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NONLINEAR GRANGER CAUSALITY BETWEEN NATURAL GAS AND HEATING OIL PRICES AND SELECTED EXCHANGE RATES

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Purpose: The currently observed uncertainty in financial markets related to changes taking place in the modern world requires investors to look for tools that allow for good forecasting of the price of financial instruments. The detection of causal relationships may contribute to improving the quality of forecasts by reducing the variance of the prediction error. The aim of the research is to detect nonlinear Granger causality in both directions between selected financial instruments and to check whether the identified relationships are stable over time.
Design/methodology/approach: The study of causal relationships between selected financial instruments was carried out using the nonparametric Diks-Panchenko test. This test identifies all types of relationships: linear and nonlinear.
Findings: In the first phase of the study, nonlinear Granger causality was tested using the nonparametric Diks-Panchenko test. Six values of lags and two distance measures were used. It is then shown that the significance of the detected relationships has changed in recent years. For this purpose, two directions of causality and three sub-periods were analyzed.
Research limitations/implications: Due to the short-term character of the detected relationships, they should be taken into consideration primarily by market participants, to create effective investment portfolios and risk-hedging strategies.
Practical implications: Application in making investment decisions on the capital market.
Originality/value: The use of information on causal relationships to improve the quality of forecasts related to the energy and currency markets.

Keywords: nonlinear Granger causality, Diks-Panchenko test, heating fuel market, exchange rates.

Category of the paper: Research paper.

1. Introduction

Due to the exceptional situation on the European and domestic market of heating raw materials that has been ongoing for over a year, a significant increase in the prices of natural gas and heating oil has been observed, which, next to crude oil and coal, are the most important sources of energy in the world. The analysis of these changes is very important because these energy carriers are of key importance for industry and national economies. They are used, among other things, to produce heat energy, which in Poland is an alternative to high-emission hard coal and lignite. Many countries, including Poland, are largely dependent on the import of these raw materials (Kaliski, 2010). Since their supplies are paid for in foreign currencies, it can be assumed that the prices of natural gas and heating oil are sensitive to changes in exchange rates. Determining the trends in price changes of these raw materials and the factors influencing them is the starting point for forecasts, necessary in long-term business planning.

There are many studies in the literature examining the relationship between crude oil prices and exchange rates (Fratzscher et al., 2014; Wen et al., 2017; Beckmann et al., 2020; Orzeszko, 2021). Among them, we can find works that examined linear Granger causality (Brahmasrene et al., 2014; Sharma, 2017; Adam et al., 2018). However, the obtained results are not so clear on the direction of the causal relationship between crude oil prices and exchange rates. This highlights the need to include nonlinear causality tests in research.

The main goals of the paper are:

- testing two-way non-linear Granger causality between the prices of natural gas and heating oil and selected currency rates, i.e. EUR/USD, PLN/USD,
- and examining whether the identified relationships are stable over time.

The research used time series composed of the closing prices of selected financial assets obtained from the investment portal investing.com. The research period covers the years 2014-2023, narrowed down to three sub-periods in individual analyzes.

The article consists of two main parts: the first is theoretical (the methodology used in the analysis is briefly discussed and references to the literature are given), and the second is the analysis of financial data and its conclusions. The article ends with a summary.

2. Natural gas and heating oil versus exchange rates

Due to its unquestionable advantages, natural gas is often called the fuel of the 21st century. After periods of dominance of coal and crude oil, changes can be observed in the structure of fuel consumption with greater use of gas. It is used not only to produce heat and electricity, but is also widely used in the chemical, heavy and food industries, where it is used, among others, for the production of plastics, detergents and paints.

Another source of energy is heating oil. It is obtained in the process of distillation of crude oil. In the late 1990s, this raw material was advertised as a cheap and ecological fuel. As a result, cooperatives, housing communities and owners of single-family houses began to use this type of heating more and more often. Heating oil differs in its use and quality. It is mainly used as: a means for heating heating installations in industrial furnaces; material for production purposes; fuel for technological purposes.

