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Effects of Economic Growth and Energy Consumptions on Environmental Degradation within the Framework of LCC Hypothesis in BRICS Countries

Mehmet Uçar*, Mücahit Ülger, Mert Anıl Atamer*****

Abstract: The purpose of this study is to analyze the effects of economic growth, nuclear energy consumption, renewable energy consumption, and hydropower energy consumption on environmental degradation within the framework of the LCC Hypothesis in BRICS countries during the period of 1993-2022. This study aims to make a significant contribution to the literature by simultaneously discussing the effects of hydropower, nuclear, and renewable energy consumption on the load capacity factor in addition to the LCC Hypothesis for the BRICS countries for the first time. Due to the autocorrelation and heteroscedasticity problem, the FGLS (Feasible Generalized Least Square) method was used in the estimated model. According to empirical findings, the LCC hypothesis is not valid in the sample group countries. It was determined that hydropower energy consumption increases the load capacity factor, whereas nuclear energy consumption decreases the load capacity factor. No relationship was found between renewable energy consumption and the load capacity factor. These findings provide important information about the effects of energy consumption strategies of BRICS countries on environmental sustainability.

Keywords: LCC hypothesis; nuclear energy consumption; renewable energy consumption; hydropower energy consumption; economic growth.

JEL classification: Q42; Q43; Q56; O44; C51.

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1. INTRODUCTION

One of the biggest global problems we face in today's world is climate change. This is one of the most obvious and devastating consequences of environmental degradation. The increase in greenhouse gases released into the atmosphere since the industrial revolution has caused temperatures to rise, weather events to become more frequent and severe, and sea levels to rise. These changes have disrupted the balance of ecosystems, threatened biodiversity, and created significant social and economic impacts on human societies. Human-induced activities such as deforestation, overuse of fossil fuels, and unsustainable agricultural practices accelerate climate change and further deepen environmental degradation by destroying natural habitats.

Therefore, in efforts to combat climate change and ensure environmental sustainability, nuclear energy, despite its low carbon emission advantages, appears to be an energy source that needs to be carefully evaluated with problems such as radioactive waste management and environmental degradation. Although nuclear energy offers the potential to produce energy with low carbon emissions, it also brings serious environmental and health problems, such as radioactive waste management and environmental degradation. In addition, it is a renewable option that emits fewer and more efficient emissions. The potential to produce energy with low carbon emissions reduces dependence on fossil fuels and plays an important role in combating environmental degradation (Wang *et al.*, 2024a; Wang *et al.*, 2024b). Additionally, nuclear energy is considered one of the best options currently available to replace fossil fuels (Murshed *et al.*, 2022).

In the study group of BRICS countries (Brazil, Russia, India, China, South Africa), according to the World Nuclear Association (2024) data, there are 2 nuclear power plants in Brazil with a nuclear energy capacity of 1,884 MWe. The share of nuclear energy production is around 2.5%. There are 37 nuclear power plants in Russia with a nuclear energy capacity of 27,727 MWe. The share of nuclear energy production is around 19.6%. There are 22 nuclear power plants in India, with a nuclear energy capacity of 7,182 MWe. The share of nuclear energy production is around 3.1%. There are 54 nuclear power plants in China, with a nuclear energy capacity of 52,181 MWe. The share of nuclear energy production is around 5%. There are two nuclear power plants in South Africa with nuclear energy capacities of 1,854 MWe. The share of nuclear energy production is around 4.9%. Among the BRICS countries, China has the largest nuclear energy capacity. There are 117 nuclear power plants operating in 5 countries with nuclear energy capacities of 90,828 MWe.

Figure no. 1 illustrates the change in nuclear energy consumption by the BRICS countries over time between 1993 and 2022. It is seen that nuclear energy consumption is highest in Russia. Compared with other countries, the nuclear energy consumption of Russia and China was increased rapidly. On the other hand, although there is not much change in Brazil and India, nuclear energy consumption was decreased in South Africa.

Hydropower energy, as a renewable and clean energy source, also plays an important role in preventing environmental degradation by reducing dependence on fossil fuels and reducing greenhouse gas emissions. As a renewable and clean energy source, hydropower energy plays an important role in reducing greenhouse gas emissions and preventing environmental degradation by reducing our dependence on fossil fuels. In the study, according to IHA (2024) data, considering the BRICS countries in terms of hydropower energy, which is a clean energy source, Brazil has 109 GW, Russia has over 55 GW, India has 51 GW, and China has over 414 GW. China is a world leader in hydropower energy production. South Africa has a 3 GW hydropower energy capacity.

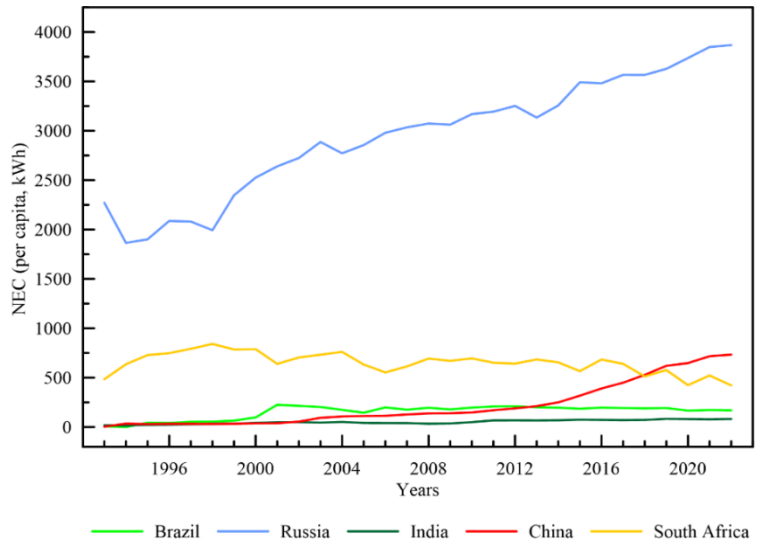

Figure no. 1 – BRICS countries' nuclear energy consumption (per capita, kWh)

Figure no. 2 illustrates the change in hydropower energy consumption of the BRICS countries over time between 1993 and 2022. It can be seen that hydropower energy consumption is highest in Brazil. Compared with other countries, China's hydropower energy consumption was increased rapidly. On the other hand, although there is not much change in South Africa and India, hydropower energy consumption is low. There have been significant ups and downs in hydropower energy consumption in Brazil and Russia.

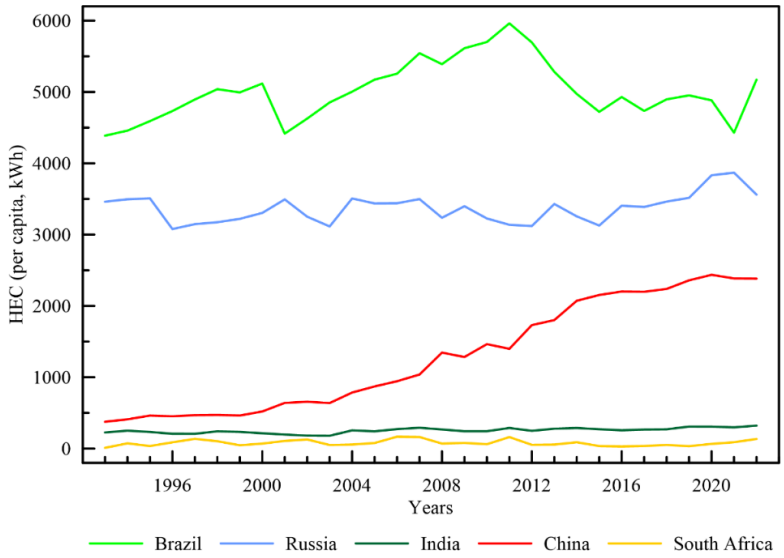

Figure no. 2 – BRICS countries' hydropower energy consumption (per capita, kWh)

Given their impact on reducing dependence on fossil fuels and greenhouse gas emissions, renewable energy sources such as hydropower energy are of critical importance in preventing environmental degradation and building a sustainable future. Renewable energy sources reduce greenhouse gas emissions by reducing dependence on fossil fuels, and they contribute to a sustainable future by preventing environmental degradation. In this context, renewable energy sources are seen as potential solutions to energy security and climate change problems (Doğan *et al.*, 2021).

Figure no. 3 illustrates the change in renewable energy consumption of the BRICS countries over time between 1993 and 2022. It is seen that renewable energy consumption is highest in Brazil. Compared with other countries, renewable energy consumption by Brazil and China was increased rapidly. On the other hand, although there is not much change in South Africa and India, renewable energy consumption is seen to be low. In this context, there has not been much change in Russia's renewable energy consumption.

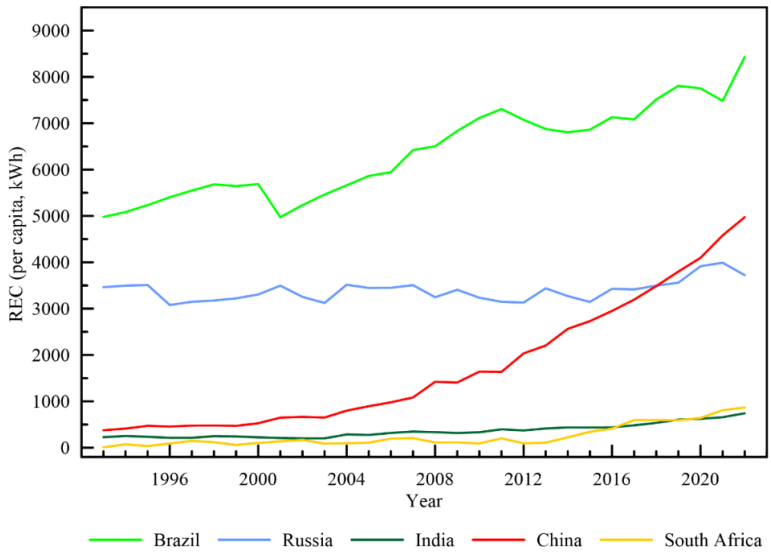

Figure no. 3 – BRICS countries' renewable energy consumption (per capita, kWh)

The ecological footprint, an indicator of environmental degradation, only shows how humans meet the need for natural resources and nature's biological capacity. An indicator showing the supply and demand sides of nature could provide a better analysis of environmental quality. In this case, the Load Capacity Factor (LCF) was proposed by Siche *et al.* (2010) to improve environmental assessment. Figure no. 4 shows the LCF indicator trends of the BRICS countries over time from 1993 to 2022. This demonstrates how a state can sustain its population according to its current lifestyle. Biocapacity and ecological footprint are used to measure LCF. LCF is measured by dividing incapacity by ecological footprint. Whereas the value of LCF is "1" or higher, it indicates that current environmental conditions are sustainable; A value below "1" indicates that environmental degradation is unacceptable. When compared among countries, it can be seen that Brazil has the best LCF. Although Russia was close to 1 in the reference period, it did not fall below 1. It is also in a

better situation than other countries. In addition, India, South Africa, and China are below the sustainability limit, indicates that current environmental conditions are not sustainable. Environmental degradation was increased over the years.

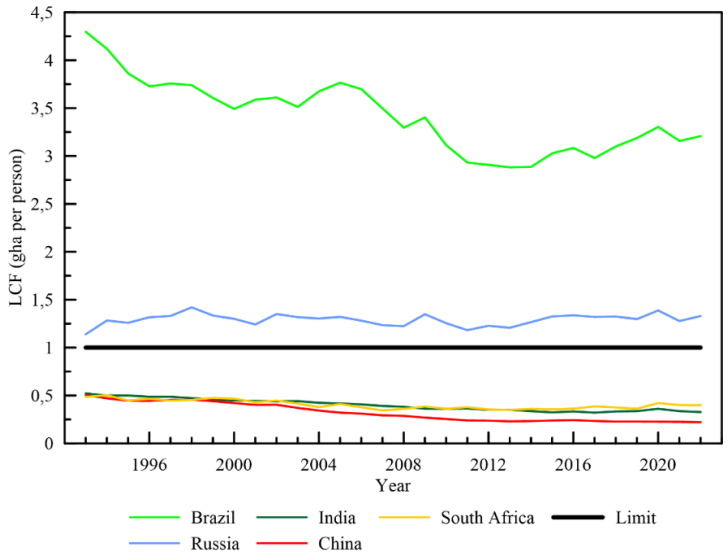

Figure no. 4 – BRICS countries' load capacity factor (gha per person)

Economic growth increases the welfare of societies, but it results in the overuse of natural resources and environmental degradation. One of the most frequently used theories developed by Grossman and Krueger (1991) to explain the relationship between economic growth and environmental quality is the Environmental Kuznets Curve (EKC). Empirical research shows for the first time that an inverted U-shaped non-linear relationship between economic growth and environmental quality (Wang *et al.*, 2023).

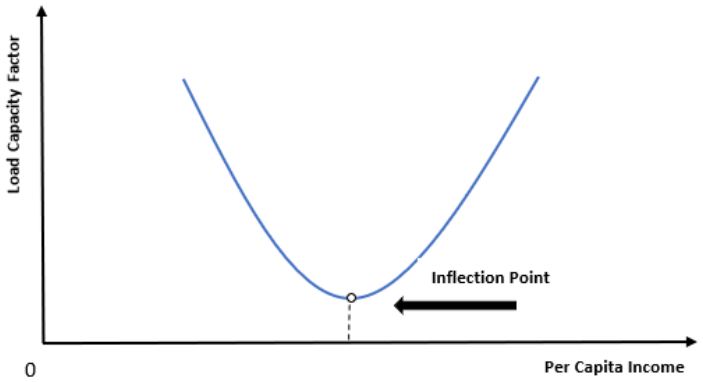

Figure no. 5 – Load Capacity Curve

Another theory to describe the relationship between economic growth and environmental quality is the Load Capacity Curve (LCC) hypothesis. This hypothesis (Figure no. 5) states that economic growth positively affects environmental quality up to a certain point. Once this point has been reached, further economic growth will reduce environmental quality. It shows that there is a U-shaped non-linear relationship between economic growth and load capacity factor (Pata and Tanriover, 2023). The EKC and LCC hypotheses provide insight into this relationship while explaining the relationship between economic growth and environmental quality. (Wang *et al.*, 2024a; Wang *et al.*, 2024b).

The main purpose of this study is to analyze the effects of economic growth, nuclear energy consumption, renewable energy consumption, and hydropower energy consumption on environmental degradation in BRICS countries within the framework of the LCC hypothesis for the period of 1993-2022. Based on this purpose of the study, it was possible to present some hypotheses.

H1: The LCC hypothesis is valid in BRICS countries.

H2: Nuclear energy consumption reduces the LCF.

H3: Hydropower energy consumption will increase the LCF.

H4: Renewable energy consumption will increase the LCF.

There are many important reasons why BRICS countries are preferred to measure renewable energy consumption, hydropower energy consumption, and nuclear energy consumption. These countries play an important role in world energy markets because of their rapid economic growth and increasing demand for energy. The diversity of BRICS countries' energy production and consumption is demonstrated by China's large-scale nuclear energy investments, Brazil's leadership in hydropower energy generation, and India's rapid expansion of renewable energy capacity. These countries were seek sustainable energy solutions because of their high greenhouse gas emissions and environmental degradation. The energy consumption patterns of the BRICS countries should be examined at both regional and global levels because of their efforts to create energy security, sustainability, and innovative policies. Therefore, it offers important insights into global energy policies and sustainable strategies for BRICS countries.

It is expected that this study will contribute to the literature by simultaneously discussing the effects of hydropower, nuclear, and renewable energy consumption on the load capacity factor in addition to the LCC hypothesis for the BRICS countries for the first time. This study has a limitation regarding the reference period. The absence of China's pre-1993 nuclear energy data and Russia's pre-1992 incapacity and ecological footprint data caused this study to determine the years 1993-2022 as the reference period.

In the second section of the study, the literature section is included. In the third section, the model, data, method, and empirical findings are discussed. The fourth section concludes with the concluding remarks and policy recommendations.

2. LITERATURE REVIEW

Although there was not many studies investigated the validity of the LCC hypothesis, it has become a popular research topic recently. Based on the literature review, the variables used in studies testing the validity of the LCC hypothesis differ. It is also possible to say that because of the research conducted, no general conclusions can be reached in the literature. Note that although most of the results show that the LCC hypothesis is valid, some studies

conclude that the LCC hypothesis is not valid. While examining the literature section in this study, studies that accept the validity of the LCC hypothesis and those that argue that the LCC hypothesis is not valid were evaluated separately. Again, while these studies were considered, studies conducted in a single country or country group were evaluated separately. Studies conducted on the BRICS countries are also included.

2.1 Studies Finding the LCC Hypothesis Valid

Within the studies supporting the LCC hypothesis, some have analyzed a single country. Güneysu (2023) investigated data between 1970 and 2018 for the Turkey economy using FMOLS and DOLS analyses, and Bozatli and Akca (2024) examined the period of 1990-2020 for the Turkey economy using ARDL analysis. Another study examining Turkey was conducted by Çamkaya (2024) using data covering the years 1961-2022 with ADF, ADL, and FMOLS analyses. Although the periods analyzed in all of these studies conducted for the Turkey economy differ, it is concluded that the LCC hypothesis is valid for Turkey.

Examples of single-country analyses can be given by Huang *et al.* (2023), which examines the 1975-2021 period for the Indian economy, and Pata and Kartal (2023), which examined the South Korean economy with data from the 1977-2018 period. ARDL analysis was used in both studies, and both studies concluded that the LCC hypothesis is valid. Additionally, Apergis *et al.* (2023) tested data from 1980 to 2015 in the United States using the Fourier estimator and again concluded that the LCC hypothesis is valid. Hakkak *et al.* (2023) analyzed data for the Russian economy between 1992 and 2018 using the ARDL method and stated that the LCC hypothesis is valid.

