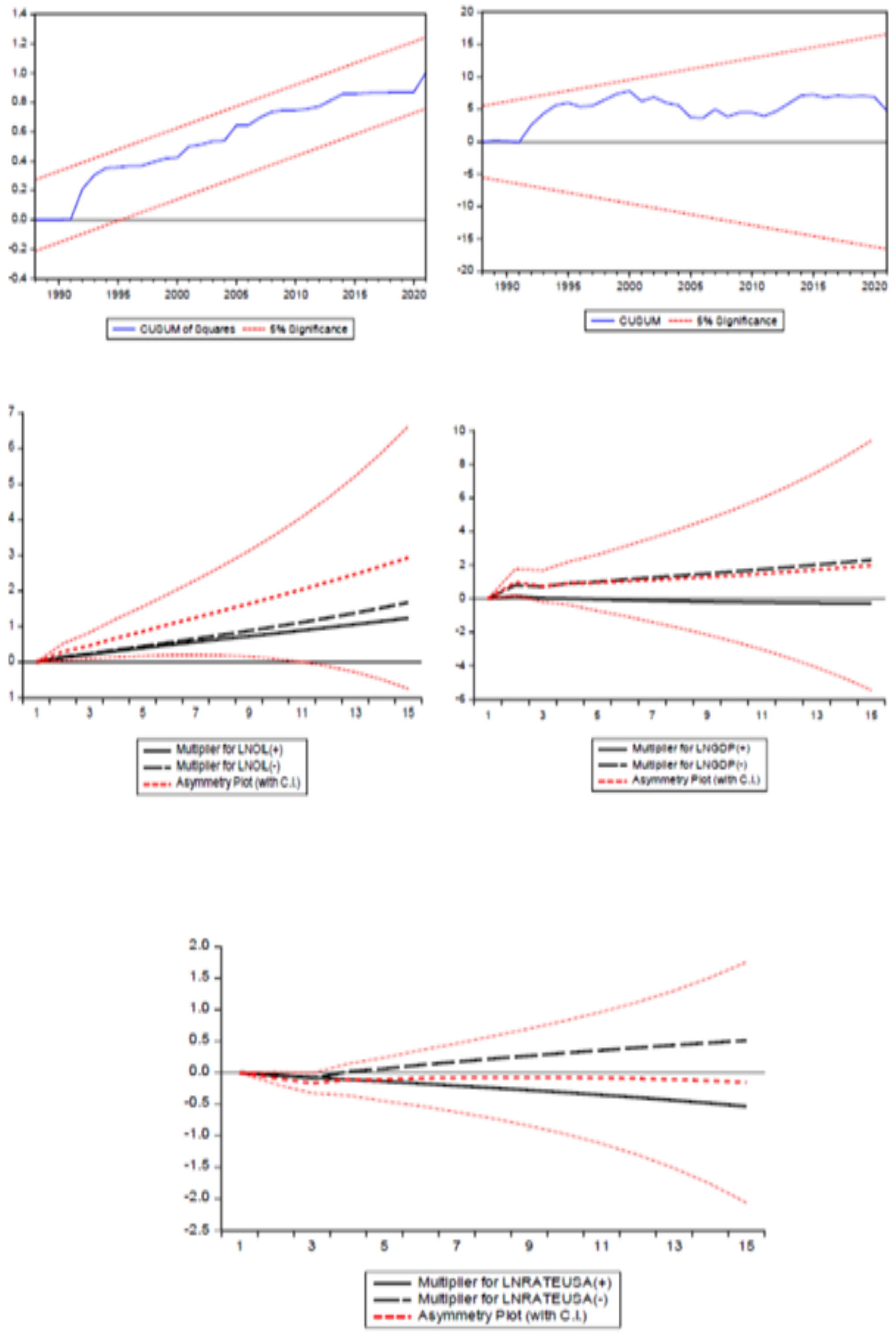
| Diagnostic Test | Serial Correlation $\chi^2$ *(p-value)* | Heteroscedasticity $\chi^2$ *(p-value)* | Normality $\chi^2$ *(p-value)* | Model specification $\chi^2$ *(p-value)* |
|---|---|---|---|---|
| LM test | 10.358(0.28) | | | |
| Breusch-Pagan-Godfrey | | 3.903(0.314) | | |
| Jarque-Bera | | | 0.327(0.84) | |

| Diagnostic Test | Serial Correlation $\chi^2$ *(p-value)* | Heteroscedasticity $\chi^2$ *(p-value)* | Normality $\chi^2$ *(p-value)* | Model specification $\chi^2$ *(p-value)* |
|---|---|---|---|---|
| Ramsey RESET test | | | | 0.444(0.57) |