Currently, natural gas and fuel oil are in high demand around the world. Their popularity has increased as a result of environmental protection requirements and reducing coal consumption. The key role of these raw materials in the global economy implies a discussion on the links between natural gas and fuel oil prices and other macroeconomic and financial factors. Both theoretical and empirical studies have pointed to the sources and potential consequences of these connections (Suleymanli et al., 2020). It was noticed that one of the most important factors influencing the prices of natural gas and heating oil are exchange rates. This is because the prices of these raw materials are quoted and settled in US dollars. When the dollar depreciates against other currencies, the prices of natural gas and heating oil rise, and when the dollar appreciates, the prices of these commodities fall (Figure 1).

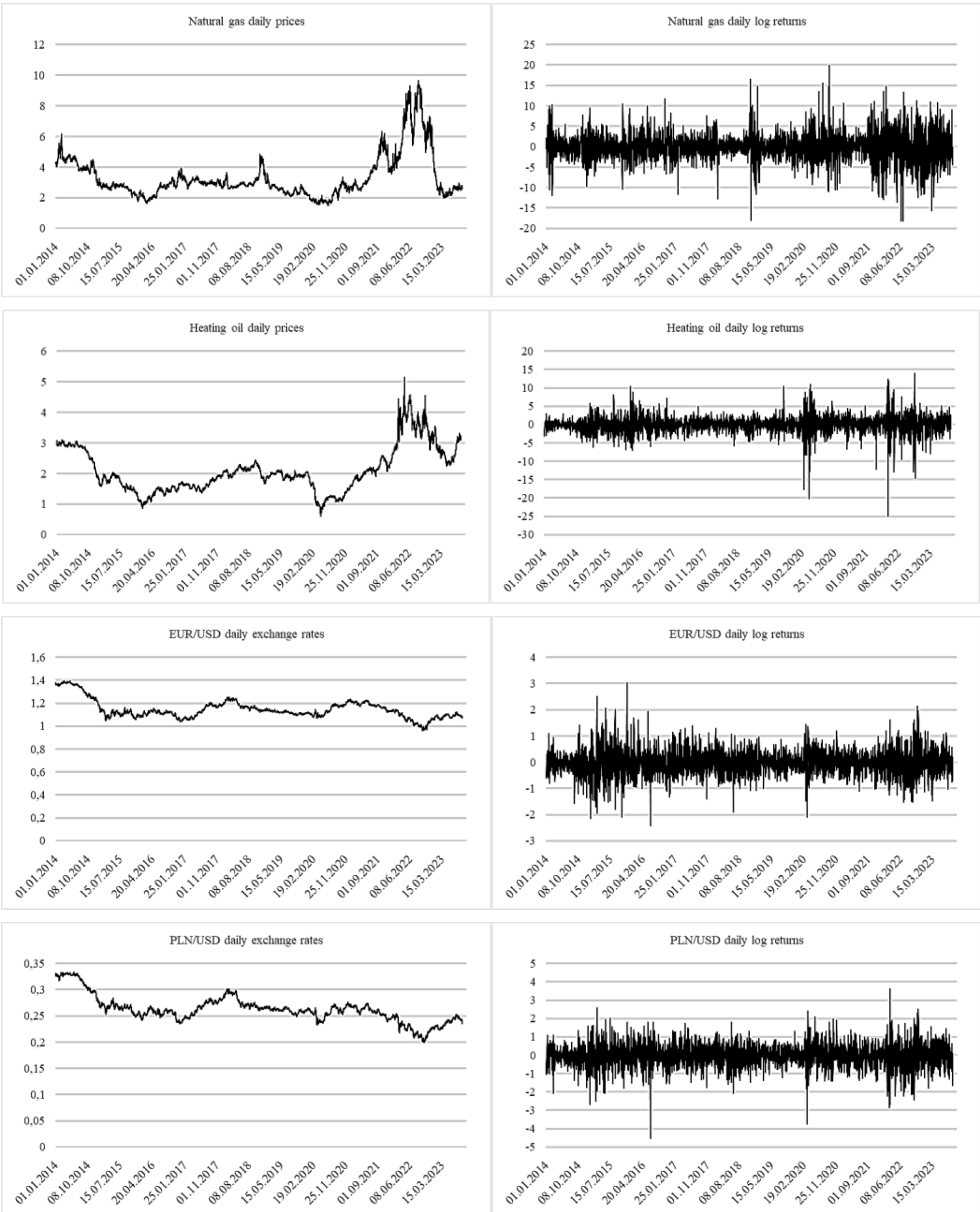

Figure 1. Selected time series from the period 1 January 2014 – 6 September 2023.