Studies supporting the LCC hypothesis are not limited to only one country. There are also studies conducted as a country group. Dogan and Pata (2022) examined the period of 1986-2017 for G7 countries. Dai *et al.* (2024) tested data for ASEAN countries from 1986 to 2018. The CS-ARDL method was used in both studies, and both studies found that the LCC hypothesis was valid. Wu *et al.* (2024) and Feng *et al.* (2024) analyzed the data between 1996 and 2019 using the QR (Panel quantile regression) method for the E7 countries and found results that support the LCC hypothesis. investigated the impact of economic policy uncertainty and renewable energy on environmental quality; Feng *et al.* (2024) included technological innovation as a variable in their analysis. Afshan and Yaqoob (2023) conducted an MMQR (Moment quantile regression) analysis using data between 2000 and 2018 for China, Brazil, Mexico, India, and Turkey. Guloglu *et al.* (2023) tested the period 1980-2018 for 26 OECD countries using QMG Estimator. Both studies concluded that the LCC hypothesis is valid. Wang *et al.* (2024a); Wang *et al.* (2024b) analyzed the data of 5 selected Asian countries between 1990 and 2020 using the panel quantile regression technique and stated that the LCC hypothesis is valid.

Caglar *et al.* (2024) analyzed the relationship between competitive industrial performance, renewable energy, urbanization, and the load capacity factor of BRICS countries. For this purpose, the period 1990-2018 was used. They used the CUP-FM and CUP-BC models in their analysis and stated that the LCC hypothesis was valid. Li *et al.* (2024) analyzed the same year's data for BRICS economies through CS-ARDL and obtained different results because the variables they used were different. They also stated that the LCC hypothesis was valid. In addition, financial development, economic growth, and non-renewable energy negatively affect ecological quality; They stated that renewable energy

positively affects ecological quality. Yang *et al.* (2024) and S. Wang *et al.* (2024); W. Wang *et al.* (2024) examined the BRICS countries for the same period. Yang *et al.* (2024) conducted an MMQR analysis and found that natural resources, social globalization, and GDP negatively affect ecological quality, whereas biomass energy negatively affects ecological quality. S. Wang *et al.* (2024); W. Wang *et al.* (2024) stated that financial development is negatively related to the load capacity factor, whereas there is a positive relationship between financial development and carbon emissions. In addition, according to their results, economic growth decreases the load capacity factor. In addition to these results, two studies found that the LCC hypothesis is valid.

2.2 Studies Finding that the LCC Hypothesis is not Valid

Although many studies in the literature accept the LCC hypothesis as valid, a few also conclude that the LCC hypothesis is not valid.

Pata and Tanriover (2023) analyzed the period 2004-2018 for the 10 countries that most tourists visit, and Deng *et al.* (2024) selected 9 countries (China, Germany, India, Japan, South Africa, South Korea, Russia, the United States). They analyzed data from 1998 to 2018 for the Kingdom of Saudi Arabia and the United States. The CS-ARDL method was used in both studies, and both studies concluded that the LCC hypothesis was not valid. Pata *et al.* (2023) analyzed data covering the period of 1974-2018 for the German economy using the Fourier ARDL method and stated that the LCC hypothesis is not valid. Yang *et al.* (2023) tested the LCC hypothesis in BRICS countries using the CS-ARDL method during the period 1990-2018 and found that the LCC hypothesis is not valid. addition, because of their analysis, they concluded that while economic development, financial development, and natural resources reduce ecological quality, renewable energy increases environmental quality. Shahzad *et al.* (2024) analyzed the 2000-2020 period for the 20 most visited countries using panel GMM and panel quantile regression models. Ulussever *et al.* (2024) tested the data between 2000 and 2019 using the AMG method for GCC countries (Gulf Cooperation Council countries). Both studies rejected the LCC hypothesis was invalid. Another study, which reached the same conclusion as these studies and found the LCC hypothesis invalid, was conducted by Erdogan (2024) using FMOLS and DOLS methods for 13 African countries with data covering the period of 1992-2020.

2.3 Relationship between Nuclear Energy Consumption and LCF

This part of the literature covers the studies analyzing the relationship between nuclear energy consumption and load capacity factor. When the literature is analyzed, it is generally concluded that nuclear energy consumption supports environmental development by increasing the load capacity factor.

An example of time series studies is the study conducted by Pata and Samour (2022) using Fourier analysis with data for the period 1977-2017 for the French economy. Pata and Samour (2022) stated that nuclear energy increases the load capacity factor by reducing carbon emissions. In addition, Hakkak *et al.* (2023) determined that nuclear energy increases the load capacity factor as a result of ARDL analysis with data for Russia between 1992-2018.

Another time series study was conducted by Raihan (2024). In his study, Raihan (2024) examined the Indian economy for the period 1070-2022 and used DOLS analysis. As a result

of his studies, he stated that nuclear energy increased the load capacity factor. Özkan *et al.* (2024) analyzed the Pakistani economy for the period 1971-2021, and Jin *et al.* (2024) analyzed the German economy for the period 1974-2018 using the ARDL method. Both studies concluded that nuclear energy increases the load capacity factor.

There are also panel studies examining the relationship between nuclear energy and load capacity. Aydin (2024) analyzed the economies of 8 countries with panel causality analysis using data between 1993-2018 and found a bidirectional causality relationship between the variables. Ozcan *et al.* (2024), on the other hand, analyzed the data covering 8 countries between the first quarter of 1995 and the last quarter of 2018 with a non-linear quantile approach and concluded that nuclear energy increases load capacity.

Another example of panel studies is the study conducted by Teng *et al.* (2024) with data covering the period 1990-2021 for the economies of 5 countries. Teng *et al.* (2024) concluded that nuclear energy increases the load capacity factor as a result of their CS-ARDL analysis. Another study reaching the same conclusion was conducted by Islam *et al.* (2024). Islam *et al.* (2024) analysed the economies of 10 countries for the period 1990-2020 with DOLS analysis and reached the same conclusion.

2.4 Relationship between Renewable Energy Consumption and LCF

In this part of the literature, the relationship between renewable energy consumption and load capacity factor is analyzed. While some of the studies have found that renewable energy consumption increases the load capacity, some studies have found that renewable energy consumption decreases the load capacity factor. In addition, there are also studies indicating that renewable energy consumption has no effect on the load capacity factor.

An example of time series studies is the study by Xu *et al.* (2022). Xu *et al.* (2022) analyzed Brazilian data for the period 1970-2017 using the ARDL method and found that renewable energy consumption decreases the load capacity factor. Hakkak *et al.* (2023) analyzed the Russian economy for the period 1992-2018, again using the ARDL method, and concluded that renewable energy consumption increases the load capacity factor.

Another example of time series studies is the study conducted by Jin *et al.* (2024) for the German economy for the period 1974-2018. Jin *et al.* (2024) concluded that renewable energy consumption increases the load capacity factor as a result of their tests using the ARDL method. Pata and Kartal (2023) analyzed the data of South Korea between 1977-2018 with the ARDL method and concluded that renewable energy consumption does not affect the load capacity factor in the long run. In the study examining the causality relationship between renewable energy consumption and load capacity factor, Pata *et al.* (2024) used Fourier causality analysis and found a bidirectional causality between the variables.

There are also panel studies examining the relationship between renewable energy consumption and load capacity factor. Shang *et al.* (2022) analyzed the data covering the period 1980-2018 for ASEAN countries with ARDL method, Sun *et al.* (2024) analyzed the period 1990-2019 for 17 APEC countries with second generation panel data analysis. In addition, Islam *et al.* (2024) analyzed the data covering the period 1990-2020 for 10 countries with the DOLS method. All of these studies have found that renewable energy consumption leads to environmental improvement by increasing load capacity.

2.5 Relationship between Hydropower Energy Consumption and LCF

Studies examining the relationship between hydropower energy consumption and load capacity factor are not very common in the literature. The rare study on this subject was conducted by Ozcan *et al.* (2024). They analyzed a panel of 8 country economies using data from the first quarter of 1995 to the last quarter of 2018 using the non-linear quantile approach. As a result of their analysis, they concluded that hydropower energy consumption reduces the load capacity factor.

3. MODEL AND DATA, METHOD, AND EMPIRICAL FINDINGS

3.1 Model and Data Definition

This study aims to investigate the effects of economic growth, nuclear energy consumption, renewable energy consumption, and hydropower energy consumption on environmental quality in BRICS countries within the framework of the LCC hypothesis. The empirical analysis period of this study consists of annual data from 1993 to 2022. In this context, Table no. 1 presents the variables used in the model.

Table no. 1 – Variables

Variables	Explanation	Reference
Hydropower energy consumption (LogHE)	Hydropower energy consumption per capita - Measured in kilowatt-hours per capita.	Our World in Data (2024)
Nuclear energy consumption (LogNE)	Nuclear energy consumption per capita - Measured in kilowatt-hours per capita.	Our World in Data (2024)
Renewable energy consumption (LogRE)	Renewable energy consumption per capita - Measured in kilowatt-hours per capita.	Our World in Data (2024)
Load Capacity Factor (LCF) (LogLCF)	Biocapacity/ecological footprint (gha per person)	Global Footprint Network (GFN)
Economic Growth (LogGDppc)	GDP per capita (constant 2015 US$)	WDI

The model used in the study is as follows:

$$LogLCF_{i,t} = \beta_0 + \beta_1 LogGDPpc_{i,t} + \beta_2 LogGDPpc_{i,t}^2 + \beta_3 LogHE_{i,t} + \beta_4 LogNE_{i,t} + \beta_5 LogRE_{i,t} + u_{i,t} \quad (1)$$

Logarithmic transformations of the variables included in the model were used. The use of logarithmic transformations of variables in econometric analysis offers many advantages from both theoretical and practical perspectives. Logarithmic transformation allows to analyze the proportional changes of variables. Logarithmic transformation reduces the impact of extreme outliers by normalizing the distribution of the data. Economic data can often have a positively skewed (right-skewed) distribution. Logarithmic transformation reduces such skewness, making regression results more reliable and stable (Gujarati and Porter, 2009; Greene, 2012; Wooldridge, 2016).

3.2 Method and Empirical Results

This section provides theoretical explanations of the methodology and empirical findings. Table no. 2 shows summary statistics of the variables.

Table no. 2 – The Summary Statistics of Variables

Variable	Observation	Mean	Std.Dev.	Min.	Max.
LogLCF	150	-0.1332373	0.4033167	-0.6556186	0.6331076
LogGDPpc	150	3.629579	0.3567486	2.748807	4.062967
LogGDPpc2	150	13.30026	2.464548	7.555939	16.5077
LogHE	150	2.895008	0.7242378	1.006552	3.775407
LogNE	150	2.412502	0.7275777	-0.0136762	3.587408
LogRE	150	3.03159	0.6529647	1.006552	3.925882

The summary statistics table shows that the number of observations is 150. This is a sufficient number for the application of panel data analysis. It can also be seen that the variables do not deviate significantly from the LogLCF mean. The deviation of this variable from the mean may indicate the presence of outliers in the data set. For example, in some periods or situations the measured variable may have exceptionally high or low values. It is also possible that some variables are naturally widely distributed. For example, the diversity of economic indicators across countries in terms of their size. Table no. 3 shows the test statistics needed to decide on the model to be estimated in the study.

Table no. 3 – The Selection of Model

Model	F-Test		Hausman Test		Decided Model
	Stats.	p-value	Stats.	p-value	
(Dep. Variable LogLCF)	3539.46	0.000***	142.59	0.000***	Fix Effect Model

Note: *** stands for significance at 1% level of significance.

The table shows that the model has a unit effect. The Hausman test shows that the appropriate model is the Fixed Effects Model. According to this result, it was decided that the coefficient estimator to be used would be based on the Fixed Effects Model. After the model was decided, autocorrelation, heteroskedasticity and cross-sectional dependency were investigated.

Wald test was used to examine the heteroscedasticity problem. The test calculates a Wald statistic for heteroscedasticity. The test tests the hypothesis sigma^2(i)==sigma for i=1, N_g. N_g represents the number of cross-section units in the hypothesis. The calculated test statistic is distributed as Chi square (N_g) under the homoscedasticity null hypothesis (Greene, 2012). The presence of heteroscedasticity can lead to biased results in the calculation of coefficients and standard errors for t-values. In such a case, OLS estimates may not be biased and inconsistencies in standard errors may also be encountered (Yaqub *et al.*, 2015). The test developed by Wooldridge (2010) was used to investigate whether the model contained autocorrelation. This test is used to detect serial correlation in the unique errors of a linear panel-data model. Drukker (2003) presented simulation evidence showing that this test has more consistent properties for reasonable sample sizes.

Cross-sectional dependence has an important place in panel data analysis. Determining cross-sectional dependence is important for determining the coefficient estimator. To investigate cross-sectional dependence, the CDLM test was used in the study (Breusch and Pagan, 1980). This test is obtained from the squares of the "pair-wise" type correlation coefficients of the error terms. In addition, it gives effective results in cases where the cross-sectional dimension (N) is smaller than the time dimension (T) (N<T) (Pesaran, 2021). The equation used to calculate the test is as follows;

$$CD_{LM} = T \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} T\hat{p}_{ij}^2 \quad (2)$$

P_{ij} in the equation represents the sample estimate for the "pair-wise" type correlation coefficients of the error terms.

In line with theoretical explanations, Table no. 4 shows the test results of autocorrelation and heteroskedasticity, as well as cross-sectional dependence of the model used in the study.

Table no. 4 – Autocorrelation, Heteroscedasticity and CD Tests

Model	**Wooldridge Test Correlation**		**Modified Wald test for groupwise heteroskedasticity**		**CD Test**		
	Wooldridge Test		Modifiye Wald Test		Test	Stat.	P-val.
					LM	10.86	0.368
	F(1,5)	9.448	$\boldsymbol{x^2}(5)$	27.70	LMadj	-0.2736	0.784
	p-değ>F	0.037	p-değ<$\boldsymbol{x^2}$	0.000	LMCD	-0.4423	0.658

In the table, autocorrelation and heteroscedasticity test statistics are significant at 5% and 1% significance level, respectively. These results show that the null hypotheses are rejected. In this context, it was concluded that the model contains both autocorrelation and heteroskedasticity. According to the CD test results, the null hypothesis was accepted, and it was concluded that the model did not contain cross-sectional dependence.

Since the model does not include cross-sectional dependence, the first-generation panel unit root test, LLC (Levin *et al.*, 2002), was used. This test allows different unit root tests to be applied for each cross-section and thus has the feature of being a more powerful panel unit root test. While the null hypothesis of the test states that the series contain unit roots, the alternative hypothesis is that the series are stationary (Baltagi, 2005). The basic equation used in calculating the test is as follows;

$$\Delta Y_{it} = pY_{it-1} + \sum_{L=1}^{p_i} \theta_{iL} \Delta Y_{it-L} + \alpha_{mi} d_{mt} + u_{it} \quad (3)$$

Table no. 5 shows the LLC unit root test results. As seen in Table no. 4, the model does not include cross-sectional dependency. Therefore, LLC, the first-generation panel unit root test, was used.

Table no. 5 – Unit Root Test

Variable	Constant Adjusted t (p-value)	Constant+Trend Adjusted t (p-value)
LogLCF	-1.334	0.875
	(0.091*)	(0.809)
d. LogLCF	-4.486	-3.155
	(0.000***)	(0.00***)
LogGDPpc	-1.908	2.764
	(0.028**)	(0.997)
LogGDPpc2	-1.280	2.410
	(0.100)	(0.992)
d.LogGDPpc2	-2.103	-1.409
	(0.017**)	(0.080*)
LogHE	-0.969	0.016
	(0.166)	(0.506)
d.LogHE	-4.023	-2.589
	(0.000***)	(0.004***)
LogNE	-3.508	-5.698
	(0.000***)	(0.000***)
LogRE	1.721	-1.026
	(0.957)	(0.152)
d.LogRE	-3.952	-2.794
	(0.000***)	(0.002**)

Note: The delay length is set to 1. *, **, *** indicate significance at 10%, 5% and 1% significance level, respectively.

Table no. 5 shows the test statistics of the stationarity test for both constant and constant and trend options. According to the stationarity test results, three variables are stationary at the I(1) level, while the other three variables are stationary at the level. In this context, it has been observed that there is no stationarity problem of the variables. For the estimator to be used in the study, it is important that the variables become stationary, not their stationarity levels. In this context, it was concluded that the necessary condition for the estimator was met.

Since the estimated model had autocorrelation and heteroscedasticity problems, it was decided to use FGLS (Feasible Generalized Least Square), which is a robust estimator in these conditions. The classic reference work of this estimator method is Parks (1967) (Moundigbaye *et al.*, 2018). While FGLS is recommended by analyzes Taylor (1977) so that the model can be used in cases where the problem of heteroskedasticity exists, it has been tested by analyzes Rao and Griliches (1969) for cases where the model contains an autocorrelation. Reed and Ye (2011) developed a structure that simultaneously provides solutions to serial correlation and cross-sectional dependence in the error term for Ω_{NT}(Ω; error heteroskedasticity) in the FGLS estimator. They used the following equation for Ω_{NT};

$$\Omega_{NT} = \sum \otimes \Pi \tag{4}$$

The FGLS estimator ensures that asymptotically inefficient estimators provide relatively better performance in finite samples (Reed and Ye, 2011). The equations used for OLS and FGLS estimation methods for $\hat{\beta}$ and Var($\widehat{\beta}$) are as follows (Beck and Katz, 1995):

$$\hat{\beta} = (X'\widehat{\Omega}^{-1}X)^{-1}X'\widehat{\Omega}^{-1}y \quad (5)$$

$$Var(\hat{\beta}) = (X'\widehat{\Omega}^{-1}X)^{-1} \quad (6)$$

In the above equations, $\widehat{\Omega}$; represents the assumptions that represent the cases of error heteroscedasticity, serial correlation and cross-sectional dependence.

Table no. 6 – FGLS Results

Variables	Coef.	Std. Err.	p-val.
LogGDPpc	1.322	0.495	0.008***
LogGDPpc2	-0.175	0.072	0.015**
LogHE	0.064	0.038	0.090*
LogNE	-0.034	0.014	0.016**
LogRE	-0.007	0.043	0.865
Cons.	-2.646	0.854	0.002***
Statistics of Models	Wald chi2: 37.87 F Value: 0.000***		

Note: ***, ** and * denote significance at 1%, 5% and 10%, respectively.

According to the statistics in Table no. 6, it was observed that only renewable energy consumption did not have a significant relationship with the dependent variable. It was concluded that a 1% increase in the growth variable increased the LCF by 1.322%. In addition, when the coefficient signs of the square of GDPpc and GDPpc are examined, it has been determined that the LLC hypothesis is not valid. A 1% increase in the LogHE variable increases the dependent variable by 0.064%. A 1% increase in the LogNE variable reduces the LCF by 0.034%. In this context, it has been observed that only the nuclear energy (LogNE) variable has a negative impact on environmental sustainability.