*Source:* Author's calculation

**Figure 3**

*CUSUM and CUSUMQ tests*




*Source:* Author's calculation

***Short-Run and Long-Run Estimates***

***Short-Run Estimates***

Table 8 reports the short-run dynamics. The error-correction coefficient is negative and statistically significant (−0.841; p < 0.001), indicating that approximately 84% of a deviation from long-run equilibrium is corrected within one year. The contemporaneous coefficient on the positive GDP component is −0.149, while the first three lagged coefficients are 2.796, 2.139, and 0.895; all are statistically significant. The contemporaneous coefficient on the negative GDP component is 0.143 and is significant only at the 10% level (p = 0.0845), whereas the first three lagged coefficients are −4.763, −2.587, and −0.819 and are statistically significant. The coefficient sequences therefore differ across the positive and negative components.

Oil-price changes also show statistically significant short-run asymmetry. The coefficients on $\pi_t^{\text{oil},+}$ at lags 0–2 are −0.325, −0.349, and −0.385, whereas the coefficients on $\pi_t^{\text{oil},-}$ at lags 0–3 are 0.099, 0.182, 0.342, and 0.395. For the U.S. interest rate, the contemporaneous positive-component coefficient is not statistically significant, but the first three lagged coefficients are negative and significant (−0.508, −0.283, and −0.556). The coefficients on the negative U.S. interest-rate component alternate in sign across lags.

German interest rates also exhibit asymmetric short-run coefficients. The contemporaneous coefficient on the positive component is 0.372, followed by lagged coefficients of 0.099, 0.215, and 0.302. The coefficients on the negative component are −0.119, −0.256, and −0.378 at lags 0–2, before turning positive (0.164) at lag 3.

**Table 8**

*Short-Run Analysis*

| Variable | Coefficient | Std. Error | t-Statistic | p-value |
|---|---|---|---|---|
| $\Delta re_{t-1}$ | -0.136 | 0.0221 | -6.1826 | 0.0035 |
| $\Delta y_t^+$ | -0.149 | 0.0330 | -4.5242 | 0.0106 |
| $\Delta y_{t-1}^+$ | 2.796 | 0.0741 | 37.7520 | 0.0000 |
| $\Delta y_{t-2}^+$ | 2.139 | 0.0523 | 40.9224 | 0.0000 |
| $\Delta y_{t-3}^+$ | 0.895 | 0.0362 | 24.7309 | 0.0000 |
| $\Delta y_t^-$ | 0.143 | 0.0625 | 2.2835 | 0.0845 |
| $\Delta y_{t-1}^-$ | -4.763 | 0.1209 | -39.3890 | 0.0000 |
| $\Delta y_{t-2}^-$ | -2.587 | 0.0867 | -29.8392 | 0.0000 |
| $\Delta y_{t-3}^-$ | -0.819 | 0.0666 | -12.3011 | 0.0003 |
| $\pi_t^{\text{oil},+}$ | -0.325 | 0.0180 | -18.0503 | 0.0001 |
| $\pi_{t-1}^{\text{oil},+}$ | -0.349 | 0.0160 | -21.7906 | 0.0000 |
| $\pi_{t-2}^{\text{oil},+}$ | -0.385 | 0.0158 | -24.4060 | 0.0000 |
| $\pi_t^{\text{oil},-}$ | 0.099 | 0.0161 | 6.1936 | 0.0035 |
| $\pi_{t-1}^{\text{oil},-}$ | 0.182 | 0.0162 | 11.1945 | 0.0004 |
| $\pi_{t-2}^{\text{oil},-}$ | 0.342 | 0.0140 | 24.3699 | 0.0000 |
| $\pi_{t-3}^{\text{oil},-}$ | 0.395 | 0.0136 | 29.0422 | 0.0000 |
| $\Delta r_t^{*,+}$ | 0.019 | 0.0119 | 1.5814 | 0.1889 |
| $\Delta r_{t-1}^{*,+}$ | -0.508 | 0.0159 | -31.8901 | 0.0000 |
| $\Delta r_{t-2}^{*,+}$ | -0.283 | 0.0150 | -18.9284 | 0.0000 |