Source: own study.

Analyzing the above charts, you can see three sub-periods in which changes in raw material prices change significantly. In the first period, i.e. from the beginning of 2014 to the end of 2016, there was a strong decline in the prices of natural gas and heating oil. Then, the prices of these raw materials stabilized at significantly lower levels in the period from 2017 to 2020. In the recent period (2020-2023), a drastic increase in the prices of energy sources was observed, which may have been caused by the Russian-Ukrainian conflict and related supply restrictions.

3. Nonlinear Granger causality

The definition of causality formulated by Granger (Grenger, 1969) concerns the occurrence of causal relationships between the stationary processes X_t and Y_t in the category of conditional probability distributions. By this definition, X_t is not the cause of Y_t if:

$$F\left(Y_t \middle| \left(X_{t-l_x}, \dots, X_{t-1}; Y_{t-l_y}, \dots, Y_{t-1}\right)\right) = F\left(Y_t \middle| \left(Y_{t-l_y}, \dots, Y_{t-1}\right)\right) \tag{1}$$

for any delay $l_x, l_y \geq 1$. In a situation where equation (1) does not hold, then X_t is the cause of Y_t, which in particular makes it possible to use the past values of X_t to predict Y_t.

The study of the occurrence of causal relationships consists in verifying the null hypothesis that X_t is not the cause of Y_t, which by definition is equivalent to condition (1). However, in econometric practice, the verification of the difficult-to-apply condition (1) is replaced by more operational methods (Orzeszko, Osińska, 2007).

Let (X, Y, Z) denote a random vector of the form $(X, Y, Z) = \left(X_{t-l_x}^{t-1}, Y_{t-l_y}^{t-1}, Y_t\right)$, and f is the probability density function. Diks and Panchenko (2006) proved that the null hypothesis, according to which X_t is not the cause of Y_t, means that the equality is satisfied:

$$\frac{f_{X,Y,Z}(x,y,z)}{f_Y(y)} = \frac{f_{X,Y}(x,y)}{f_Y(y)} \frac{f_{Y,Z}(y,z)}{f_Y(y)} \tag{2}$$

They also indicated that the following equality is equivalent to the key formula of Hiemstra and Jones (1994) as the starting point for nonlinear causality analysis:

$$\frac{E[f_{X,Y,Z}(x,y,z)]}{E[f_Y(y)]} = \frac{E[f_{X,Y}(x,y)]}{E[f_Y(y)]} \frac{E[f_{Y,Z}(y,z)]}{E[f_Y(y)]} \tag{3}$$

where

$$E[f_W(w)] = \int f_W^2(s)\, ds \tag{4}$$

is interpreted as a measure of the concentration of the random vector W.

In their study, they showed that in order to study causality, one should not focus on equality (3), but study the following formula:

$$E\left[\frac{f_{X,Y,Z}(x,y,z)}{f_Y(y)} - \frac{f_{X,Y}(x,y)}{f_Y(y)} \frac{f_{Y,Z}(y,z)}{f_Y(y)}\right] = 0 \tag{5}$$

Thus, the implication of the null hypothesis is as follows.