4. CONCLUSIONS

The study tested the LCC hypothesis of BRICS countries and investigated their environmental quality in this context. The dependent variable in the model is Load Capacity Factor (LCF), while the independent variables are economic growth, nuclear energy consumption, renewable energy consumption and hydropower energy consumption. These relationships were investigated with annual data from 1993-2022. According to empirical findings, it has been observed that the LCC Hypothesis is not valid in the sample group countries. In this case, the hypothesis "the LCC hypothesis is valid in BRICS countries." could not be confirmed. Our findings are consistent with the results of the studies by Pata and Tanriover (2023), Pata *et al.* (2023), Yang *et al.* (2023), Deng *et al.* (2024), Shahzad *et al.* (2024), Ulussever *et al.* (2024) and Erdogan (2024).

LCF is calculated as the ratio of a region's or world's capacity to produce natural resources to the resources consumed by that region or world. In this context, this phenomenon is a very important indicator for understanding nature's supply capacity and sustainability. In line with this information, the relationship between economic growth and LCF is important. In the findings, it was determined that economic growth increased LCF. This result is unexpected. Since growth generally increases the ecological footprint, its impact on environmental quality is negative. The LCF phenomenon demonstrates nature's supply capacity. The positive relationship between

growth and growth is an unexpected finding. There may be possible reasons for this situation. If growth is supported by increased productivity, use of renewable energy and sustainable production methods, it can be possible to limit the increase in ecological footprint. In such a case, economic growth does not push the limits of biocapacity and may have positive effects on the Load Capacity Factor. When evaluated over the sample group, it may be due to the policies implemented by the countries in question or the relatively better condition of nature's supply capacity. Therefore, importance should be given to innovative growth strategies in order to achieve the balance between economic growth and ecological balance in sustainable development goals. The positive impact of growth on LCF can be increased through various policies such as efficient use of resources, transition to renewable energy and adoption of environmentally friendly technologies.

It has been found that hydropower consumption increases LCF. This situation confirms the hypothesis "Hydropower energy consumption will increase the LCF.". In this context, this result shows that this type of energy is an important tool for sustainable development. In order to increase the positive impact of this energy on the environment, it would be appropriate to reduce dependence on fossil fuels and encourage clean energy production by increasing the number and capacity of hydropower power plants. In addition, by increasing the efficiency of the energy produced, reducing unit energy consumption and reducing the ecological footprint will increase environmental quality. Tax reductions, subsidies and financial incentives should be provided to increase hydropower energy as well as other renewable energy investments.

It has been observed that nuclear energy consumption has a negative effect on LCF. It was predicted that this finding may be related to various environmental and social risks of this energy source. Nuclear energy production produces highly radioactive waste. These wastes are difficult to store and manage safely and pose long-term environmental risks. Therefore, it is an expected result that the impact on the environment will be negative. This situation confirms the hypothesis "Nuclear energy consumption will reduce the LCF.". Innovative and safe technologies should be developed to increase safety for the storage of radioactive waste. Additionally, the development of technologies and practices that will optimize water use of nuclear power plants and reduce thermal pollution will help create a positive impact on LCF. As an alternative policy proposal, diversity in energy production should be ensured and dependence on nuclear energy should be reduced. In this context, it is a necessity for economies to turn to more sustainable energy sources.

No relationship could be detected between renewable energy consumption and LCF. In this case, the hypothesis "Renewable energy consumption will increase the LCF." could not be confirmed. The expected potential impact of renewable energy consumption is positive. However, no relationship was found. There may be possible reasons for this situation. The production of renewable energy sources may not meet the energy consumption needs in some regions. In this case, a mismatch between energy consumption and production may occur. In addition, in this type of energy, the lack of sufficient and effective energy storage solutions to store the energy obtained from renewable energy sources may not be able to balance the fluctuations in energy supply. Another reason may be that these energy-oriented policies are missing or inadequate. In such a case, infrastructure investments should be made and network capacity should be increased to facilitate the integration of renewable energy sources into existing energy networks. Tax reductions, subsidies and other financial incentives should be provided for renewable energy investments. International collaborations should be established to facilitate technology transfer from developed countries regarding renewable energy technologies. By implementing such policies, the contribution of renewable energy consumption to environmental sustainability can be increased.

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Investigating the Determinants of Public Debt Sustainability for European Union Countries

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Abstract: This study investigates the determinants of public debt sustainability in the European Union (EU) countries, focusing on the combined effects of the COVID-19 pandemic and the Ukraine conflict. Utilizing the Generalized Method of Moments (GMM) for the 2000-2022 period to address the endogeneity and heterogeneity aspects, the research incorporates various factors, such as military and healthcare expenditures, private debt, and political stability to provide a comprehensive analysis of public debt dynamics. The findings revealed that lagged debt has a significant positive impact on current public debt, indicating its persistence over time. Economic downturns, military spending, and private debt are identified as key drivers of rising public debt, especially during periods of geopolitical tension and economic instability. Additionally, the study highlighted the roles of GDP per capita, inflation, and government expenditure in influencing fiscal stability. The research underscores the importance of adopting long-term fiscal discipline and counter-cyclical measures to manage public debt, particularly during crises. The study offers a comprehensive and original perspective upon the dynamics of EU countries' public debt and suggests that fiscal policies encouraging investments and supporting political stability contribute to the sustainable management of public debt.

Keywords: public debt sustainability; COVID-19 pandemic; Generalized Method of Moments; fiscal policy; European Union.

JEL classification: E61; E62; H63; F61.

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1. INTRODUCTION

The problem of public debt has once again emerged as a prominent subject of debate among academics, politicians, and journalists in the European Union (EU). In the last twenty years, the European Union has faced four significant crises that have had a tremendous effect on its economies. The subprime mortgage crisis of 2007–2008 sparked the failure of hedge funds, banks, and insurance firms, which in turn caused the global financial catastrophe. Mortgage-backed securities and credit default swaps drove the housing bubble. This bubble burst when the Federal Reserve increased interest rates, leading to a significant number of defaults and ultimately resulting in the 2008 financial crisis.

The implementation of the Euro, which brought together monetary policy but allowed individual states to control their fiscal policies, caused the sovereign debt crisis, which reached its peak between 2010 and 2012. This resulted in unregulated borrowing, especially in Greece and Portugal, worsened by the 2008 financial crisis. The Euro's incapacity to undergo additional devaluation exacerbated the crisis, leading to the implementation of several bailouts for economies in distress.

The COVID-19 pandemic reached its highest point between 2020 and 2022. Without a doubt, this health issue has posed a significant obstacle to a substantial recovery that followed the previous sovereign debt crisis (2009–2012). Significant public budget deficits and an unprecedented increase in public debt confront the EU economies, which have not fully recovered from the pandemic. These issues have arisen due to the mandatory two to three months of quarantine, social immobilization, border closures, reduced international trade, and high unemployment rates. Many developing nations have received financial aid and support from institutions like the World Bank and the International Monetary Fund, while the G20 countries have waived some portions of foreign loan payments for the poorest nations. However, European governments have had difficulties acquiring equivalent assistance. In the midst of policy disputes, the European Union has approved the establishment of a €100 billion fund, following a proposal from Spain and other nations. The primary objective of this fund is to offer monetary assistance for costs associated with employee layoffs and unemployment insurance, specifically targeting initiatives such as ERTE, which were enacted during the COVID-19 quarantine period. The ERTE program in Spain offers financial assistance to those who are temporarily out of work because of disruptions caused by the COVID-19 pandemic. The pandemic exacerbated problems by triggering a global economic recession and necessitating an unparalleled level of government expenditure to alleviate its socio-economic consequences, leading to a substantial rise in public debt levels among European Union member states. According to figures from the European Commission, the average ratio of public debt to GDP in EU member states was above 90% by the end of 2020, with notable differences between countries. Greece, Italy, and Portugal had the highest levels of debt, of over 100% of their Gross Domestic Product (GDP), while Estonia, Lithuania, and the Czech Republic had comparatively lower debt ratios, below 50% of their GDP. Particularly in countries disproportionately affected by the crisis, like Italy and Spain, the pandemic exacerbated the economic burden, leading to increased levels of debt.

And most recently the ongoing Ukraine crisis, which reached its climax in 2022 and continues to this day, presents significant financial issues that need massive investments to address the intricate socio-economic repercussions. The conflict in Ukraine also imposes a financial burden, with projected immediate fiscal costs for the European Union and its member

states totaling €175 billion, equivalent to between 1.1% and 1.4% of GDP in 2022. These costs encompass a wide range of operations, including efforts to stabilize domestic pricing, implementing policies for achieving energy independence, providing assistance to refugees, and adopting steps to enhance security and defense. Consequently, we anticipate a rise in borrowing, potentially leading to elevated levels of public debt throughout the European Union.

This research significantly enhances the current understanding of public debt's sustainability in EU nations by filling a critical void in the previous literature. Prior research has investigated several facets of public debt, but it has not extensively analyzed the collective influence of the COVID-19 epidemic and the Ukraine war. Furthermore, this study incorporates additional variables such as military expenditures, healthcare expenditures, private debt, and political stability into the analysis, providing a more comprehensive insight into the factors that affect the sustainability of public debt. The research aims to get a more comprehensive understanding of the intricate connections among economic, political, and external issues by utilizing the Generalized moment method (GMM). The main objective is to improve our understanding of the interplay between these components and their impact on financial results over a period, especially in relation to current geopolitical and macroeconomic occurrences.

This study used two main variables to characterize the Covid-19 pandemic and Ukraine conflict. For the health crisis, the variable of health expenditure into GDP was chosen, as this variable reflects the level of resources allocated to improving the healthcare system and responding to health crises such as the COVID-19 pandemic. As for military conflicts, they were measured using the Military Expenditure Index, which represents the financial burden associated with military preparations and operations related to conflicts. These two variables were chosen because they provide comprehensive and reliable data at the level of EU countries, and they directly reflect the impact of health crises and military conflicts on public financial resources. The use of the health expenditure ratio helps understand financial priorities during health crises, while military expenditure provides an indicator to measure the challenges associated with conflicts and their impact on public debt's sustainability. This choice aligns with previous literature that emphasized the importance of these indicators in analyzing the public debt in crisis contexts.

This study consists of six main sections. The first section presents the importance of studying the determinants of public debt sustainability in EU countries and the research objectives. The second section presents a literature review, where previous studies related to public debt sustainability and the factors affecting it are reviewed. The third section discusses the methodology used in the study, including the research design and analytical methods. Section four presents the empirical results derived from the statistical analysis. Section five addresses the discussion and challenges faced by the study, with a focus on interpreting the results and the limitations of the research. Finally, section six presents a conclusion that includes recommendations and proposed policies to enhance the sustainability of public debt in EU countries.

2. LITERATURE REVIEW

The determinants and dynamics of public debt have been a persistent focus in the academic literature, yet substantial gaps remain in understanding the multifaceted interactions influencing public debt sustainability across different regions and economic groupings. Thuan (2018) examined the role of macroeconomic variables in lower middle-income countries, employing the DGMM regression method with data from 40 nations covering the 1996-2015

period. While the study highlights the importance of trade openness, interest rates, and budget surplus in shaping public debt, it overlooks potential structural factors like governance and institutional quality, which may further explain the variation in debt sustainability across regions. Toth *et al.* (2022) expanded the focus to the European Union (EU), particularly in the aftermath of the COVID-19 pandemic, using panel data regression to identify key determinants of public debt from 1999 to 2019. Although their findings underline the debt-reducing effects of GDP growth and budget balances, the study does not fully address the dynamic role of fiscal rules and policy compliance among EU member states, especially those with high pre-existing debt burdens. Semik and Zimmermann (2022) offered a narrower geographical scope, focusing on Central and Eastern European EU countries. Their results emphasized the effectiveness of expenditure-based fiscal adjustments in reducing debt levels. However, the paper does not consider the potential trade-offs of such measures, such as the social costs of cuts in benefits and public sector wages, leaving room for further investigation into the long-term sustainability of these strategies. Chirwa and Odhiambo (2018) applied a panel ARDL approach to EU countries, demonstrating that economic growth reduces debt primarily in the short run, while long-term debt drivers include real interest rates and population growth. While comprehensive, their study's results raise questions about the differential impact of these factors during economic crises versus periods of stability, an area warranting further exploration. Aleme (2019) focused on external debt sustainability in Ethiopia, emphasizing the role of debt service ratios and real exchange rates. Although contextually rich, its applicability to other nations is limited due to Ethiopia's unique economic structure and debt composition, suggesting a need for more comparative analyses across developing economies. Sinha *et al.* (2011) analyzed panel data from 31 countries, including some European nations, for the 1993–2008 period. They found that GDP growth, government spending, education expenditure, and the current account balance significantly impact public debt in high- and middle-income countries. However, the study does not delve deeply into the varying regional dynamics that might influence these relationships. Dincă and Dincă (2015) studied the correlation between public debt and economic growth for 10 former communist countries from Central and Eastern Europe for the 1999-2010 period. They found that public debt can support countries' economic growth up to a limit of 50% of the GDP (weight of public debt into GDP) after which increased indebtedness can hinder that growth.

Other country-specific studies, such as those by Pirtea *et al.* (2013) and Dumitrescu (2014) in Romania, identified the primary fiscal balance, real interest rate, real GDP growth, and exchange rates as key factors affecting debt-to-GDP ratios. However, these studies lack a comparative perspective that could illuminate broader patterns across regions. Veiga and Veiga (2014) extended the scope by examining how debt impacts revenue and expenditure structures, identifying unemployment as a critical driver of debt. Although their findings are insightful, they leave unanswered questions about how labor market policies might mitigate such effects. In a broader analysis, Swamy (2015) used panel Granger causality tests to demonstrate that GDP growth, direct investments, government expenditures, and inflation negatively affect debt, while gross fixed capital formation and trade openness positively influence it. Similarly, Galiński (2015) explored public sector financial variables in Poland, emphasizing the cost of capital. These studies highlight macroeconomic influences but overlook institutional and governance factors, which Briceño and Perote (2020) argue are critical. Studies like those by Gargouri and Ksantini (2016) and Omrane Belguith and Omrane (2017) adopted regional and panel approaches, examining European countries and new EU

member states. Their findings underscored the role of nonperforming loans, military expenditures, imports, and balanced budgets in debt sustainability. However, the persistence of debt-to-GDP ratios over time raises questions about the structural factors that perpetuate debt cycles. Kudła (2018) introduced dynamic panel econometrics to analyze social and economic variables like unemployment and population growth, but the research lacks a focus on crisis-specific impacts. Recent studies have incorporated broader socio-political factors.

The theory of fiscal federalism is based on the idea that local governments' debts are closely linked to the internal organization of the state, which is defined through the financial relations between governments. Given the importance of local levels in financial federalism from both theoretical and practical perspectives, the research conducted by Moćević and Lazović-Pita (2024) aims to empirically investigate the factors that determine the debt of local units in the Federation of Bosnia and Herzegovina. Based on panel data from 2011 to 2019 and using the Generalized Method of Moments, the model is estimated using a set of financial, institutional, economic, and demographic variables. The results indicate that local units' debt is significantly determined by financial relationships between governments through a range of financial and institutional variables, in addition to demographic factors. However, the research does not adequately address the impact of major economic factors on these dynamics, indicating a research gap that can be explored in future studies. For example, studying the effects of global economic crises on these dynamics could be beneficial in expanding the understanding of the sustainability of local government debts. The study by Bokemeier and Stoian (2016) focuses on debt sustainability for 10 Central and Eastern European countries for the 1997-2013 period. Using a financial reaction function to determine stable debt in a balanced panel with fixed effects, the study compares stable debt with actual debt and historical returns to assess debt sustainability. While this study provides estimates of debt sustainability in Bulgaria and Romania, it is limited to specific countries and does not address the role of national and international fiscal policies in the impact of public debt on financial sustainability. This gap could be of interest in future studies that seek to examine the role of international financial institutions such as the International Monetary Fund in public debt's sustainability. Filip (2019) study addressed the factors affecting the level of public debt in 28 EU countries for the 1995-2017 period. The results indicate that public debt is significantly and positively affected by previously accumulated public debt, unemployment rate, and population size, while factors such as GDP growth and foreign direct investment flows help reduce public debt. However, the study does not prioritize analyzing the impact of economic crises such as the global financial crisis or the COVID-19 pandemic on public debt, which opens the door for subsequent studies that could focus on the impact of these crises on public debt in European countries. The study by Naveed and Islam (2024) explored the factors affecting the dynamics and sustainability of public debt in Pakistan between 1975 and 2021 using a debt dynamics approach and ARDL analysis. The study's results indicate a positive impact of fiscal deficits, currency depreciation, and interest rates on public debt. However, the study is limited to Pakistan only and does not take into account the impact of regional or global factors on public debt in similar countries, reflecting a gap that can be addressed in future research, which may include a comparison between other developing countries in South Asia. As for the study by Ye and Guo (2024), it addressed the sustainability of public debt in Sub-Saharan African countries. While the results indicate that public debt in these countries is unsustainable in the long term, the study does not address the potential impacts of global economic crises or changes in global markets on these dynamics. The study also does not