| Variable | Coefficient | Std. Error | t-Statistic | p-value |
|---|---|---|---|---|
| $\Delta r_{t-3}^{*,+}$ | -0.556 | 0.0123 | -45.2876 | 0.0000 |
| $\Delta r_{t}^{*,-}$ | 0.618 | 0.0141 | 43.8466 | 0.0000 |
| $\Delta r_{t-1}^{*,-}$ | -0.058 | 0.0105 | -5.4686 | 0.0054 |
| $\Delta r_{t-2}^{*,-}$ | 0.247 | 0.0147 | 16.8553 | 0.0001 |
| $\Delta r_{t-3}^{*,-}$ | -0.256 | 0.0149 | -17.1065 | 0.0001 |
| $\Delta r_{t}^{+}$ | 0.372 | 0.0147 | 25.3597 | 0.0000 |
| $\Delta r_{t-1}^{+}$ | 0.099 | 0.0090 | 10.9723 | 0.0004 |
| $\Delta r_{t-2}^{+}$ | 0.215 | 0.0101 | 21.3569 | 0.0000 |
| $\Delta r_{t-3}^{+}$ | 0.302 | 0.0121 | 24.9413 | 0.0000 |
| $\Delta r_{t}^{-}$ | -0.119 | 0.0102 | -11.7032 | 0.0003 |
| $\Delta r_{t-1}^{-}$ | -0.256 | 0.0146 | -17.5150 | 0.0001 |
| $\Delta r_{t-2}^{-}$ | -0.378 | 0.0144 | -26.1583 | 0.0000 |
| $\Delta r_{t-3}^{-}$ | 0.164 | 0.0143 | 11.4807 | 0.0003 |
| $\text{ECM}_{t-1}$ | -0.841 | 0.0193 | -43.6237 | 0.0000 |

*Source:* Author's calculation

### *Long-Run Estimates*

Table 9 reports long-run coefficients for the positive and negative components. Because NARDL decomposes each regressor into separate components, the sign and label of each coefficient must be interpreted together.

The positive GDP partial sum has a negative coefficient of −4.757 ($p = 0.0012$), whereas the negative GDP partial sum has a positive coefficient of 7.502 ($p = 0.0040$). These opposite signs indicate a long-run asymmetric association between GDP per capita and renewable energy consumption.

**Table 9**

*Long-Run Analysis*

| Variable | Coefficient | Std. Error | t-Statistic | p-value |
|---|---|---|---|---|
| $y_t^{+}$ | -4.757 | 0.5839 | -8.1464 | 0.0012 |
| $y_t^{-}$ | 7.502 | 1.2641 | 5.9344 | 0.0040 |
| $(\ln P_t^{\text{oil}})^{+}$ | 0.644 | 0.1442 | 4.4664 | 0.0111 |
| $(\ln P_t^{\text{oil}})^{-}$ | -0.558 | 0.1569 | -3.5555 | 0.0237 |
| $r_t^{*,+}$ | 0.330 | 0.0919 | 3.5860 | 0.0230 |
| $r_t^{*,-}$ | 0.461 | 0.1296 | 3.5545 | 0.0237 |
| $r_t^{+}$ | 0.338 | 0.1305 | 2.5858 | 0.0610 |
| $r_t^{-}$ | 0.411 | 0.1172 | 3.5076 | 0.0247 |

*Source*: Author's calculation

Oil prices also exhibit long-run asymmetry. The positive partial sum $(\ln P_t^{\text{oil}})^{+}$ has a coefficient of 0.644 ($p = 0.0111$): a 1% positive oil-price shock is associated with approximately 0.644% higher renewable energy consumption. By contrast, the negative partial sum $(\ln P_t^{\text{oil}})^{-}$ has a coefficient of −0.558 ($p = 0.0237$): a 1% negative oil-price shock is associated with approximately 0.558% lower renewable energy consumption. The two estimates therefore refer to different shock directions.