$$E\left[\left(\frac{f_{X,Y,Z}(x,y,z)}{f_Y(y)}-\frac{f_{X,Y}(x,y)}{f_Y(y)}\frac{f_{Y,Z}(y,z)}{f_Y(y)}\right)g(X,Y,Z)\right]=0 \quad (6)$$

where $g(X,Y,Z)$ is a positive weighting function. Assuming that the null hypothesis is true, this expression is zero because by the formula (5) the value in parentheses is equal to zero. We reject the null hypothesis when the calculated value of the test statistic is too high. For $g(X,Y,Z)=f_Y^2(Y)$ formula (6) takes the form:

$$E\left[f_{X,Y,Z}(x,y,z)f_Y(y)-f_{X,Y}(x,y)f_{Y,Z}(y,z)\right]=0 \quad (7)$$

Its estimator is based on the indicator function and is expressed by the formula:

$$T_n=\frac{(2\varepsilon)^{-l_x-l_y-1}}{n(n-1)(n-2)}\sum_i\left[\sum_{k,k\neq i}\sum_{j,j\neq i}\left(I_{ik}^{XYZ}I_{ij}^{Y}-I_{ik}^{XY}I_{ij}^{YZ}\right)\right] \quad (8)$$

where *n* is number of observations, *I*(.) is indicator function:

$$I_{i,j}^{W}=I\left(\left\|W_i-W_j\right\|\leq\varepsilon\right)=\begin{cases}1, \left\|W_i-W_j\right\|\leq\varepsilon\\ 0, \left\|W_i-W_j\right\|>\varepsilon\end{cases} \quad (9)$$

$\|.\|$ denotes norm supremum. In the case of $l_x=l_y=1$, Diks and Panchenko proved that their test statistics is asymptotically distributed as standard normal and diverges to positive infinity.

It should be noted that the value of the estimator depends on the parameters l_x, l_y, and ε. In practice, lags $l_x=l_y=1,2,\dots,l_{max}$, are considered, where l_{max} is a fixed natural number. In the studies presented in the literature, the value of a distance measure ε between 0.5 and 1.5 is recommended for consideration (Orzeszko, 2021).

4. Results of nonlinear Granger causality

Conducting a study of nonlinear causality requires quite a complicated time series analysis. In the study, for each analyzed variable, daily time series covering the period from the beginning of 2014 to September 2023 were prepared. In order to check the stability of causal relationships, the entire period was divided into three separate subperiods. For comparison purposes (i.e., to preserve the same power of the applied test) considered three subperiods of the same length: Period 1 (1/1/2014 - 24/03/2017), Period 2 (27/03/2017 - 16/06/2020) and Period 3 (6/17/2020 – 9/06/2023). All data were transformed to log returns using the formula $r_t=100\ln(p_t/p_{t-1})$, where p_t is the price at time.

The abbreviations used in the further considerations are presented in Table1.

Table 1.
Full and abbreviated variable names

Full name of the time series	Abbreviate name of the time series
Natural Gas	NG_F
Heating Oil	HO_F
Exchange rate EUR/USD	EUR_USD
Exchange rate PLN/USD	PLN_USD

Source: own study.

The selection of the above series for the study was based on a previous analysis of the factors influencing changes in the prices of natural gas and heating oil.

The basic descriptive statistics for the variables under consideration are presented in Table 2.

Table 2.
Descriptive statistics of the selected returns

Measures/Series	NG_F	HO_F	EUR_USD	PLN_USD
Mean	-0,01977	0,00158	-0,00984	-0,01365
Stan. Dev.	3,52136	2,40539	0,49620	0,65868
Min	-18,06609	-24,75355	-2,41725	-4,54446
Max	19,79844	13,98724	3,02491	3,60479
Skewness	-0,04420	-0,80628	0,08682	-0,23753
Kurtosis	2,91181	11,00023	2,23212	2,52978
Period 1				
Mean	-0,03789	-0,08518	-0,02873	-0,03184
Stan. Dev.	2,94152	2,06216	0,56999	0,67041
Min	-11,93123	-7,07761	-2,41725	-4,54446
Max	11,63348	10,38329	3,02491	2,58253
Skewness	0,14570	0,39532	0,18842	-0,38059
Kurtosis	1,59991	2,14126	2,60221	3,04331
Period 2				
Mean	-0,07659	-0,02809	0,00500	-0,00019
Stan. Dev.	2,85004	2,30059	0,42744	0,57858
Min	-18,05452	-19,99576	-2,06460	-3,69946
Max	16,50638	10,94612	1,42533	2,40376
Skewness	0,00296	-1,20469	-0,11909	-0,35994
Kurtosis	5,22948	14,14649	1,41836	2,68956
Period 3				
Mean	0,05527	0,11813	-0,00580	-0,00893
Stan. Dev.	4,51941	2,79156	0,48005	0,71900
Min	-18,06609	-24,75355	-1,49855	-2,87186
Max	19,79844	13,98724	2,12072	3,60479
Skewness	-0,13356	-1,08777	0,12441	-0,04237
Kurtosis	1,43546	10,95824	1,08647	1,74186