sufficiently clarify the relationship between monetary and fiscal government policies and their impact on debt sustainability. Kijjambu *et al*. (2023) investigate Uganda's debt sustainability determinants, using a public debt dynamics model that explores the relationship between public debt and macroeconomic factors, including GDP, primary balance, exchange rates, and interest rates. This study extends prior research by incorporating additional variables such as the production gap and non-interest current account balance. The findings suggest that fiscal surplus, low interest rates, and currency appreciation contribute positively to debt reduction and sustainability. However, the study finds that GDP growth does not significantly affect debt dynamics in Uganda, pointing to a potential gap in understanding the role of economic growth in debt sustainability. This underscores the need for future research to investigate other structural factors that may influence Uganda's debt dynamics, such as the informal economy or institutional capacity. Khan *et al*. (2021) examine the sustainability of public debt in South Asian Association for Regional Cooperation (SAARC) countries for the 1996-2017 period, using a panel ARDL model. They find that the saving-investment gap and economic growth negatively affect public debt, while budget deficits and current account balances positively contribute to debt levels. Their sustainability analysis indicates that public debt remains unsustainable for most years, highlighting the vulnerability of these economies to fiscal imbalances. While this study offers valuable insights, it overlooks potential long-term structural factors, such as demographic trends or political instability, that could contribute to the unsustainable debt trajectory in these countries. Future research could explore the role of such variables in debt sustainability. provide a detailed decomposition of public debt dynamics in Romania from 2000 to 2011, focusing on primary fiscal deficits, real interest rates, and GDP growth. Their analysis finds that fiscal policy, particularly the real interest rate, is a significant determinant of public debt. The study also reveals limited effectiveness of monetary policy as an automatic stabilizer. However, the authors do not consider the broader macroeconomic environment, such as the impact of external shocks or global market conditions, which could influence Romania's debt trajectory. This gap calls for further investigation into the interaction between domestic policies and global economic factors in shaping public debt. Saikouna and Matarr (2023) analyze the determinants of public debt in Gambia for the 2000-2019 period using the ARDL method. They identified trade openness and gross fixed capital formation as significant long-term drivers of public debt, while GDP growth and government effectiveness have the opposite effect. Interestingly, none of the variables show a significant relationship with public debt in the short run. This study highlights the importance of governance effectiveness in managing debt levels, which suggests that institutional reforms could play a critical role in debt sustainability. However, the study does not explore the role of international factors, such as foreign aid or external borrowing conditions, which could also impact Gambia's public debt. Manalo *et al*. (2022) explore the determinants of public debt in the Philippines, focusing on Foreign Direct Investment (FDI), gross capital formation, inflation, and trade balance. The study found that FDI negatively impacts public debt, while inflation and trade balance show insignificant effects. These findings suggest that FDI could be a viable strategy for reducing public debt, but the study neglects other important factors, such as the exchange rate or interest rates, which could influence debt accumulation. Future research could expand the model by including these variables to provide a more comprehensive understanding of debt dynamics in the Philippines. Omrane Belguith and Omrane (2017) investigate the macroeconomic determinants of Tunisia's public debt for the 1986-2015 period using the VECM model. The

study finds that inflation and investment reduce public debt, while real interest rates, budget deficits, and trade openness increase it. The budget deficit emerges as the most significant determinant of Tunisia's public debt. However, the study overlooks the impact of political factors or institutional quality on debt sustainability. A more nuanced approach could consider the role of governance and political stability in shaping fiscal outcomes. Waheed and Abbas (2021) analyze external debt sustainability in Islamic countries, differentiating between oil and gas exporters and importers. The study finds that economic growth and government revenue negatively affect external debt, while expenditure, inflation, and trade openness increase debt levels. This research, however, fails to consider the potential impact of oil price fluctuations on the fiscal balance, which is crucial for oil-exporting countries. Future studies could incorporate the role of global commodity markets in shaping external debt dynamics. Musah (2023) investigates the macroeconomic determinants of Ghana's public debt using the ARDL model. The study identifies merchandise trade, gross fixed capital formation, interest payments, and government spending as key drivers of public debt. While the findings underscore the importance of fiscal discipline, the study does not consider the role of external factors such as foreign aid or global financial market conditions. Incorporating these elements could provide a more comprehensive understanding of Ghana's debt dynamics. Khan (2021) addressed the accumulation of public debt in developing countries using a multi-regional analysis methodology for the period 2000-2015, covering Africa, Asia, Latin America, and the Caribbean. The study showed that regional determinants vary; in Africa, economic growth, corruption, and the quality of regulation were crucial factors, while in Asia, government spending and political stability played a central role. In Latin America, trade openness was the key. Despite the importance of the findings, the study lacked an analysis of economic crises' dynamics and their impact on these determinants, highlighting the need for deeper studies to clarify the interaction of political, economic, and social factors in shaping public debt. The study by Sadik-Zada and Gatto (2019) reviews the main factors affecting public debt growth in 184 countries, and shows that oil abundance, economic growth rate, share of mineral revenues in total revenues, and interest payments on external borrowing have a statistically significant impact on public debt growth. In contrast, defense spending, the unemployment rate, or the inflation rate did not have a statistically significant impact on public debt's rate. The study also showed that being a developing country has a statistically negative impact on the level of public debt. However, the study lacks an analysis of the impact of economic crises, political stability, or governance quality on shaping public debt, which limits its ability to provide a comprehensive view of public debt in various contexts. Additionally, the reliance on data from 2013 may limit the generalizability of the results across different time periods or to other countries with diverse economic and political conditions. The study by Ngasamiaku and Ngong'ho (2022) examines the macroeconomic determinants of Tanzania's public debt for the 1970-2019 period using the ARDL model. The results derived from the ARDL bounds test showed a long-term relationship among the macroeconomic determinants of public debt. The study also showed that in the short term, there is significant evidence that imports and government spending positively affect public debt, while the inflation rate negatively impacts public debt. Also foreign direct investments do not show any statistically significant effect on public debt. The study recommends that the Tanzanian government adopt prudent macroeconomic policies to reduce public debt, ensuring that resources are directed towards productive sectors to enhance local production, increase revenues, and improve export performance in the post-COVID-19 pandemic phase. This study

focused only on macroeconomic factors such as imports and government spending, without considering the political and social factors that may also affect the levels of public debt. Additionally, the use of a long time period (from 1970 to 2019) may expose the study to economic and political fluctuations that could affect the interpretation of the results. Furthermore, the study did not adequately address the impact of economic crises such as the COVID-19 pandemic on public debt directly. See Table no. 1.

Table no. 1 - Literature review

Study (Author/ Year)	Methodology	Regional Coverage	Main Results
Thuan (2018)	DGMM regression method	Lower-Middle Income Countries	The study results indicate that public debt in lower-middle-income countries is influenced by multiple macroeconomic factors, including trade openness, interest rates, budget surplus or deficit, inflation, economic growth, foreign direct investment, infrastructure, and the size of the financial system, highlighting the role of these factors in shaping the debt-to-GDP ratios during the period 1996-2015. However, it was found that the unemployment rate has no impact on public debt in these countries, indicating that labor market policies may not be effective in managing debt levels.
Chirwa and Odhiambo (2018)	A panel ARDL approach	Euro area	The study results indicate that economic growth reduces public debt in the short term, while factors such as the real exchange rate, investment, and population growth contribute to reducing debt in the long term. Conversely, the real interest rate is considered a factor that increases debt in both the short and long term, while government consumption leads to an increase in debt in the long term with a varying relationship in the short term.
Moćević and Lazović-Pita (2024)	Empirical analysis using panel data and generalized method of moments (GMM).	the Federation of Bosnia and Herzegovina	The study results indicate that the debt of local government units (LGUs) in the Federation of Bosnia and Herzegovina is significantly influenced by financial relations between governments, where a range of financial, institutional, and demographic variables play an important role. Funding the expenditure needs of certain local units, in addition to those located within cantons with special needs, is considered one of the main determinants of debt in both the short and long term. Transfers from other government levels also significantly affect the debt of local government units in both the short and long term.
Bokemeier and Stoian (2016)	Balanced panel with fixed effects	Ten Central and East European countries	The study results indicate that in 2017, public debt exceeded the stable debt ratio in all the countries examined. However, the public debt remains stable and below the tipping point. Moreover, it has been shown that governments are still far from the thresholds of "debt distress" that may indicate difficulties in financial sustainability.
	Survey and data analysis	28 European Union countries	The study results indicate that the debt-to-GDP ratio is significantly and positively affected by previously accumulated public debt, in addition to the impact of both unemployment and population size. Conversely, the growth of real GDP, foreign direct investment flows, gross capital formation, and the trade balance significantly impact the reduction of public debt.
Toth *et al.* (2022)	panel data regression model	European Union	The study results indicate that an increase in certain variables such as the current account balance, the budget balance, investments in public administration, the inflation rate, and GDP growth leads to a reduction in public debt in EU countries. On the other hand, an increase in variables such as the annual change in population density and budget costs leads to an increase in public debt. The study

Study (Author/ Year)	Methodology	Regional Coverage	Main Results
			results also showed that the impact of both the unemployment rate and purchasing power on public debt is not statistically significant.
Naveed and Islam (2024)	Debt dynamic approach and ARDL approach	Pakistan	The study results indicate that the fiscal deficit, currency depreciation, and interest rates have a significantly positive impact on public debt in Pakistan. The debt sustainability analysis also showed that public debt was unstable throughout the study period, except for a few years. The regression results confirmed the stability analysis findings, showing that the main forces increasing the debt burden in the country are poor financial discipline, high costs resulting from currency depreciation, and rising interest rates.
Ye and Guo (2024)	the theoretical model is known as the Present Value Budget Constraint (PVBC) model and the System-Generalized Method of Moments (System-GMM) method	Sub-Sahara African countries	Findings reveal that public debt in SSA countries is not sustainable in the long run, with factors such as the previous government debt, long-term debt ratio, debt repayment capacity, economic growth rate, inflation rate, export to GDP, and government fiscal deficit rate influencing sustainability. Additionally, the factors exhibit heterogeneity attributed to regional, natural resource, and income variations among SSA countries.
Kijjambu *et al.* (2023)	The Public Debt Dynamics Model	Uganda	The study results indicate that the fundamental balance, the real interest rate, and the real effective exchange rate have a significant positive impact on the public debt ratio, suggesting that a financial surplus, low interest rates, and currency appreciation are favorable factors for reducing public debt and ensuring its sustainability. It was also found that the debt ratio is negatively and significantly affected by the current account balance, indicating that a trade surplus is beneficial in managing debt. However, the study did not show a significant impact of economic growth on the dynamics of debt in Uganda. Based on that, the study recommends that policymakers focus on maintaining a financial surplus and prudent government financial management, taking measures to enhance revenues, control government expenditures, and reduce the fiscal deficit to achieve long-term debt sustainability.
Pirtea *et al.* (2013)	OLS regression to estimate the relationships between public debt and its determinants and the Newey-West procedure to correct for issues of heteroscedasticity and autocorrelation, ensuring more reliable results	Romania	The study results indicate that the ratio of public debt to GDP responded more significantly to the real growth rate of production after the financial crisis. The real interest rate on government bonds remained an important determinant of public debt throughout the study period. Additionally, it was found that monetary policy had limited effectiveness as an automatic stabilizer throughout the study period.
Saikouna and Matarr (2023)	An Autoregressive Redistributed Lag (ARDL) bound Cointegration Technique	Gambia	The study results show that trade openness and fixed capital formation have an increasing impact on public debt in the long term. On the other hand, GDP growth, the official exchange rate, and government effectiveness have a downward effect on public debt levels in the long term. However, none of the variables show a significant relationship with public debt levels in Gambia in the short term.

Study (Author/ Year)	Methodology	Regional Coverage	Main Results
Manalo *et al.* (2022)	Multiple Linear Regression	Philippines	The study results show that foreign direct investment (FDI) has a significant negative impact on public debt, where an increase of one unit in FDI leads to a decrease of 272.559 in public debt. The study also showed that the trade balance had a negative impact, but the result was similar to the inflation rate, which showed non-significant results. Based on these results, the researchers recommend focusing on other variables such as interest rates, exchange rates, and the debt-to-GDP ratio. The researchers concluded that FDI can be relied upon as a tool to reduce public debt, as an increase in the flow of foreign direct investments would be beneficial in alleviating the heavy reliance on debt.
Gargouri and Ksantini (2016)	Panel ARDL	12 Europeans countries	Identified macroeconomic variables influencing public debt across countries.
Omrane Belguith and Omrane (2017)	VECM model	Tunisia	The study results show that inflation and investment reduce the size of public debt in Tunisia, while the real interest rate, fiscal deficit, and trade openness increase public debt. The study also indicates that the fiscal deficit is the most influential factor on public debt in Tunisia.
Musah (2023)	ARDL method	Ghana	The study results show that there is a positive relationship between merchandise trade and public debt in Ghana, indicating that an increase in trade, due to the heavy reliance on foreign trade to meet local consumption needs, leads to an increase in public debt. The study also shows a positive relationship between fixed capital formation, economic growth, and public debt, where public debt increases with the rise in investment in fixed assets. Government interest payments also contribute to the accumulation of public debt. The study also indicates that government spending plays a crucial role in determining the trajectory of public debt, as increased spending leads to an increase in public debt. The results indicate that fiscal policies, external borrowing, trade, interest payments, and fiscal deficits significantly affect the levels of public debt in Ghana.
Waheed and Abbas (2021)	A Panel Data Analysis	Islamic Countries	The study results indicate that the factors affecting external debt in oil and gas-exporting Islamic countries include a negative impact from economic growth, central government revenues, foreign direct investment (FDI), and population size on external debt. While central government expenditures, trade openness, inflation, and current account deficits positively affect external debt. As for the Islamic countries that import oil and gas, economic growth, central government revenues, current account deficits, local investment, and the workforce negatively affect external debt, while foreign direct investment and foreign exchange reserves positively affect external debt. As for sustainability analysis, many oil and gas importing countries face a more precarious situation, where their actual debt exceeds the expected debt based on their macroeconomic performance, while oil and gas exporting countries remain in a better position regarding external debt, with some exceptions.

3. METHODOLOGY

Current research explores the determinants of public debt sustainability in the European Union countries. The GMM methodology is applied to establish public debt sustainability's

determinants for the 2000-2022 period and their effects, for all the EU-27 countries, respectively Belgium, Bulgaria, Czechia, Denmark, Germany, Estonia, Ireland, Greece, Spain, France, Croatia, Italy, Cyprus, Latvia, Lithuania, Luxembourg, Hungary, Malta, Netherlands, Austria, Poland, Portugal, Romania, Slovenia, Slovakia, Finland and Sweden.

Table no. 2 below presents the variables used in the model, abbreviations, units, and data sources used to gain insight into the relation between public debt and economic growth.

Table no. 2 – Variables used in the econometric analysis

Variables Name	Abbreviation	Unit	Source
		Dependent variables	
Public debt	DEBT	% GDP	International Monetary Fund 2000-2022
		Independent variables	
GDP per capita	GDPP	% growth	International Monetary Fund 2000-2022
Foreign direct investment	FDI	% of GDP	World Bank 2000-2022
Inflation rate	INF	% increase of consumer prices	World Bank 2000-2022
Government expenditure	GE	%GDP	World Bank 2000-2022
Unemployment rate	U	% of total labor force	World Bank 2000-2022
Military expenditure	ME	% of GDP	World Bank 2000-2022
Healthcare expenditure	HE	% of GDP	World Bank 2000-2022
Privet debt	PD	% of GDP	International Monetary Fund 2000-2022
Political stability	PS	Standard Error	World Bank 2000-2022

Source: Adapted from Toth *et al.* (2022), Sinha *et al.* (2011), Omrane Belguith and Omrane (2017)

Empirical analysis uses the following model**:**

$$debt_{it} = \beta_0 + \beta_1\, debt\text{-}1_{it} + \beta_2\, gdpp_{it} + \beta_3\, fdi_{it} + \beta_4\, inf_{it} + \beta_5\, u_{it} + \beta_6\, milit_{it} + \beta_7\, health_{it} + \beta_8\, pd_{it} + \beta_9\, ps_{it} + \varepsilon_{it}$$

In the regression equation, Debt to GDP – is a proxy for *Public debt*. The subscripts *i* and t represent the number of nations and study periods, *i* = (1 to 27) and *t* = (2000 to 2022).

The variables examined in this research are crucial for comprehending the dynamics of public debt.

$Debt_{it-1}$, as defined by Pirtea *et al.* (2013) is the value of the debt variable from the preceding time period of (*t–1*). This variable is used to analyze the impact of previous debt levels on current levels, offering insights into the long-term patterns of debt persistence or adjustment. Furthermore, the regression analysis incorporates GDP per capita growth as a measure to assess economic growth's influence on public debt. According to Imran (2016), stronger economic growth results in more domestic revenue, which reduces the need to borrow money. Additionally, the inclusion of Foreign Direct Investment (FDI) is justified by its ability to improve productivity, as highlighted by Pirtea *et al.* (2013) ultimately resulting in a reduction in the debt-to-GDP ratio. Reinhart and Rogoff (2008) emphasize the importance of foreign direct investment (FDI) in elucidating the relationship between the debt-to-GDP ratio and the low- and middle-income nations. Furthermore, the inflation rate (Inf) is incorporated to quantify its impact on the dynamics of debt. According to Imran (2016), increasing inflation diminishes debt worth by counteracting interest rates' increase. In

addition, an increase in government spending or government expenditures (ge) can exceed government revenues, calling for borrowing and thus raising public debt, as explained by Uguru (2016). The inclusion of the unemployment rate (u) is based on the idea that governments may use public debt to tackle economic downturns during recessionary periods, as proposed by Sadik-Zada and Gatto (2019). Military expenditure (ME) had a negative relationship with public debt. Higher military spending, especially on arms imports, tends to lead to increased external borrowing and debt accumulation, particularly in developing countries. This negative impact occurs because military expenditures often create budget deficits that are covered by borrowing, thus contributing to the rise of public debt (Brzoska, 1983; Looney, 1991). Healthcare expenditure had a negative relationship with public debt (Said and Sani, 2020). Private debt (PD) had an interconnectedness between private and public debt, demonstrating that financial shocks and sovereign risk can intensify financial instability, resulting in increased public liabilities during economic downturns (Corsetti *et al.*, 2013; Andrés *et al.*, 2020). Political stability (PS) had no significant relationship between political stability and public debt (Briceño and Perote, 2020).

From a statistical perspective, Table no. 3 below lists the key descriptors of the variables employed in all the EU27 countries.