The positive and negative U.S. interest-rate components have positive, statistically significant long-run coefficients of 0.330 and 0.461, respectively.

For German interest rates, the positive-component coefficient is 0.338 ($p = 0.0610$), so it is statistically significant at the 10% level but not at the conventional 5% level. The negative-component coefficient is 0.411 ($p = 0.0247$) and is significant at the 5% level. The evidence is therefore asymmetric, with weaker statistical support for the positive component.

***Discussion***

***Economic Growth***

Taken together, the GDP estimates point to adjustment that varies by both the direction of the shock and the time horizon, rather than to a uniform growth effect. In the short run, the initial negative association is followed by positive lagged responses, while negative GDP changes show the opposite sequence. This pattern is consistent with evidence reported by Al-Mulali et al. (2013), Ohler and Fetters (2014), Apergis and Payne (2014), and Rahman and Rahman (2025). In the long run, the opposite signs of the positive and negative GDP partial sums confirm asymmetry. The positive-shock result is consistent with Güler et al. (2024), whereas the negative-shock estimate is comparable with the heterogeneous transition patterns discussed by Taghizadeh-Hesary et al. (2020). The findings may reflect short-run reliance on existing fossil-fuel infrastructure and longer-run changes in renewable-energy investment; however, these mechanisms remain interpretations of reduced-form associations rather than identified causal channels.

***Oil Prices***

The short-run oil-price coefficients indicate opposite responses to positive and negative changes. In the long run, positive oil-price shocks are associated with higher renewable energy consumption, whereas negative shocks are associated with lower consumption. This asymmetry is consistent with Karacan et al. (2021), Al-Maamary et al. (2016), Apergis and Payne (2014), Sadorsky (2009), and Mukhtarov (2024). The pattern may reflect two countervailing channels highlighted in the literature: higher oil prices can raise production and technology-input costs, yet they can also encourage substitution away from fossil fuels towards renewable energy. Because the NARDL estimates are reduced-form, the results should not be interpreted as causal effects.

***Interest Rates***

The lagged negative short-run coefficients on positive U.S. interest-rate shocks are consistent with delayed transmission through exchange-rate movements and dollar-denominated input costs (Mohsin et al., 2022; Egli et al., 2018). In the long run, the positive coefficients on both U.S. interest-rate components may reflect different channels, including portfolio reallocation during tightening and lower financing costs during easing. These estimates are comparable with the financial-channel evidence discussed by Schmidt et al. (2019) and Samour and Pata (2022), but they do not establish that changes in U.S. monetary policy cause higher renewable energy consumption.

The German interest-rate estimates also vary by shock direction and horizon. The short-run sequence should not be characterised as uniformly expansionary or contractionary, and the weaker 10% significance of the positive long-run coefficient warrants caution. Possible explanations involving financing costs, long-term contracts, and institutional stability remain interpretive rather than causal (Schmidt et al., 2019; Samour & Pata, 2022).

***Policy Implications***

These findings have several policy implications. First, renewable-energy investment should be supported counter-cyclically through instruments such as green investment guarantees and stabilisation funds, particularly during recessions. Second, Germany should strengthen carbon pricing, fossil-fuel taxation, and renewable-energy support schemes so that short-term oil-price volatility does not derail the transition.

Third, resilience to external financial shocks can be strengthened by promoting domestic production of renewable-energy technologies, reducing dependence on dollar-denominated imports, and expanding euro-denominated green finance. Fourth, long-term power-purchase agreements and green bonds can help sustain investor confidence across interest-rate settings. Finally, renewable-energy targets should remain integrated into long-term industrial, fiscal, and innovation planning.