Source: own study.

The averages calculated for all the examined series: were negative in the first period; in the second period they were also negative except for the EUR/USD series; while in the third period they were negative only for the exchange rate series. Other statistics showed noticeable differences between natural gas and heating oil and exchange rates; raw materials proved to be much more volatile than the exchange rates (especially in Period 3). As a consequence, it was characterized by the highest absolute values of the minimum and maximum returns and a very high standard deviation. Moreover, the distribution of heating oil returns exhibited the strongest skewness (except Period 1) and the highest kurtosis.

In the case of selected series, the following stepwise procedure was used, filtering possible dependencies in conditional variance and linear dependencies. The next steps in the procedure were as follows:

- filtering with the GARCH(1,1) model and calculating standardized residuals,
- elimination of linear dependencies – VAR model,
- normalization of the obtained series,
- calculation of the value of the Dicks-Panchenko statistics,
- comparison with critical values N(0,1) – two-sided distribution.

To calculate the value of the Dicks-Panchenko statistics, six delay values were used: $\boldsymbol{l_x = l_y = 1, 2, \dots, 6}$ and two distance measures $\boldsymbol{\varepsilon} \in \{\mathbf{1, 1.5}\}$ (Syczewska, 2014). We analyzed two directions of causation for the entire period from the beginning of 2014 to September 2023 and three subperiods. The results of these analyzes are presented in Tables 3 – Tables 6. Each cell in the table contains *p*-values of test. Values less than 0.1 are in bold, indicating rejection of the null hypothesis of noncausality.

Table 3.
Diks-Panchenko test results for pairs of natural gas and EUR/USD

NG_F⟶EUR_USD	**Number of lags $l_x = l_y$**					
	1	**2**	**3**	**4**	**5**	**6**
ε	All period					
1.0	0.32074	0.68891	0.50512	0.12477	0.34154	0.16066
1.5	0.18636	0.63932	0.47323	0.48281	0.64240	0.47201
	Period 1					
1.0	0.17635	0.82786	0.67001	0.35353	0.51601	0.39527
1.5	0.11721	0.76047	0.80770	0.45039	0.77012	0.37147
	Period 2					
1.0	0.36392	0.77992	0.59086	0.52952	0.68910	0.47448
1.5	**0.08559**	0.38080	0.38643	0.53580	0.49513	0.44386
	Period 3					
1.0	0.95401	0.91924	0.64272	0.39609	0.55669	0.58468
1.5	0.83107	0.76015	0.59052	0.39623	0.28134	0.59793
EUR_USD⟶NG_F	All period					
1.0	0.13085	0.18564	0.28036	0.46174	0.53639	0.64493
1.5	**0.06910**	**0.04709**	**0.05579**	0.14878	0.25135	0.56059
	Period 1					
1.0	0.24167	0.29264	0.17508	0.58523	0.67735	0.50414
1.5	0.18616	0.14624	**0.06773**	**0.05449**	**0.01902**	**0.06597**
	Period 2					
1.0	0.16578	0.16351	0.64438	0.92755	0.84664	0.67729
1.5	**0.06689**	0.18440	0.33649	0.76735	0.81837	0.84956
	Period 3					
1.0	0.35173	0.35121	0.42027	0.57753	0.51527	0.47818
1.5	0.37681	0.27927	0.41700	0.64498	0.55880	0.66963

Source: own study.