Table no. 3 – Descriptive statistics EU27 countries

Variables	Obs	Mean	Std.dev.	Min	Max
Debt	621	59.92	35.70	3.8	212.4
L.debt	621	3.88	0.7028	1.33	5.35
Gdpp	621	2.32	4.04	-14.46	23.3
Fdi	621	10.77	42.57	-391.4	449.0
Inf	621	2.88	3.67	-1.7	45.7
Ge	621	44.82	6.92	21.2	66.8
U	621	8.68	4.44	1.9	27.5
ME	621	1.42	0.5641	0.2251	3.86
He	621	8.08	1.83	4.20	12.82
Pd	614	148.2	78.17	10.74	406.8
Ps	594	0.2418	0.0342	0.1922	0.3962

Source: processed by the authors

The analysis of the data reveals substantial variability across several economic and financial indicators in Table no. 3. Public debt (DEBT) accounts for an average of 59.92% of GDP, accompanied by a significant standard deviation of 35.70%, underscoring considerable differences in debt levels among countries. The lagged debt ratio (L.DEBT) demonstrates an average of 3.88 with a standard deviation of 0.7028, indicating varying degrees of debt persistence over time. Economic performance, as represented by GDP growth rate (GDPP), shows a mean value of 2.32% and a high standard deviation of 4.04%, reflecting fluctuating economic conditions across the sample. Foreign direct investment (FDI) exhibits a mean of 10.77% of GDP, coupled with a substantial standard deviation of 42.57%, signaling notable variability in investment inflows and outflows. Inflation (INF) averages 2.88%, with a significant standard deviation of 3.67%, highlighting pronounced changes in price levels. Government expenditures (GE) represent 44.82% of GDP on average, with a standard deviation of 6.92%, indicating substantial public spending differences among countries. The labor market conditions, as captured by the unemployment rate (U), reveal an average of

8.68% and a standard deviation of 4.44%, pointing to varying employment dynamics. Military expenditures (ME) show a mean of 1.42% of GDP and a standard deviation of 0.5641%, reflecting moderate variability in defense spending. Health expenditure (HE) averages 8.08% of GDP with a standard deviation of 1.83%, demonstrating quite different investments in healthcare across countries. Private debt (PD) records an average of 148.2% of GDP, with a high standard deviation of 78.17%, signaling considerable differences in borrowing levels. Lastly, political stability (PS) shows an average value of 0.2418 with a standard deviation of 0.0342, indicating moderate stability with some regional variations.

4. EMPIRICAL RESULTS

The matrix in Table no. 4 shows the data correlations for all EU countries. It is observed that deferred debt (LDEBT) shows a strong positive correlation with current debt, indicating that previous debt levels significantly affect current debt. The per capita GDP (GDPP) also shows a negative correlation with public debt, reflecting that higher economic output is associated with a reduction in debt. Foreign Direct Investment (FDI) shows a weak positive correlation with debt, while inflation (INF) also shows a negative correlation, reflecting that high inflation is associated with a reduction in real debt. Government expenditure (GE) shows a moderate positive correlation, indicating that an increase in spending is associated with an increase in public debt. Unemployment (U) is also positively correlated with debt, highlighting that rising unemployment puts pressure on public finances. Military spending (ME) and healthcare spending (HE) show a positive correlation with public debt, indicating that increased spending in these areas contributes to higher levels of debt. Finally, political stability (PS) shows a negative correlation with public debt, indicating that lower political stability is associated with higher debt accumulation.

Current research employs four modeling approaches in its statistical analysis: Pooled OLS, Random effects model (REM), Fixed effects model (FEM), and Generalized moments of methods (GMM). These approaches are commonly used in related analyses of panel data Dawood *et al.* (2021), Ye and Guo (2024), and Ouhibi (2021). However, each model has its limitations, and thus the panel-corrected standard errors model (PCSE) was chosen for all 27 EU countries, considering its advantages in addressing potential issues of heteroscedasticity and autocorrelation in the data.

For all the 27 European countries the analysis started with Pooled OLS, using the data from 2000-2022. On the sampled data was used the Breusch-Pagan/ Cook-Weinsberg and White test, showed p-values of 0.8226, respectively 0.000. Therefore, the OLS model is suitable, but the data shows signs of heteroskedasticity. The multicollinearity test using the variance inflation factors averages all variables at 1.58 with no values above 5, therefore there is no multicollinearity within the dataset. The Breusch and Pagan Lagrangian test that assesses the random effects within the panel shows a *p-value* of 0.0000<0.05, which means that it is appropriate to use REM over OLS within the sample. The Hausman test was used on the data set in order to assess the better fit between REM and FEM. The *p-value* 0.0000< 0.05 concluded that FEM is a better fit. The data was tested using the Breusch-Pagan LM test of independence for cross-sectional dependence and it resulted in a *p-value* of 0.0000<0.05. The Wooldridge and Wald tests both revealed a *p-value* of 0.0000<0.05, therefore the panel data displays signs of heteroskedasticity, autocorrelation, and cross-dependence. Ramsey RESET test for robustness shows a value of 0.0000<0.05. To correct the previous issues, the panel-

corrected standard errors (PCSE) were used due to having the number of observations higher compared to the period of time. Afterwards, the GMM model was used. Table no. 5 illustrates the analysis of pooled OLS models, random effects models (REM), fixed effects models (FEM), panel-corrected standard errors (PCSE), and geometric models. (GMM). Through the Pooled OLS model for all European countries, it was found that deferred debt (L.DEBT) has a significant positive impact on the current public debt, reflecting the continuity of high debt levels from previous periods. In periods of financial crises, such as the global financial crisis and the Eurozone crisis, the unemployment rate (U) significantly affects public debt, as rising unemployment leads to increased government spending on social benefits and a shrinking tax revenue base. Military spending (ME) also has a significant impact, as an increase in defense spending contributes to raising public debt, especially during geopolitical crises such as the Ukraine crisis. Private debt (PD) also has a strong positive impact on public debt, indicating that increased borrowing from the private sector can put pressure on public finances, especially during periods of economic recession. Finally, political stability (PS) affects public debt, as low stability exacerbates the fiscal deficit, especially during times of crisis, leading to a higher accumulation of debt. In the REM model, deferred debt (L.DEBT) plays an important role, reflecting how previous debt levels affect the current debt. During crises such as the global financial crisis and the Eurozone debt crisis, public debt increased significantly due to increased government spending and reduced public revenues. Economic growth affects the per capita GDP (GDPP), which in turn affects the public debt. The inflation rate (INF) also affects the debt through its impact on the real values of the debt and economic stability, which was particularly volatile during the pandemic. Government expenditure (GE) is also a key factor; excessive government spending during crises such as the COVID-19 pandemic and the Ukraine crisis has led to increased levels of debt. The impact of the unemployment rate (U) on public debt was significant, as the rise in unemployment during crises led to increased government spending on social benefits. Spending on healthcare (HE) increased, especially during the COVID-19 pandemic, contributing to the rise in public debt. Private debt (PD) also has a significant impact on public debt. In the FEM model, lagged debt (L.DEBT), per capita GDP (GDPP), inflation rate (INF), government expenditure (GE), unemployment rate (U), healthcare expenditure (HE), private debt (PD), and political stability (PS) are included as factors affecting public debt. (DEBT). In the GMM model, it is shown that lagged debt (L.DEBT) remains a crucial factor, illustrating how previous debt levels continue to affect the current public debt. Economic fluctuations during crises such as the global financial crisis and the Eurozone debt crisis affect GDP per capita (GDPP), which in turn impacts public debt through its effect on government revenues. Foreign direct investment (FDI) also affects public debt, as changes in investment flows can impact economic stability and public finances, especially during periods of global turmoil. Government expenditure (GE) is a key variable, as the increase in spending during the COVID-19 pandemic and the Ukraine crisis has led to higher levels of public debt. The unemployment rate (U) significantly affects public debt, as periods of recession and crises lead to increased unemployment and higher government spending on social benefits. Military spending (ME) also plays a role in increasing public debt, especially during geopolitical conflicts such as the Ukraine crisis. Finally, political stability (PS) affects public debt, as low political stability exacerbates the financial deficit, especially during crises such as the Eurozone debt crisis and the Ukraine crisis, leading to a higher accumulation of debt.

Table no. 4 – Correlation matrix EU27

	(1) Debt	(2) L.debt	(3) Gdpp	(4) Fdi	(5) Inf	(6) Ge	(7) U	(8) Milit	(9) Health	(10) Pd	(11) ps
(1)	1.0000										
(2)	0.8965***	1.0000									
(3)	-0.2549***	-0.2662***	1.0000								
(4)	0.0183*	0.0393*	-0.0002*	1.0000							
(5)	-0.2198***	-0.2222***	0.1923***	-0.0578*	1.0000						
(6)	0.5100***	0.5339***	-0.4434***	-0.1042**	-0.2185***	1.0000					
(7)	0.3203***	0.2177***	-0.0663**	-0.0272*	-0.1249***	0.0738**	1.0000				
(8)	0.2115***	0.1142***	0.0338*	-0.1035***	0.2301***	0.1070***	0.3027***	1.0000			
(9)	0.4840***	0.5456***	-0.3413***	-0.0475*	-0.2565***	0.6745***	-0.1247***	-0.1268***	1.0000		
(10)	0.1189***	0.1238***	-0.2810***	0.1707***	-0.2776***	0.1829***	-0.1665***	-0.3810***	0.3336***	1.0000	
(11)	-0.2494***	-0.2439***	0.1625***	0.0640*	0.2824***	-0.0939**	0.0120*	0.1287***	-0.2517***	-0.1846***	1.0000

Note: *, ** and *** denote significance at 1%, 5% and 10% respectively

Source: processed by the authors

Table no. 5 – P-values showing the statistical significance of considered variables

	Dependent variable GDPP				
Independent Var	**Pooled OLS**	**REM**	**FEM**	**PCSE**	**GMM**
l.debt	41.7594***	36.3463***	35.8408***	35.1954***	46.8747***
	(1.1585)	(1.3992)	(1.4659)	(1.7329)	(6.0817)
Gdpp	0.1295*	0.4343***	0.4381***	0.0099*	-0.3326***
	(0.1702)	(0.1034)	(0.1037)	(0.0456)	(0.0959)
Fdi	-0.0028*	0.0038*	0.0035*	-0.0069*	0.0209***
	(0.0144)	(0.0089)	(0.0089)	(0.0043)	(0.0213)
Inf	0.0079*	0.2800***	0.3080***	0.0073*	-0.2434*
	(0.2094)	(0.1309)	(0.1315)	(0.0832)	(0.0873)
Ge	0.1415*	0.5525***	0.6011***	0.2269***	0.7052***
	(0.1350)	(0.1444)	(0.1481)	(00934)	(0.2812)
U	1.0043***	1.0702***	1.0768***	0.3363***	-1.1382***
	(0.1566)	(0.1269)	(0.1309)	(0.1635)	(0.2492)
Me	8.0148***	-0.0432*	-0.5995*	2.4733**	-13.6094***
	(1.2944)	(1.5756)	(1.6551)	(1.3042)	(3.9086)
He	0.3290*	1.3526***	1.3311***	0.7669**	-0.9088*
	(0.5210)	(0.5529)	(0.5724)	(0.4488)	(0.9837)
Pd	0.0305***	-0404***	-0.0512***	0.0240***	0.0287*
	(0.0092)	(0.0146)	(0.0159)	(0.0120)	(0.0317)
Ps	-55.0093***	-90.3168***	-97.5238***	-21.7506***	43.7578***
	(19.5346)	(16.8614)	(18.1381)	(12.9227)	(17.6816)
_cons	-122.93	-100.10	-96.13	-98.29	-153.16
	(7.1469)	(9.08)	(9.40)	(7.75)	(18.70)
Obs	587	587	587	587	560
F-statistic	297.88	1877.85	176.31	901.44	42122.70
Prob	0.0000	0.0000	0.0000	0.0000	0.000
R^2	0.8380	0.8078	0.8000	0.7716	
Sargan test					0.809
Hansen test					0.435

Note: *, ** and *** denote significance at 1%, 5% and 10% respectively

Source: processed by the authors

5. DISCUSSION AND LIMITATIONS

The empirical findings of our study offer useful insights into the variables and patterns that impact public debt in European Union (EU) nations, especially in light of the continuing challenges related to post-pandemic recovery efforts and the Ukraine war. Current research showed that lagged debt (L.DEBT) has a significant positive effect on current public debt, reflecting the persistence of high debt levels from previous periods, which aligns with the findings of Naveed and Islam (2024). Our results also support Omrane Belguith and Omrane (2017) regarding the notable effects of factors such as inflation and investment on changes in public debt, which are crucial under increasing inflationary pressures and unpredictable investment conditions. Furthermore, current findings highlight the significant impact of government spending on public debt trajectory, as noted by Musah (2023), underscoring the importance of fiscal policies in supporting economic recovery while addressing debt sustainability issues. Our results also align with Manalo *et al.* (2022) concerning the negative relationship between foreign direct investment (FDI) and debt levels, which is significant in the context of current efforts to attract investments amidst global instability. However, the divergence of our results from those of Kijjambu *et al.* (2023) regarding the effect of GDP growth on debt dynamics underscores the need for a thorough examination of economic recovery plans amidst ongoing post-pandemic uncertainty. Additionally, the complexities between inflation rates, GDP growth, and debt levels, as emphasized by Toth *et al.* (2022), suggest the need for flexible policy frameworks to address changing economic conditions. Ngasamiaku and Ngong'ho (2022) provides unique insights into the integration of macroeconomic factors affecting public debt, highlighting the complex nature of debt accumulation and offering valuable recommendations for policymakers aiming for fiscal sustainability in uncertain economic conditions. Pirtea *et al.* (2013) noted the increased endurance of debt-to-GDP ratios following the 2007 global financial crisis, emphasizing the importance of enhancing fiscal resilience in response to economic shocks. Dawood *et al.* (2021) highlighted the importance of economic growth and investment in reducing external debt, providing significant perspectives on managing debt in the current economic environment. On the other hand, Toth *et al.* (2022) emphasized the negative impact of real GDP growth, foreign direct investment, government spending, and inflation on debt levels, highlighting the complexity of managing public debt amidst diverse economic conditions. Vale (2022)examined the relationship between unemployment and public debt, while Khan (2021) revealed regional disparities as another factor affecting public debt, advocating for tailored policy interventions to address different economic contexts. Khan *et al.* (2021) also noted that in Africa, GDP growth and gross capital formation influence public debt, while in Asia, government spending affects public debt, whilst in Latin America and the Caribbean, trade openness determines public debt. Furthermore, Chirwa and Odhiambo (2018) emphasized the immediate benefits of economic growth in reducing debt and the long-term benefits of investment. These insights can assist policymakers in making informed decisions on financial planning and prioritizing investments. Kudła (2018) identified unemployment and foreign direct investment (FDI) as critical determinants of public debt, suggesting that specific interventions are needed to effectively address debt sustainability. Thuan (2018) highlighted the importance of macroeconomic factors in influencing public debt patterns in lower and middle-income countries, offering valuable insights for policymakers in similar economic situations. Finally, Semik and Zimmermann (2022) provided valuable insights into the relationship between economic growth rates and the

reduction of government debt, supporting policymakers in achieving fiscal sustainability amid changing economic conditions.

The current study presents several new variables that have not been extensively explored in previous research. While current analyses have shown that military expenditures (ME) significantly affect public debt, especially in the context of geopolitical crises such as the conflict in Ukraine, this finding indicates the need for further research to understand the broader impacts of defense spending on public finances. Similarly, the significant impact of health expenditures (HE) on public debt, especially during the COVID-19 pandemic, highlights the importance of exploring how increases in health spending contribute to the rise in public debt. The strong positive impact of private debt (PD) on public debt indicates that borrowing in the private sector can put pressure on public finances, especially during periods of economic downturns and financial crises, necessitating a deeper study of the interactions between private and public debts. Moreover, the study results show that political stability (PS) significantly affects public debt, as a decline in stability exacerbates financial imbalances and contributes to the accumulation of public debt, especially during crises such as the conflict in Ukraine and the Eurozone debt crisis.

On the other hand, this study faces some limitations that may affect the interpretation of the results. The study relies on annual data, which may limit our ability to capture rapid changes in public debt and the factors affecting it in the short term. Additionally, the study is limited to analyzing the main economic and political factors without extensively addressing the social and cultural factors that may influence public debt. In the future, the research can be expanded to include quarterly data or individual-level data, as well as examining the impact of social factors such as education and innovation on the sustainability of public debt.

6. CONCLUSION AND POLICY IMPLICATION

This empirical study offers useful insights into the factors and actions that influence public debt in European Union (EU) nations. It presents both confirming evidence and discoveries in comparison to previous research, and it emphasizes that lagged debt (L.DEBT) had a significant positive effect on current public debt, indicating the persistence of debt levels over time. Economic downturns, such as the global financial crisis and the Eurozone crisis, led to increased unemployment (U), which in turn pressured public finances through higher social spending and lower tax revenues. Military expenditure (ME) was also a key driver of rising public debt, particularly during geopolitical tensions, such as the Ukraine conflict. Furthermore, private debt (PD) strained public finances, leading to higher public debt, particularly during periods of economic instability. The study also highlighted the impacts of GDP per capita (GDPP) and inflation rate (INF) on public debt, showing that economic fluctuations and inflation volatility influenced fiscal stability. Government expenditure (GE), particularly during crises such as the COVID-19 pandemic, significantly contributed to debt accumulation. Healthcare expenditure (HE) similarly grew, reflecting the financial burden of managing public health crises. Political stability (PS) was crucial, as reduced stability exacerbated fiscal imbalances, leading to increased debt accumulation during crises. Finally, foreign direct investment (FDI) played a role in public debt dynamics, where shifts in investment flows affected economic stability and government finances, particularly during global disruptions.

The results of this study indicate the necessity of adopting comprehensive financial policies in EU countries to address the multiple factors affecting public debt. It is recommended to enhance long-term financial sustainability by reducing accumulated debt, decrease the fiscal deficit and improve public spending's efficiency. Counter-cyclical measures should be implemented, such as strengthening social safety nets and increasing tax revenues, to mitigate the impact of recession on public finances. It is also essential to carefully manage defense spending to avoid placing an additional burden on public finances during periods of geopolitical tensions and to regulate private borrowing to reduce pressure on public debt during financial crises. Policies that stimulate economic growth should be adopted, such as enhancing per capita GDP and controlling inflation to ensure financial stability, with the necessity of monitoring government spending during crises like the COVID-19 pandemic to avoid debt accumulation. Finally, it is recommended to enhance political stability and attract foreign direct investments to help strengthen economic stability and reduce the impact of global disruptions on public debt.