***Conclusions and Recommendations***

The study employed a nonlinear model to analyse the associations between U.S. interest rates, oil prices, economic growth, and German interest rates and renewable energy consumption in Germany from 1970 to 2021. The results indicate that economic progress could, in the short term, restrict renewable energy use due to reliance on cheaper fossil fuels. However, favourable GDP shocks can spur investment in renewables. A reduction in GDP negatively affects the use of renewable resources. High oil prices in the near term may restrict the diffusion of renewables due to higher costs, but sustained price increases may shift demand toward renewable energy sources. Higher U.S. interest rates raise the coshort-term st of imported renewable technology ine to exchange rate volatility. However, in the long term, rising U.S. interest rates strengthen renewable energy by diverting investment to stable economies such as Germany. German interest rates suggest that renewable energy is resilient to financing limitations. High interest rates help deployment under favourable conditions; low interest rates help reduce project costs. The importance of long-term contracts is evident.

These findings suggest several policy implications. First, investment in renewables should be counter-cyclical, using governmental instruments such as green investment guarantees and stabilisation funds to protect projects during recessions, when GDP contractions seriously affect the use of renewables. Second, Germany should strengthen its carbon pricing systems, fossil fuel taxes and renewable energy assistance schemes to make the transition to renewable energy unaffected by changes in fossil fuel prices, reducing the effects of short-term oil price fluctuations. Third, resilience to external financial shocks needs to be strengthened. This is accomplished by promoting domestic production of renewable energy technologies, reducing dependence on dollar-denominated imports and expanding the availability of euro-denominated green finance to mitigate the negative effects of rising U.S. interest rates. Fourth, the long-run benefits from both tightening and loosening domestic monetary conditions are positive. Therefore, Germany's institutional framework is very robust. Long-term power purchase agreements and green bonds are therefore critical to keeping investor confidence across different interest rate settings. "Finally, renewable energy targets should be integrated into long-term industrial, fiscal and innovation plans in an effort to implement Germany's energy transition objectives successfully and sustainably, as long-term economic growth will eventually lead to higher consumption of renewable energies. Future studies may explore the impact of other financial and energy market factors on renewable energy consumption such as exchange rate volatility, carbon market price and geopolitical risk.

Several limitations qualify the findings. Initially, the chosen NARDL specification includes numerous positive and negative and lagged terms, which, given the sample size, increases the likelihood of overfitting and finite-sample uncertainty. Furthermore, the single-country framework restricts the external validity of the findings. Additionally, omitted variables—including exchange-rate volatility, carbon prices, technological advancements, geopolitical shocks, and changes in energy policy regimes or structural breaks—may affect the estimated coefficients. Given that the model is reduced-form, the coefficients should be regarded as conditional dynamic associations rather than causal relationships. Future research could incorporate higher-frequency data, more parsimonious lag structures, break-robust specifications, and cross-country comparative analyses.

### *Suggestions for Future Research*

Future studies could include additional financial and energy market variables in the model, such as exchange-rate volatility, carbon market prices, geopolitical risk and technological innovation. These may be particularly important in the context of Germany's energy use, especially for renewable energy, as the economy is sensitive to external events such as global financial markets, imported energy costs, and other international developments. Second, further research could incorporate quarterly or monthly data to better capture short-run variation. The data are annual and thus suitable for long-term analysis, but may not reflect the rapid pace of changes in interest rates, oil prices, carbon prices, and geopolitical conditions. Third, future research could employ more sophisticated econometric methods that account for structural breaks, regime shifts, and time-varying relationships. In addition, the impact of the energy transition on Germany has been shaped by significant changes in energy policy, market conditions, and the broader macroeconomic environment. Germany, robust techniques (e.g. Fourier NARDL, time-varying parameter ARDL or wavelet-based approaches) may provide additional insights into the evolving links between macro-financial shocks and renewable energy consumption. Future studies might compare Germany with other European Union (EU) countries, or, as a fourth option, with other advanced economies, to further elucidate whether the asymmetric relationships revealed in this study are unique to Germany or also applicable to countries where energy structures, monetary and renewable energy policies differ from those of Germany. The comparative work could also examine the role of institutional quality, the development of green finance and energy dependence on the response of renewable energy to external shocks. Future research could also explore other renewable energy indicators. These include renewable electricity generation, renewable installed capacity, renewable energy investment, and renewable energy use in specific sectors. These indicators could provide a more comprehensive view of how financial and macroeconomic shocks can affect the various aspects of the energy transition.

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## Ethical approval

Not applicable. This study relies exclusively on secondary data from publicly available sources and does not involve human participants, animals, or identifiable personal data. Therefore, ethical approval was not required.

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