Table 4.
Diks-Panchenko test results for pairs of natural gas and PLN/USD

NG_F⟶PLN_USD	Number of lags $l_x = l_y$					
	1	**2**	**3**	**4**	**5**	**6**
ε	All period					
1.0	0.19789	0.33698	**0.05170**	0.36751	0.48132	0.65203
1.5	0.13904	0.15468	**0.07181**	0.28561	0.24398	0.27923
	Period 1					
1.0	**0.01037**	0.22557	0.24605	0.11335	0.35077	0.55497
1.5	**0.01085**	**0.05559**	**0.07022**	**0.05655**	0.11167	0.10025
	Period 2					
1.0	0.23044	0.56195	0.42960	0.58851	0.27277	0.18800
1.5	**0.06312**	0.15038	0.35198	0.86306	0.69323	0.77558
	Period 3					
1.0	0.96440	0.38858	0.20624	0.43596	0.20523	0.32850
1.5	0.94530	0.66545	0.20817	0.38330	0.13544	0.37779
PLN_USD⟶NG_F	All period					
1.0	0.16784	0.30946	0.49558	0.78330	0.45411	0.64675
1.5	0.16354	**0.07677**	**0.07523**	0.17686	0.10692	0.28472
	Period 1					
1.0	0.39138	0.50116	0.54800	0.71806	0.41391	0.36178
1.5	0.37935	0.30921	0.24455	0.33694	0.09683	0.26606
	Period 2					
1.0	0.25458	0.49223	0.74343	0.95271	0.48533	0.40279
1.5	0.29239	0.40387	0.47628	0.62696	0.59763	0.77133
	Period 3					
1.0	0.17249	**0.08321**	0.21874	0.49651	0.12956	0.54237
1.5	0.23711	**0.05452**	0.14688	0.30013	0.26442	0.32085

Source: own study.

Table 5.
Diks-Panchenko test results for pairs of heating oil and EUR/USD

HO_F⟶EUR_USD	Number of lags $l_x = l_y$					
	1	**2**	**3**	**4**	**5**	**6**
ε	All period					
1.0	0.27041	0.21557	0.17205	0.38937	0.36380	0.30241
1.5	0.32877	0.26063	**0.07010**	0.16792	0.19479	0.14987
	Period 1					
1.0	0.71248	0.41241	0.34908	**0.08300**	0.11356	0.20481
1.5	0.57623	0.32291	0.11955	**0.02174**	**0.04018**	**0.02067**
	Period 2					
1.0	0.35093	0.42575	0.68375	0.88686	0.88539	0.78019
1.5	0.51797	0.47218	0.50150	0.70795	0.75720	0.76172
	Period 3					
1.0	**0.06532**	0.24258	0.26497	0.40632	0.40865	0.15896
1.5	0.10078	0.41118	0.52742	0.71130	0.50553	0.61526
EUR_USD⟶HO_F	All period					
1.0	0.42507	0.20773	0.14055	0.21922	0.31106	0.33107
1.5	0.32500	0.16820	0.17003	0.12291	0.09529	0.13623
	Period 1					
1.0	0.60730	0.27625	0.21686	0.33710	0.29526	0.34515
1.5	0.59989	0.33021	0.59693	0.33466	0.27885	0.19798
	Period 2					
1.0	0.22114	0.52784	0.46358	0.60722	0.11659	0.17559
1.5	0.14411	0.16813	0.21615	0.37993	0.20285	0.45097
	Period 3					
1.0	0.33288	0.35622	0.19685	0.32974	0.53648	0.21861
1.5	0.46169	0.57807	0.37383	0.38028	0.71425	0.62935

Source: own study.