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Assessing the Quality and Transparency of Financial Audit Reporting in the Context of Gender Differences – Evidence from Companies Listed on the Regulated Market

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Abstract: Analyzing the impact of gender differences in financial auditing has become an important research issue with the aim of promoting equity and fairness within profession, on the one hand, and to determine the impact that gender disparities may have on quality, diversity and innovation in financial auditing, on the other hand. Quality and transparency are important elements that characterize audit reporting as they contribute to providing reliable and relevant information to stakeholders. Including the impact of gender differences in this equation helps to highlight how quality is perceived, as well as to identify associated risks, evaluate the audit process and communicate audit results. The aim of this study is to investigate how the gender of the signatory of the audit report influences the level of quality and transparency of the issued report, the sample including the firms listed on the Regulated Market of the Bucharest Stock Exchange (BSE) that are subject to the audit of annual financial statements for period 2016-2022. Regression and multiple correspondence factor analysis models are applied on 469 observations. The results of this study show that the quality and transparency of reporting in financial auditing are influenced by gender differences, with mixed teams of auditors leading to higher quality of reporting. Obtaining these results underscores the importance of investigating and raising awareness of the impact of gender

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disparities in financial auditing and the need to address this issue with utmost care and objectivity in efforts to promote a fairer and more efficient audit profession.

Keywords: audit quality; audit report; gender differences; key audit matters (KAM); audit opinion.

JEL classification: G19; M10; M40.

1. INTRODUCTION

Today's economic environment is marked by uncertainty in the light of the countless crises affecting it, starting with the COVID 19 pandemic and continuing with the war in Ukraine. These unforeseen situations have brought new challenges to economic entities and raised questions among users of financial information as to the going concern of enterprises. In this situation the role of the financial audit has increased significantly and has become a key point in mitigating the risk that investors face when making decisions, as the role of the auditor is to provide reasonable assurance that the financial statements are transparent, complete and free from material misstatement due to fraud or error (Chen *et al.*, 2014).

The impact of gender differences on different areas of the economy has become an important topic on which many researchers have focused their attention. Although significant progress has been made in reducing gender disparities in some industries and countries, there is still evidence that gender disparities still exist in terms of access to career opportunities, pay, promotion and participation in decision-making in organizations (Hao *et al.*, 2022).

The motivation for this research is the existence of subtle and systematic disparities between men and women in the professional environment, including in the field of financial auditing, despite the progress made in promoting gender equality. These differences could influence how auditors (men and women) perceive and interpret financial information, and how it complies quality criteria when reported and communicated to stakeholders. The aim of this study is to investigate how the gender of the signatory of the audit report influences the level of quality and transparency of the issued report, which is previously assessed by an audit quality assessment model, a model designed based on the literature reviewed. The applied econometric models - regression and multiple correlation factor analysis - facilitate the results of the study, which show us that the quality of financial audit reporting is influenced by gender differences, and that the solution for higher quality of financial audit reporting can be provided by mixed teams of auditors. Therefore, we believe that the present study will make a significant contribution to the understanding and development of financial auditing practices in a way that takes into account the diversity and influence of gender within organizations. This will promote a fair and balanced environment for all financial audit practitioners.

In order to deepen the theoretical knowledge necessary to carry out the study, a number of articles, books and websites were consulted as a basis for the theoretical and methodological research, through Scopus, Web of Science, including Google Scholar databases. For the realization of the practical study, a population of all listed companies (86 companies) on the Regulated Market of the Bucharest Stock Exchange (BSE) that are subject to the audit of annual financial statements in the period 2016-2022 was used. The final sample included 67 listed firms as a result of the refinement performed.

In the following, the study is organized in sections. Section two presents the relevant literature to identify variables that may influence the quality of reporting in financial auditing,

with a focus on gender differences. Section three presents the research methodology in which a financial audit quality assessment model is proposed from the literature to further test the influence of gender differences on financial audit quality. Section four presents the results of the research and section five presents the conclusions of the study.

2. LITERATURE REVIEW AND RESEARCH HYPOTHESIS FORMULATION

The audit profession has emerged and developed over time, hand in hand with the development of accounting, out of the need to meet the information needs of users in terms of ensuring a reasonable level of confidence in the information provided by public interest entities in their annual financial statements. It is for these reasons that the importance of auditing in the capital market has been steadily growing, and the financial market has become a much more dynamic place, with a strong battle for primacy.

The complexity of the financial audit process stems from the new changes in the capital market and in the economic-financial environment, referring to the increased information requirements of users of financial information, changes in legislation, the emergence of new standards, both in the accounting and auditing field (Baker *et al.*, 2014). Also Werner *et al.* (2012) argue that a new challenge for auditors arises from the audit of financial statements that are based on automated transaction processing in ERP systems, as the obstacle arises to efficiently evaluate a large number of process instances that need to be considered (Werner *et al.*, 2012).

Researchers such as Knechel *et al.* (2013) argue that financial auditing has the quality of an economic service, which denotes the complex nature of auditing. This means that the auditor is part of a complex collaborative network of the client and all users of the client's financial information, and the audit process is based on a set of accounting standards in order to provide a true and fair view and representation of all significant economic phenomena. As with any service, the purpose of the audit is to obtain a fee, but unlike other companies, the nature of the service provided by the auditor also includes an element which does not generate direct costs for the client, namely the independence and quality of the audit.

Ifergan and Bescos (2010) argue that the complexity of an audit engagement is influenced by two categories of factors, which can cause errors in professional judgment when not taken into account: subjective factors and objective factors. The first category is related to the auditor (experience in the audited area, skills, adaptability, gender, female or male), while the second category is context-specific (size of the company, risks, accounting and tax legislation, structure of the internal control system). These two categories of factors, working together, make the audit engagement a complex task that requires analytical thinking on the part of the auditor and a sound basis for the opinion expressed in the audit report so that errors of judgment are avoided and audit risk is kept at an acceptable level (Ifergan and Bescos, 2010).

Chung and Monroe (2001) investigated how auditors of different genders perform on a complex task. Thus they showed that men perform better in less complex assignments whereas women perform better in complex assignments (Chung and Monroe, 2001). In addition to this subjective element special attention should be paid to the risks associated with the assignment. Thus, Wallace argues that the auditor must be able to understand the audited entity, explain information systems, and skeptically consider the interplay of inherent risk, control and non-control risk, and combinations of controllable and uncontrollable elements, including human ingenuity (Wallace, 2004).

Thus, among the factors identified in the literature as underlying the opinion expressed by auditors in the reports issued, the gender of the signatory can have significant effects on audit quality. Specifically, gender diversity in audit teams is seen as improving the overall quality of financial reporting (Hardies *et al.*, 2016; Cameran *et al.*, 2018; Kung *et al.*, 2019). It is also important to consider the geographical context, as differences may arise due to country or regional specificities. Previous studies are mainly conducted on developed countries, whereas our study is conducted on companies listed on an emerging market. In order to analyze how the gender of the signatory of the audit report influences the level of quality of the report issued, the literature review further focuses on studies that have assessed quality in financial auditing, which is identified as a dependent variable in the research methodology.

Quality and transparency are fundamental elements that define the work of financial auditing, as they provide a solid basis for ensuring the confidence of capital market participants (Kalita and Tiwari, 2023). Another paper presents the concept of quality from the perspective of market reaction to audit work and states that it is "the market-assessed common probability that a given auditor will discover a violation in the client's accounting system and report the violation" (DeAngelo, 1981). The probability of discovering a violation depends on the auditor's capabilities in terms of competence (Solichin *et al.*, 2022), experience (Jenkins and Velury, 2008), infrastructure, and reporting discovered violations, and reporting discovered violations depends on the auditor's degree of independence from a given client, objectivity (Knechel *et al.*, 2013) and professional skepticism (Herawati *et al.*, 2023).

The literature provides us with a variety of analyses of the elements that influence audit quality, precisely because of the lack of a concrete definition that encompasses all influencing factors. However the most widely used proxies for quantifying audit quality, presented in most of the reviewed studies, include: audit firm size (Francis and Yu, 2009; Alsmady, 2022) and auditor competence (Zahmatkesh and Rezazadeh, 2017; Alsughayer, 2021). Along with these, we find: auditor independence, audit report quality, discretionary engagements, audit fees - NAS report, Ln_tenure, EMP10-49 (Aghaie Ghehie *et al.*, 2022).

Although only a few audit quality measurement proxies have been enumerated, the list is much more comprehensive and constantly extended, taking into account the extensive research in this field. Thus we note the growing interest in studying the impact of gender differences on audit quality and its various components. Kung *et al.* (2019) show that if the audit manager is female, performance management techniques are more limited. Other authors find that the influence of gender disparities on audit quality stems from psychological factors such as prudence, empathy (Nettle, 2007), perfectionism, conscientiousness (Weisberg *et al.*, 2011) and extends to the effect it can have on a person's ability to minimize uncertainty. Thus, Charness and Gneezy (2012) have shown that women are more risk averse compared to men which may influence professional judgment and not least the quality of audit services. In support of this assertion, Garcia-Blandon *et al.* (2019) conducted a research on Spanish firms and concluded that the presence of women in audit teams, especially as audit partner, leads to an increase in the quality of audit services (Garcia-Blandon *et al.*, 2019). In support of these results, it was found that although the audit market is dominated by males (Menezes Montenegro and Bras, 2015), nevertheless, the auditing of financial statements by females contributes to better information processing and increased sensitivity to risk and ethical issues (Hardies *et al.*, 2016; Al-Dhamari and Chandren, 2018). Equally curious is the research of Srinidhi *et al.* (2017) because in their study audit quality increased significantly only when the two audit partners were of different genders; as well as the study of Grosu *et al.* (2022), which shows that female auditors express

an unmodified opinion regardless of the level of discretionary engagements reported, whereas men will issue a qualified opinion which is in contradiction with research that has shown that women are more risk averse (Ittonen *et al.*, 2013) and more cautious.

Transparency is most often seen through the prism of accounting information and less often through financial auditing, and this is demonstrated by the little research that has examined this topic. However, the audit engagement lends itself to the service sphere, and like any organization, both audit offices and individual auditors are influenced to a large extent by the opinion and reaction of stakeholders to the work they do. Transparency, in this case, is intended to provide that sense of confidence and accountability (Parris *et al.*, 2016) that the information provided through the audit report and the work performed by the auditor lends itself to the highest standards.

From an economic perspective, transparency is defined as the extent to which investors have ready access to the necessary financial information about a company, such as price levels, market depth, and audited financial reports (Chen and James, 2021). Under these conditions, through transparent communication, uncertainty is reduced and the information provided by companies becomes more credible. While greater transparency increases the informational usefulness of audited financial reports for investors, it may have a negative effect on the auditor's incentives and, as a consequence, may reduce the expected audit quality and investment efficiency (Chen *et al.*, 2014).

Transparency is intended to increase user confidence in the audit and financial statements (Charron, 2004), which can be achieved by including Key Audit Matters (KAMs) in the auditor's report. KAMs will serve the role of increasing the relevance of the audit report to investors and other users of financial information, while having positive effects on audit quality (IAASB, 2015). According to ISA 701, KAMs are defined as "those matters that, according to the auditor's professional judgment, were of most significance in the audit of the current period's financial statements and were selected from those matters communicated to those charged with governance" (IAASB and IFAC, 2022). The incorporation of KAMs in the auditor's report is intended to reduce the information gap with respect to user requirements and disclosures available through the audit report (Knechel *et al.*, 2015) which would lead to greater transparency in auditors' work.

Gender diversity has been the subject of a number of specialized studies in various fields, including those that have analyzed its impact on the audit report. Thus some of the results have indicated that women tend to be more transparent than men, as they disclose more KAM in audit reports, being more analytical and more concerned with the issue of going concern of the client's business (Grosu *et al.*, 2023), an opinion also supported by Herghiligiu *et al.* (2023). Bédard *et al.* (2024) investigated the influence of gender differences of audit partners on audit results under the adoption of PCAOB Rule 3211 in the public sector, which requires the inclusion of the name of the audit partner in the auditor's report in order to enhance the transparency of the audit. The results of the study show that women are associated with improved audit quality and increased audit fees, as well as better enforcement of Rule 3211 compared to male partners. Hao *et al.* (2022) explained this result by the difficulties that women face in obtaining a certain status in the firm – discrimination, fear of public failure (Hao *et al.*, 2022).

Following the literature review on the impact of gender differences on audit reporting quality and transparency we highlight the following research hypothesis:

***H1**: The quality of financial audit reporting is influenced by gender differences.*

***H2**: Female auditors positively influence the transparency of information presented in financial audit reports.*

3. RESEARCH METHODOLOGY

The present study aims to analyze the impact of gender differences on the quality of audit reporting, and for this purpose, two hypotheses, presented above, have been submitted for validation. In order to deepen the knowledge necessary to carry out the study, a number of articles, books and websites were consulted as a basis for theoretical and methodological research.

In order to carry out the practical study, a population consisting of all listed companies (86 companies) on the Regulated Market of the Bucharest Stock Exchange (BSE) that are subject to the audit of annual financial statements was used. Following a refinement, which eliminated: state-owned institutions, public institutions, holding companies, financial institutions and recently listed companies, for which it was not possible to obtain sufficient data for the 2016-2022 period, a sample of 67 listed companies was obtained, which provides a total of 469 observations. The audit reports of the companies included in the sample, as well as the financial information, which was obtained from the companies' and the BVB's website (www.bvb.ro), are the source of data collection. The methods of analysis consider descriptive statistics, logistic regression and linear regression, applied using SPSS 29.0 software.

Descriptive statistics on the quality variables analyzed are presented in Table no. 1.

Table no. 1 – Descriptive statistics on the analyzed qualitative variables

Variables	Value	Frequency of occurrence
Gender of auditor	Female	38%
	Male	62%
Auditor Type	Big 4 (B4)	30%
	Non-Big 4 (NB4)	70%
Opinion	Op1: Unqualified opinion	75%
	Op2: Qualified opinion	19%
	Op3: Disclaimer of opinion	4%
	Op4: Adverse opinion	2%
SmlProfit/BigProfit	SmlProfit (ROA<3%)	47%
	BigProfit (ROA>3%)	53%
KAM Existence	Nu	13%
	Da	87%
Going Concern	Going-Concern Opinion	27%
	(Non)Going-Concern Opinion	73%

Source: Authors' elaborations

From Table no. 1, it can be seen that the financial audit engagement managers of the companies analyzed are 62% male and 38% female, and 30% of them are part of the Big 4. 70% of them are either only internationally affiliated or are representatives of national audit firms. The opinions expressed by the auditors of the selected companies are mostly unqualified (75%), and the sampled companies have an ROA above 3% for 53% of the companies over the period analyzed. Most of the financial audit reports of the analyzed companies contain a section for KAMs (87%). 13% of them have no KAMs highlighted. For 27% of the sampled companies a going concern opinion was issued and for 73% of the sampled companies there was no mention of going concern in the audit report.

In order to validate the hypotheses under analysis, we have chosen to calculate, in a first step, the audit quality based on the measures proposed by Rajgopal *et al.* (2021) the following model:

$$\text{Qualit}_{\text{A(Big4)}} = \alpha + \beta_1 * \text{SmlProfit} + \beta_2 * \text{LnAT}_{\text{F}} + \beta_3 * \text{Opinion}_{\text{A1}} + \beta_4 * \text{GCO} + \varepsilon \quad (1)$$

where:

α; β1; β2; β3; β4 - are the parameters of the regression model

ε - the random error variable, quantifying the influence of random-acting factors

The explanations of the variables used in the model I are shown in Table no. 2.

Table no. 2 – Presentation of variables for Model I

Variables	Categories	Explanation
$\text{Qualit}_{\text{A(Big4)}}$	Big4 = 1	Big4 Member
	Non Big4 = 0	Not part of the Big4
$\text{Opinion}_{\text{A1}}$	FR = 5 UO	Unqualified opinion
	OR = 4 QO	Qualified opinion
	DO = 3	Disclaimer of opinion
	OC = 2 AO	Adverse opinion
SmlProfit	SmlProfit = 1	If ROA < 3%
	BigProfit = 0	If ROA > 3%
LnAt_F		Log natural logarithm total assets audited firm (Dang *et al.*, 2018)
GCO	GCO = 1	Going-Concern Opinion
	GCO = 0	(Non)Going-Concern Opinion

Source: authors' elaborations

Table no. 2 highlights the variables used, thus the dependent variable (Qualit_A (Big4)) is given by the audit firm's membership in Big4 as it is believed that they would provide audit services of higher quality (Jiang *et al.*, 2019). The independent variables include: auditor's opinion; firm size, calculated as the natural logarithm of total assets; SmlProfit/BigProfit which shows the profitability level of the entity; and GCO (Going Concern Opinion) which indicates whether or not the auditor has issued an opinion on the Going Concern of the client.

The result obtained in the previous equation will form the basis of the final econometric model, being integrated into the dependent variable *Qualit_A*[1], according to the following linear regression equation:

$$\begin{aligned}\text{Qualit\_A}^1 = {} & \alpha + \beta_1 * \text{Gend\_A} + \beta_2 * \text{Impairm\_fA} + \beta_3 * \text{Impairm\_cA} + \beta_4 * \text{DI\_high} + \beta_5 \\ & * \text{Limit\_access\_info} + \beta_6 * \text{Equ\_neg} + \beta_7 * \text{Reorg\_plan} + \beta_8 \\ & * \text{Non\_part\_invent} + \beta_9 * \text{ICS\_ineffic} + \beta_{10} * \text{Classif\_val\_FfA\_rel\_part} \\ & + \beta_{11} * \text{(Non)GCO} + \beta_{12} * \text{Assess\_prod\_prog} + \beta_{13} * \text{Rev\_TA\_IFRS 5} \\ & + \beta_{14} * \text{Recog\_Inc} + \beta_{15} * \text{Recog\_Defer\_Inc\_tax} + \beta_{16} * \text{Litigat\_Provis} \\ & + \beta_{17} * \text{Assess\_REInvest\_JV} + \beta_{18} * \text{LnCA\_F} + \beta_{19} * \text{LEV\_F} + \beta_{20} \\ & * \text{LnAt\_A} + \varepsilon\end{aligned} \quad (2)$$

where:

α; β1; β2; …; β19 - are the parameters of the regression model

ε - the random error variable, quantifying the influence of random-acting factors.

The independent variables used in the model are mostly represented by the types of KAMs as shown in Table no. 3. Some control variables such as the leverage LnAt_A, LnCA_F and LEV_F were also included. The choice of these variables in the model is conditioned by the literature (Carey and Simnett, 2006; Svanström, 2013; Garcia-Blandon *et al.*, 2019) which help to predict a view on audit reporting quality under the influence of gender differences.

Table 3 – Presentation of variables related to Model II

Variables	Categories	Explanation
LnAt_A	-	Natural logarithm of total assets audit firm
LnT_F	-	Natural logarithm of the audited firm's turnover
Gend_A	F = 1	Female
	M = 0	Male
LEV_F	$\frac{Total\ liabilities}{Total\ Assets}$	Financial leverage of the audited firm
KAM	*Impairm_fA*	Impairment of fixed assets
	Impairm_cA	Impairment of current assets
	DI_high	High degree of indebtedness
	Limit_access_info	Limiting access to information/No confirmations
	Equ_neg	Negative equity
	Reorg_plan	Reorganization plan
	Non_part_invent	Non-participation in the inventory - appointment after the closing date of the financial year
	ICS_ineffic	Inefficient internal control system
	Classif_val_FfA_rel_part	FfA (JV)(financial fixed assets) classification and valuation and related party transactions
	(Non)GCO	(Non)Going-Concern Opinion
	Assess_prod_prog	Assessment of production in progress
	Rev_TA_IFRS 5	Revaluation of property, plant and equipment and IFRS 5
	Recog_Inc	Income recognition
	Recog_Defer_Inc_tax	Recognition of receivables/liabilities with deferred corporate income tax
	Litigat_Provis	Litigation and related provisions
	Assess_REInvest_JV	Assessment of real estate investments at JV

Source: authors' elaborations

The categories of KAMs presented are dummy variables that took the value 1 when the characteristics were present in the audit report, with the corresponding mentions made by the auditor, and 0 when the auditor did not mention this element in the section dedicated to the presentation of KAMs. At the time of data collection, 39 key audit matters were identified, hence it was decided to refine the number of occurrences. Thus, those key matters with more than 20 occurrences were taken into account, as well as those KAMs of significant importance (High indebtedness (10 occurrences), Ineffective internal control system (18 occurrences), Limited access to information/Confirmations (19 occurrences); Non participation in inventory - appointment after the year-end (20 occurrences). Concerning the impairment of assets, they have been grouped into two categories according to their nature: impairment of tangible fixed

assets and impairment of current assets. This resulted in a total of 16 key audit matters which were used in the model.

Following the presentation of the methodological data, we turn our attention to the results section, in which the effects obtained by applying econometric models on the dependent and independent variables mentioned above will be examined. The purpose of presenting the research effects is to validate or disprove the hypotheses formulated in order to determine the impact and influence of gender differences in financial auditing. The results obtained will help to establish the quantitative effects of the influence of gender disparities, as well as to develop new impact measurement frameworks by broadening the perspective to a larger sample or to different domains.

4. RESEARCH RESULTS

Using various statistical and econometric models, the relationship between the key research variables (independent variables) and the dependent variable was explored for each of the two models proposed for analysis. In this section we aim to examine the results obtained on the basis of the sample researched, highlighting the estimation coefficients, their statistical significance and the practical implications of the resulting findings. Last, but not least, we aim to provide a profile for understanding the relationships and phenomena studied (the association between auditor gender and reporting quality in financial auditing). Thus we will proceed to calculate the audit quality using a linear regression model according to equation (1), and the obtained values, as a dependent variable, will be the basis for determining the influence of gender differences on audit quality according to equation (2).

Table no. 4 summarizes the model of equation (1).

Table 4 – Summary Model (Model 1)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	ChangeStatistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	0,430[a]	0,185	0,177	0,417	0,185	25,514	4	451	<0,001

Note: a. Predictors: (Constant), GCO, LnAt_F, SmlProfit, Opinion_A1
b. Dependent Variable:Qualit_A (Big4)

Source: authors' elaborations in SPSS 29.0

Table no. 4 shows a moderate correlation between the dependent variable (Calit_A(Big4)) and the independent variables (R = 0.430). The determination ratio (R Square) indicates that the variation in the dependent variable is explained by 18.5% of the variation in the independent variables. The model is validated with a Sig. value for the Fisher test lower than the significance threshold of 0.05.

Table no. 5 provides information on the estimation coefficients in the multiple linear regression model, which allow us to interpret the relationships between the dependent variable and the independent variables used.

Table 5 – Coefficients (Model 2)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1,099	0,285		-3,851	<0,001
	SmlProfit	-0,034	0,042	-0,037	-0,808	0,419
	LnAt_F	0,078	0,011	0,311	7,068	<0,001
	Opinion_A1	-0,003	0,037	-0,004	-,079	0,937
	GCO	-0,251	0,050	-0,244	-4,973	<0,001

Note: a. Dependent Variable: Calit_A(Big4)

Source: authors' elaborations in SPSS 29.0

We note from Table no. 5, that the variables Opinion_A1 and SmlProfit have Student's t-test sig. values above the 0.05 confidence limit (SmlProfit = 0.419; Opinion_A1 = 0.937), which indicates a low influence of these variables on the dependent variable Qualit_A(Big4), but not nonexistent. A significant and positive influence on audit quality is given by the size of the client firm (LnAt_F). When increasing LnAt_F by one unit, the dependent variable will increase on average by 0.078 units, which means that with increasing firm size it is more likely to be audited by a Big4 member firm. According to research in the field (Lopes, 2018), Big4 audit firms are associated with higher quality of the services rendered and implicitly of the report issued, they also increase users' trust in the information provided by the audited firm. This is explained by the standardized and high-performance audit methodologies they use, as well as the adequate quality control reviews of the audit engagement. As for the independent variable GCO (Going Concern Opinion), it is negatively and significantly associated with the audit firm's Big4 membership, indicating that for an increase by one unit, the dependent variable will decrease on average by 0.251 units. When the auditor's opinion refers to GCO, the likelihood of the auditor being a Big4 member is lower compared to cases where the opinion does not refer to non-GCO.

In order to establish the correspondences between the variables SmlProfit, Opinion_A1 and the dependent variable (Qualit_A(Big4)) we extend the analysis using Multiple Correspondence Factor Analysis-MCFA (Figure no. 1).

As can be seen in Figure no. 1, companies with high profits and high efficiency in asset utilization are audited by Big4 member firms, while entities with low profits are associated with Non-Big4 firms. In terms of audit opinion, Big4 member firms tend to express an unqualified opinion to a greater extent than Non-Big4 firms. If we follow the modified opinions (AO - adverse opinion; DO – disclaimer of opinion; QO - qualified opinion) there is no obvious association between these and SmlProfit or the auditor's Big4 membership.

Taking into account that the analyzed sample consists of companies listed on the Main Market of the BSE it is expected that they show an increased interest in their image and stakeholder satisfaction. The larger the size of a company, and the more it is subject to the scrutiny of a wider number of investors, customers, creditors, etc., the more its association with a Big4 auditor will increase the confidence in the information provided and the work performed. On the other hand, there may also be a cost element in this calculation. Businesses with low returns or making losses will prefer to use a non-Big4 auditor because their services are cheaper on the one hand, and on the other hand there will be a tendency to issue an unmodified opinion in the absence of major financial difficulties in order not to lose the client.

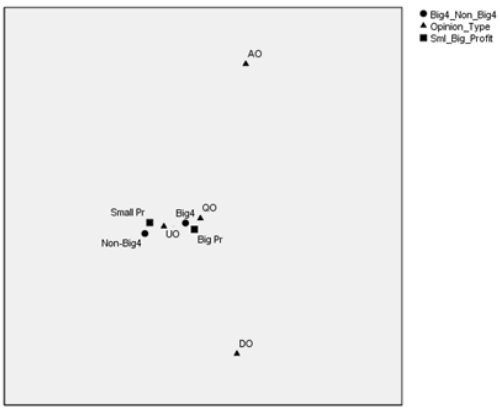

Figure no. 1 – Association between the auditor's opinion, SmlProfit and Big4

Source: Authors' elaborations in SPSS 29.0

The results obtained within model 1, as a result of the application of the computational relationship (1), will constitute the dependent variable for which the influence of the factors will be analyzed, according to the multiple linear regression equation (2). In the following, we aim to validate the hypotheses and the adequacy of the model to the data entered.

Table no. 6 summarizes the performance of the regression model in terms of data fit and prediction of the dependent variable.

Table 6 – Summary Model (Model 2)

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	ChangeStatistics					Durbin-Watson
					R Square Change	F Change	df1	df2	Sig. F Change	
1	0,933[a]	0,870	0,863	0,0733	0,870	138,360	20	415	<0,001	0,695

Note: a. Predictors: (Constant), LnAt.A, Limit_acces_info, Litigat_Provis, Gend_A, Assess_REInvest_JV, Rev_TA_IFRS 5, DI_high, Classif_val_FfA_rel_part, Recog_Inc, ICS_ineffic, Recog_Defer_Inc_tax, LEV_F, Impairm_fA, Impairm_cA, Non_part_invent, Assess_prod_prog, LnCA_F, (Non)GCO, Reorg_plan, Equ_neg
b. Dependent Variable: Qualit_A_H1

Source: authors' elaborations in SPSS 29.0

We find a significant correlation between the independent variables and the dependent variable, which denotes a good fit of the model to the analyzed data. The coefficient of multiple correlation (R) has a value of 0.933, significantly higher than the threshold of 0.750, which confirms the strong correlation between variables. According to the coefficient of determination, 87% of the variation in the dependent variable is explained by the variation in the independent variables.

The standard deviation of the residual errors is very small (Std. Error of the Estimate = 0.0733) and the Durbin-Watson statistic approaches the threshold value of 2 (D-W = 0.695), supporting the claim of the goodness of fit of the model to the sample data used. The model is validated with a Sig. value for the Fisher test less than the significance threshold of 0.05.

Table no. 7 with coefficients presents the influences of the independent variables on the dependent variable and estimates the parameters of the multiple linear regression model.

Table 7 – Coefficients (Model 2)

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.
	B	Std. Error	Beta		
(Constant)	-0,679	0,039		-17,515	<0,001
Gend_A	-0,025	0,008	-0,060	-3,209	0,001
Impairm_fA	0,026	0,009	0,062	3,050	0,002
Impairm_cA	-0,002	0,009	-0,006	-0,268	0,789
DI_high	-0,035	0,030	-0,025	-1,170	0,243
Limit_acces_info	-0,030	0,020	-0,030	-1,502	0,134
Equ_neg	0,013	0,022	0,019	0,591	0,555
Reorg_plan	0,027	0,018	0,038	1,550	0,122
Non_part_invent	0,041	0,020	0,043	2,078	0,038
ICS_ineffic	-0,083	0,021	-0,083	-3,912	<0,001
Classif_val_FfA_rel_part	-0,035	0,012	-0,056	-2,949	0,003
(Non)GCO	-0,202	0,010	-0,461	-19,442	<0,001
Prod_assess_prog	-0,011	0,014	-0,017	-0,759	0,449
Rev_TA_IFRS 5	-0,005	0,012	-0,008	-0,416	0,678
Recog_Inc	-0,029	0,008	-0,074	-3,882	<0,001
Recog_Defer_Inc_tax	0,001	0,012	0,002	0,122	0,903
Litigat_Provis	0,041	0,010	0,078	4,032	<0,001
Assess_REInvest_JV	0,034	0,015	0,041	2,223	0,027
LnCA_F	0,045	0,002	0,477	21,257	<0,001
LEV_F	-0,039	0,010	-0,124	-3,984	<0,001
LnAt.A	0,016	0,002	0,190	7,673	<0,001

Note: a. Dependent Variable: Qualit_A_H1

Source: authors' elaborations in SPSS 29.0

Analyzing the results obtained in Table no. 7, we note a non-significant association, in terms of sig. (greater than 0.05, confidence limit), between audit quality and the following key audit matters (independent variables): impairment of current assets (sig. = 0.789); high debt (sig. = 0.243); limited access to information or non-confirmation (sig. = 0.134); existence of a reorganization plan (sig. = 0.122); evaluation of work in progress (sig. = 0.449); revaluation of tangible fixed assets and IFRS 5 (sig. = 0.678); negative equity (sig. = 0.555) and recognition of deferred income tax liabilities/claims (sig. = 0.903). For the other independent variables we have a statistically significant relationship, with the Student's t-test sig. value being less than 0.05.

In terms of the direction of influence we find that the one-unit upward variation of the 6 independent variables leads to an increase in audit quality in the following form: a) by 0.045 as a result of the influence of LnCA_F; b) by 0.041 under the influence of the variable Litigat_Provis; c) by 0.016 as a result of the influence of LnAt_A; d) by 0.026 under the influence of the variable Impairma_fA; e) by 0.034 as a result of the influence of Eval_REInvest_JV; f) by 0.041 under the influence of the variable Non_part_invent. The positive influence of the 4 key audit matters can be explained in terms of auditor caution. When the client company reports problems with the level of impairment of fixed assets, the way fixed assets are valued, the inability to participate in the annual inventory and the

existence of provisions for litigation, these items will prompt auditors to be more careful, to extend their audit procedures in order to maintain an acceptable level of audit risk. All of this can contribute to a more accurate assessment of the company's financial situation by disclosing material issues in the audit report, which will lead to higher quality audit reporting.

Analyzing the control variables included in the model we notice that the size of the audit firm (measured by the natural logarithm of total assets) is associated with higher audit quality, because in the case of large firms the audit is performed with greater objectivity and independence. For small audit firms there is a greater degree of financial dependence on the client which could contribute to the manipulation of the audit partner and the entire engagement by a representative of the client in order to obtain a favorable opinion on the information reported in the annual financial statements. Large audit firms will try to avoid such situations in order to preserve their reputation, which is their calling card in dealing with stakeholders, a view supported by Martani *et al.* (2021). Customer size (as measured by the level of sales) is also a driver of audit quality. This can be explained by the fact that companies with large turnovers are subject to stricter regulations from the authorities and additional scrutiny from the auditor, who will more accurately and more completely assess their annual financial statements.

In the same formula increasing the 6 independent variables by one unit produces the following decreases in audit quality: (a) by -0.025 due to the influence of Gend_A; (b) by -0.029 due to the influence of the variable Recog_Inc; (c) by -0.039 due to the influence of LEV_F; (d) by -0.083 due to the influence of the variable ICS_ineffec; (e) by -0.202 due to the influence of (Non)GCO; (f) by -0.035 due to the influence of the variable Classif_val_FfA_rel_part.

The negative current asset impairment ratio indicates problems in the management of inventories, receivables and a poorer financial situation of the analyzed company. This can complicate the audit process, as it increases the risk of accounting errors and thus the risk of undetected errors that can lead to wrong estimates by the auditors and thus reduce the quality of audit reporting. The same may also be due to the existence of an ineffective internal control system, which makes it difficult to carry out the audit work, as certain distortions cannot be detected because there is no basis in the ICS. The existence of going concern risk and incorrect revenue recognition may distort the financial statements of the client company. In this case, the auditors have to make an additional effort to review the accounting policies and practices and yet there is no assurance that the information provided in the annual financial statements by the client will be fully reviewed, which will adversely affect the quality of the audit. Financial leverage shows the extent to which debt is used in relation to equity to finance the business. Its negative influence on quality is due to the same additional risks (bankruptcy, manipulation of results, wrong estimates) that arise when financial difficulties arise and which the auditor has to reduce to a tolerable level, but sometimes this is not possible, either because of insufficient audit procedures or because of undetected fraud.

By analyzing the influence of the gender variable, we note that the presence of female auditors as audit partner is not clear whether it leads to increased audit quality, because of the 16 key audit issues included in the model: 8 are not associated with the dependent variable; 4 exert a positive influence on quality, and 4 exert a negative influence.

In order to eliminate this inconsistency, the association between audit quality and auditor's gender was proceeded, after coding the audit quality variable into High and Low, according to the sign obtained from its determination in equation (1) (High>1; Low<1), and the factorial analysis of multiple correspondences presents the results as in Figure no. 2.

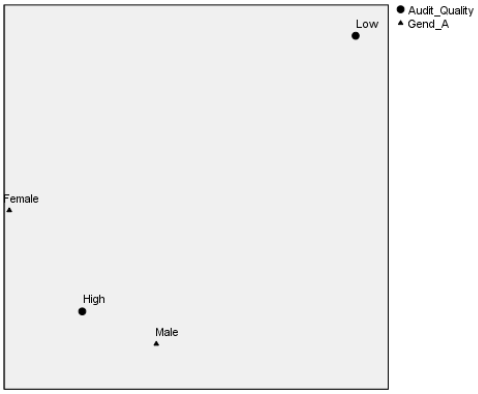

Figure no. 2 – The association between audit quality and auditor gender

Source: authors' elaborations in SPSS 29.0

It is therefore found that, regardless of the gender of the signatory of the audit report, audit quality is on average higher, but with a stronger association with the male side, with low quality depending much less on the gender of the auditor. Under these circumstances, mixed teams of auditors could be the solution to balance the scales in terms of audit quality.

The analysis of the distribution of audit opinion and KAMs by gender can be seen in Table no. 8.

Table no. 8 – Distribution of audit opinion and KAM by gender

Gender	Opinion	Frequency of opinion	Media KAM	No. KAM	Proportion opinion	Proportion KAM
Female	Modified	41	5	222	23,56%	41,04%
	Not modified	133	2	319	76,44%	58,96%
Male	Modified	55	5	302	19,50%	37,28%
	Not modified	227	2	508	80,50%	62,72%

Source: authors' elaborations in SPSS 29.0

Table no. 8 shows that female auditors tend to issue a higher number of modified opinions (23.56%) compared to male audit partners (19.5%), which demonstrates the high level of caution they assume. However, looking at the average number of KAMs reported by the two genders for each type of opinion, we find that on average both male and female auditors report the same number of KAMs, 5 for modified and 2 for unmodified. At a first glance there are no differences in the level of transparency and detail of material information. Referring to the total number of KAMs, we find that women report more key matters in the modified opinion (41.04%) as opposed to men (37.28%). This emphasizes the conservative approach of female auditors and the extra attention to detail.

Although we have two camps of influence of the dependent variable (one positive and the other negative), the impact exerted by the independent variables is not very large, with increases averaging 0.0338 units and decreases averaging -0.0688 units, which means that audit quality is influenced, but not to a large extent, by the signatories of the audit report, asserting once again that joint financial audit teams are the solution for higher audit quality.