Table 6.
Diks-Panchenko test results for pairs of heating oil and PLN/USD

HO_F⟶PLN_USD	**Number of lags $l_x = l_y$**					
	1	**2**	**3**	**4**	**5**	**6**
ε	All period					
1.0	0.19632	0.12044	0.09992	0.15776	0.21260	0.27981
1.5	0.29074	0.37335	0.19624	0.09766	0.13133	**0.07116**
	Period 1					
1.0	0.56547	0.29627	0.27399	0.15766	**0.06848**	0.09428
1.5	0.46896	0.33490	0.19128	**0.02867**	0.11967	**0.05716**
	Period 2					
1.0	0.32530	0.24258	0.19194	0.23717	0.14178	0.28707
1.5	0.26865	0.20496	0.25592	0.57387	0.66511	0.44026
	Period 3					
1.0	0.18609	0.63970	0.11025	0.30315	0.26127	**0.08007**
1.5	0.33847	0.88919	0.72387	0.45454	0.43601	0.51269
PLN_USD⟶HO_F	All period					
1.0	0.26625	0.11977	0.12287	0.06630	0.12632	0.25130
1.5	0.16823	**0.08748**	**0.06608**	**0.00609**	**0.01887**	0.11464
	Period 1					
1.0	0.48162	0.50570	**0.07639**	0.19717	0.25892	0.29609
1.5	0.45990	0.32898	**0.05022**	**0.01090**	**0.05966**	0.09787
	Period 2					
1.0	0.43740	0.53787	0.50942	0.86440	0.87605	0.35949
1.5	0.36722	0.44674	0.67668	0.68616	0.58786	0.64779
	Period 3					
1.0	**0.06958**	0.09640	0.16629	0.21550	0.13757	0.44147
1.5	**0.08710**	0.17843	0.27841	0.11739	0.25603	0.61815

Source: own study.

The presented test results indicate the existence of causality between the tested financial instruments. Bidirectional relationships throughout the research period were detected for the following pairs: natural gas and PLN/USD and heating oil and PLN/USD. This is important information from the point of view of market participants investing in the fuel raw materials market or investors conducting currency transactions. Knowledge about this type of relationship may contribute to obtaining better forecasts, both on the energy market and the currency market.

The second aim of the study was to check the stability of the detected causal relationships. In the first period, the hypothesis of lack of causality was rejected for most series. The exceptions were the pairs NG_F ⟶ EUR/USD, PLN/USD ⟶ NG_F and EUR/USD ⟶ HO_F. In the second period, the lack of causal relationships was observed for most pairs, and in the case of the pairs NG_F ⟶ EUR/USD, EUR/USD ⟶ NG_F, NG_F ⟶ PLN/USD, the rejection of the lack of causality was no longer so clear (only a certain value of the delays used in the test procedure led to the rejection null hypothesis). A similar situation was also observed in the third period for pairs: HO_F ⟶ EUR/USD and HO_F ⟶ PLN/USD. However, non-linear causality occurred only in the case of the following pairs: PLN/USD ⟶ NG_F and PLN/USD ⟶ HO_F.

To sum up, it can be stated that the non-linear Granger causality observed throughout the analyzed period does not occur when divided into sub-periods.

5. Summary

Detecting the causality between heating fuels and currency exchange rates are important from the point of view of investors and policy makers since knowledge of the directionality of relationships may help them to take effective decisions from the price signals received from these commodities. Moreover, they may have important implications for market efficiency and predictability.

The study checked bidirectional causal relationships between the prices of two heating raw materials (natural gas and fuel oil) and selected exchange rates (EUR/USD, PLN/USD) in the period from January 2014 to September 2023. For this purpose, the Diks and Panchenko nonlinear causality test was used. In order to analyze the stability of the examined relationships, the period in question was divided into three sub-periods, in which first the prices of natural gas and fuel oil showed a decreasing trend, then the prices stabilized, and in the last period there was a sharp increase in the prices of raw materials. Based on the results obtained, it was established that throughout the entire period under study, most of the analyzed series were linked by causal relationships. The study also revealed significant differences between the considered sub-periods. Relationships that appear in the first period disappear in subsequent sub-periods.

The analysis was performed for daily data, which means that the detected relationships can be considered more short-term. For this reason, they should be taken into account primarily by market participants when creating effective investment portfolios and risk hedging strategies.

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