However, Hypothesis H2 is validated as female auditors were associated with the issuance of more key audit matters. The results are also in line with other studies (Srinidhi *et al.*, 2017; Chen *et al.*, 2019; Hao *et al.*, 2022).

5. CONCLUSIONS

Through this scientific research has approached a current and interesting topic for the business environment, which aims to analyze the impact of gender disparities on reporting in financial auditing, thus managing to reach the most discussed topics of the current time such as gender equality, quality and transparency in the field of financial auditing. The analysis focused on all companies listed on the regulated market of the Bucharest Stock Exchange, as they are required to be subject to statutory audit of annual financial statements.

Previous academic research has tried to develop various models for calculating audit quality, but has encountered major problems, on the one hand in collecting data on audit documentation, methodology, procedures, which are often not publicly available, and on the other hand in summarizing and taking into account all the defining elements of quality and its influencing factors. We have tried to develop a model, within the limits of the available data, by aggregating a number of variables related to audit quality, as previously researched. Because of this, the results may differ from studies that have measured quality through discretionary engagements. The conclusions reached on the influence of the gender of the auditor on audit quality lead to the idea that mixed teams of male and female auditors are the solution to increase the quality of audit reporting. The results obtained indicate that there are not very large differences between the influence of male auditors on quality and that of female auditors. If we analyze the elements of audit quality separately we notice some differences. First, female auditors were associated with issuing a higher number of key audit matters, which denotes a greater aversion to potential risks, are more cautious and investigate in a more analytical way each item under scrutiny. In analyzing the impact of a number of key audit matters on quality, we found that the influences were both positive and negative. This means that KAMs are not a key determinant of quality, as there are other more significant elements, and this may form the basis for further research.

The study was conducted on companies listed on the regulated market in an emerging market country. Although similar studies have been carried out in other countries, the added insight we have gained is that we have analyzed the situation in a different geographical context and the results can be a benchmark for the audit profession in such a country. In addition, the proposed quality assessment model has been formulated based on the literature, but has been developed to include as many variables as possible that could influence the quality of audit reporting.

This study also has a number of limitations. First, the sample was composed only of companies listed on the main market of the BSE, not including financial institutions and public companies. Given these aspects, the results obtained cannot be externalized or in case of externalization, this should be done with utmost care in order to provide some homogeneity. Secondly, the study uses an individual model to calculate audit quality by combining several elements proposed by academic research (Rajgopal *et al.*, 2021) such as Big 4 membership, SmlProfit etc., which may provide a less exact calculation of audit quality. Future research may attempt to develop a more evolved proxy that would better represent audit quality, such as analyzing audit procedures and documentation in conjunction with audit fees charged.

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Energy Consumption, Economic Growth and CO_2 Emissions: Empirical Evidence for EU Countries

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Abstract: This paper explores the relationship between economic growth, energy consumption (from fossil fuels and renewable sources), and CO_2 emissions in the EU, highlighting the causal relationships between these variables. Through a Panel Vector Autoregressive (VAR) model and statistical test, it is found that fossil fuel consumption has a strong positive effect on CO_2 emissions, while renewable energy has a milder negative effect. Granger causality tests confirm the significant causal relationship between fossil fuel consumption and CO_2 emissions, highlight the positive impact of renewables on economic growth, showcase the link between economic growth and both emissions growth and renewable energy consumption. The findings emphasize the urgent need for a more aggressive shift towards renewable energy and enhanced energy efficiency to meet the EU's climate neutrality objectives. This study contributes critical insights for policymakers, emphasizing the importance of balancing economic growth with environmental sustainability by accelerating the transition to cleaner energy sources.

Keywords: renewable energy consumption; CO_2 emissions; panel vector autoregressive (VAR) model; mitigation.

JEL classification: O13; Q43; O44.

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1. INTRODUCTION

Climate change and its impacts have shown the urgent need to take action in mitigation and adaptation to the new conditions it brings. It is well established that the increase in CO_2 emissions has been directly linked to climate change. The greenhouse effect is the main cause of trapping heat in the Earth's atmosphere, thereby blocking it and leading to global warming. Carbon dioxide is considered the most crucial component in the process. Therefore, the reduction of carbon dioxide emissions is central to worldwide efforts to mitigate climate change (IPCC, 2022). On the other hand, economic growth often relies on high levels of energy consumption, a large proportion of which still comes from fossil fuels such as coal, oil, and natural gas. This dependence has directly led to increased carbon dioxide emissions, thus exacerbating global warming (Campbell and Krol, 2023). The European Union has cut emissions in CO_2 as the center theme of its climate policy, ahead of economic stability and growth (European Commission, 2020). Considering these consequences, the European Union has taken significant steps to mitigate emissions while at the same time still providing significant economic growth.

In particular, the EU has set a target of achieving climate neutrality by 2050 and has committed to a 55% reduction in emissions by 2030 under the European Green Deal (European Commission, 2019). It advocates policies that will reduce emissions, enhance energy efficiency, develop renewable sources of energy, and promote clean technology. The European Climate Law (European Commission, 2020) sets legally bound targets for climate neutrality and emission reduction. In other words, through the laws and projects put forward, the EU Member States decided together that reduction in carbon emissions and sustainable development are among the most important concerns. In any case, this means that economic growth will occur with the aim of striking a balance between growth and Environmental Protection.

In accordance with the literature (Lee, 2019; Pejović *et al.*, 2021), this study focuses on investigating the relationship between energy consumption (fossil fuels and renewables), economic growth (GDP per capita) and CO_2 emissions in EU countries. The analysis of these relationships mentioned above is highly relevant because economic growth, energy consumption, and CO_2 emission reduction are at the core of taking action by states in the process of mitigation of climate change. During the past years, EU officials have issued several legislative initiatives related to the development of renewable energy sources and the reduction of CO_2 emissions, such as the Renewable Energy Directive (European Parliament and Council of the European Union, 2023), the Fit for 55 Package (European Commission, 2021), and the REPowerEU Plan (European Commission, 2022). It is, therefore, necessary to further investigate the causality relationship between these factors, based on prior literature, in order to consider their direction of influence. Some studies, for instance, have suggested that re-examination is in order, including Manta *et al.* (2020), Dritsaki and Dritsaki (2014) and Akadiri *et al.* (2019).

This paper provides empirical evidence on the causal nexus of energy consumption, economic growth, and CO_2 emissions within European Union countries. More specifically, it considers the relationships of causality between different types of energy consumption (from both fossil fuel and renewable source) and CO_2 emissions in the EU. Among the key questions this paper tries to answer are to what extent economic growth directly contributes to the increase in CO_2 emissions, and whether the energy use of both fossil fuels and renewable sources plays a significant role in altering these trends.

Another important part of this analysis consists in investigating the direction of causality between the considered variables. Specifically, the aim is to reveal whether higher economic growth results in higher energy consumption, which increases CO_2 emissions. Furthermore, it examines whether the introduction of renewables is helping to decouple growth from environmental damage. This analysis is highly relevant given the EU's target to reach Climate Neutrality by 2050. The critical question it seeks to answer is whether GDP growth and CO_2 emissions can be decoupled through cleaner energy consumption.

Additionally, the study investigates the impact of renewable energy on emission reductions. It assesses whether the increasing share of renewable energy in the energy mix can offset the negative environmental impacts traditionally associated with fossil fuel consumption. By addressing these research questions, the study contributes valuable insights into possible pathways to sustainable economic growth in the EU, helping policy makers to understand the complex dynamics between energy, growth and environmental sustainability.

This study differs from previous research as it applies the Panel VAR model to an extensive sample of EU countries for the period 2000-2020. Furthermore, this analysis focuses on identifying the causality between economic growth and renewable energy consumption, providing new empirical evidence on whether GDP growth can be achieved in parallel with CO_2 emission reductions.

The paper is organized as follows: Section 2 presents a brief literature review, Section 3 develops the methodology applied for the empirical analyses, Section 4 provides details on the data used, Section 5 presents the results of the empirical analyses and their interpretation, and Section 6 offers conclusions, discussion, and suggestions for future research.

2. LITERATURE REVIEW

Over the years, there has been increased studies by several researchers on how energy consumption and economic growth are directly related to CO_2 emissions. Particularly, the issues of energy consumption and CO_2 emissions are examined in the context of sustainable development, where countries must find ways to mitigate climate change while fostering economic growth. Furthermore, numerous researchers have examined the relationship between energy consumption and economic indicators, analyzing carbon dioxide emissions to test the hypothesis of a causal relationship between these variables. The relationship between energy consumption and economic indicators has been investigated at the country-specific level by researchers including Ozturk and Acaravci (2010), Ozturk and Al-Mulali (2015) and Shahbaz *et al.* (2013). Additionally, some studies enable the comparison of groups of countries, as outlined by Lee (2005), Halilbegović *et al.* (2023) and Sharma *et al.* (2021).

The relationship between energy consumption and economic growth has been a topic of research, with a particular examination of whether there is a causal link between the two. In the context of neoclassical growth theory, for instance, it is proposed that energy constitutes a crucial element in the production process, exerting a direct influence on output (Stern, 2004). However, empirical studies on the topic indicate a degree of inconsistency in the results obtained with regard to the direction of causality, which has given rise to a heightened interest in further exploration. Some studies, such as those conducted by Ozturk and Acaravci (2010) and Akadiri *et al.* (2019), have found evidence to suggest that energy consumption drives economic growth. However, other studies, including those by Shahbaz *et al.* (2013), have

presented arguments that posit a different conclusion, namely that economic growth increases energy demand.

This relationship is of particular importance in the context of the European Union, given that the transition towards climate neutrality requires the overcoming of long-term dependence on fossil fuels, which have historically played a significant role in energy consumption (European Environment Agency, 2022). Research conducted within the European Union has demonstrated the significance of renewable energy sources (RES) in reducing CO_2 emissions and achieving sustainable development goals. As an example, Pejović *et al.* (2021) focus on the utilization of renewable energy sources in the European Union and the Western Balkans. Their findings confirm that an increase in renewable energy usage results in a reduction in CO_2 emissions, thereby contributing to sustainable development. Furthermore, Halilbegović *et al.* (2023) examine the impact of both renewable and non-renewable energy consumption on economic growth in South-Eastern Europe. The findings substantiate the assertion that both types of energy sources have a beneficial impact on economic growth, thereby supporting the view that renewable energy can foster economic growth while simultaneously reducing CO_2 emissions.

In addition, Manta *et al.* (2020) posit that financial growth and CO_2 emissions are mutually reinforcing. The authors present the proposition that governments may implement environmentally focused policies, such as the increased utilization of renewable energy sources and a transition from coal to natural gas as a fuel source, with the objective of reducing energy consumption and CO_2 emissions without negatively impacting economic growth in the short or long term.

Analyzing the nexus of economic growth and CO_2 emission, several studies have taken different theoretical standpoints. Among them, the widely used hypothesis of the Kuznets Environmental Curve posits that with economic growth, initially the degradation of the environment increases, but after reaching an income threshold beyond a certain limit, people start giving priority to environmental quality, leading to a reduction in emissions (Grossman and Krueger, 1995). However, the empirical findings regarding verification of EKC are still not convincing. The EU studies indicate that economic growth has traditionally been related to increased CO_2 emissions, but politico-intervention unveiling has started to decouple growth from emissions in recent years in developed countries (Ozturk and Al-Mulali, 2015; Lee, 2019).

The European Union's policy measures to reduce CO_2 emissions, such as carbon pricing, emissions trading schemes, and promoting renewable energy, have reshaped the trend of emissions. Research by Dritsaki and Dritsaki (2014) points out that the progress in separating economic growth from emissions has varied among member states, with outcomes influenced by each country's energy resources and industrial structure.

Many studies in the current literature do not analyze energy consumption as a whole but instead look at renewable and non-renewable energy separately. Despite strong efforts to shift towards renewable energy, fossil fuels continue to be a major energy source in the EU. Numerous studies, including those by Shahbaz *et al.* (2013) and Rahman and Velayutham (2020), have confirmed a strong positive link between fossil fuel use and CO_2 emissions. Research by Ozturk and Acaravci (2010) further shows that increased fossil fuel consumption directly drives higher CO_2 emissions, worsening the EU's climate challenges. This trend aligns with global patterns showing a connection between higher fossil fuel consumption and greater environmental damage (Sharma *et al.*, 2021).

In contrast, studies indicate that renewable energy sources significantly lower CO_2 emissions, though their economic benefits are not always clear-cut. Rahman and Velayutham (2020) found that while renewable energy does contribute to economic growth, its impact tends to be smaller compared to fossil fuels. This suggests that renewables still represent a smaller portion of the overall energy mix. Additionally, Sharma *et al.* (2021) note that although renewable energy reduces emissions, the extent of this impact varies depending on the technology used and the region.

While most studies have focused on the separate analyses of renewable and non-renewable energy sources, this study contributes to the existing literature by determining their interaction and deriving the overall impact on economic growth and CO_2 emissions. This approach allows for a more holistic understanding of the energy transition in the EU.

3. DATA

The data used in this research is annual for the period from 2000 to 2020 and includes the variables: CO_2 emissions (metric tons per capita), GDP per capita (in constant 2015 US dollars), consumption of renewable energy, and fossil fuels per capita. The data has been transformed to a logarithmic scale. The description of the variables and the data sources are presented in Table no. 1.

Table no. 1 – Variables description and source

Variable label	Description	Source
CO_2 Emissions	Carbon dioxide emissions are those stemming from the burning of fossil fuels and the manufacture of cement. They include carbon dioxide produced during consumption of solid, liquid, and gas fuels and gas flaring.	World Bank (2023)
GDP per capita (constant 2015 US dollar)	GDP per capita is gross domestic product divided by midyear population. GDP is the sum of gross value added by all resident producers in the economy plus any product taxes and minus any subsidies not included in the value of the products. It is calculated without making deductions for depreciation of fabricated assets or for depletion and degradation of natural resources. Data are in constant 2015 U.S. dollars.	World Bank (2023)
Renewables consumption per capita	Measured in kilowatt-hours of primary energy per person, using the substitution method. The category of renewables encompasses hydropower, wind, solar, geothermal, wave and tidal energy, and bioenergy, excluding traditional biofuels.	Energy Institute (2024)
Fossil fuel consumption per capita	Fossil fuel consumption per capita is measured as the average consumption of energy from coal, oil and gas, in kilowatt-hours per person.	Our World in Data (2023)

Source: authors' construct

Table no. 2 presents the descriptive statistics of the variables used in the analysis (CO_2 emissions, GDP per capita, fossil fuel consumption per capita, renewable energy consumption per capita). The number of observations, mean, standard deviation and the maximum and minimum value obtained for each variable are shown in the table. The total number of observations for each variable is 525. The initial goal of the analysis was to include all EU27

countries. However, due to a lack of available energy consumption data, Cyprus and Malta were excluded.

We observe that CO_2 emissions have a mean value of 7.628 and a relatively high standard deviation (3.602), suggesting significant variability between countries or over time. In terms of GDP per capita, it shows large variations which are strongly indicated by the minimum and maximum values (3.72 to 112.41) suggesting that the dataset includes countries at very different stages of economic development. Fossil fuel consumption shows a wide range, reflecting the different dependence of countries on fossil fuels, while renewable energy consumption per capita has a lower average (5.21) but also shows significant variation (6.626 minimum value to 30.217maximum value) which highlights the different energy profiles in the sample.

Table no. 2 – Descriptive statistics

Variable	Obs.	Mean	Std. dev.	Min	Max
CO_2 emissions	525	7.628	3.602	2.927	25.61
GDP per capita (constant 2015 US dollar)	525	29565.52	21517.56	3721.051	112417.9
Fossil fuel consumption per capita	525	32993.59	16497.35	12289.74	111848.4
Renewables consumption per capita	525	5216.57	5710.68	66.26	30217.09

Source: authors' construct

For a better understanding of the sizes of the variables used in the analysis, Figures no. 1, no. 2 and no. 3 are needed. These figures show the trends of the main variables of the analysis (CO_2 emissions, GDP per capita, renewable and fossil fuel consumption per capita) or possible changes in the behavior of the variables over time.

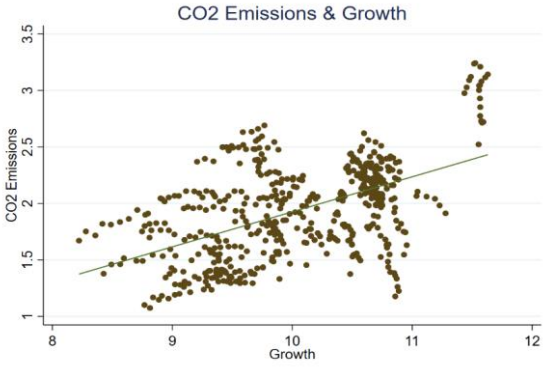

Figure 1 – Relationship between CO_2 Emissions and Economic Growth

Figure no. 1 shows the data for the variables CO_2 emissions and GDP per capita. The regression line shows the linear relationship between growth and CO_2 emissions. The fact that the line is positively sloped suggests that as growth increases CO_2 emissions tend to increase as well. Although there is a general trend for CO_2 emissions to increase with growth, it appears that the data are highly scattered and probably suggests that growth does not fully explain CO_2 emissions. There are obviously other factors that influence CO_2 emissions.

Figure no. 2 shows the relationship between CO_2 emissions and renewable energy consumption. The regression line shows a slightly negative slope, indicating that there is a

weak negative relationship between renewable energy and CO_2 emissions. In other words, as renewable energy consumption increases, CO_2 emissions tend to decrease, but the relationship is not very strong. Furthermore, there is a large variation in the data, which means that renewable energy is not the only factor affecting CO_2 emissions.

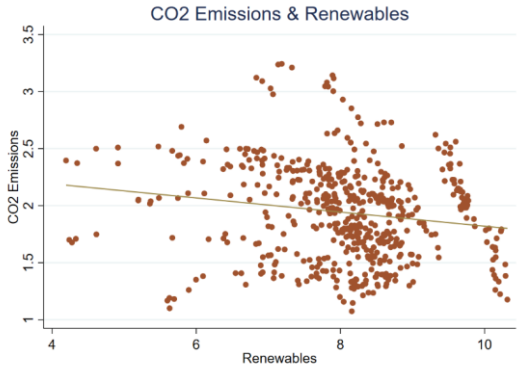

Figure 2 – Relationship Between CO_2 Emissions and Renewable Energy Consumption

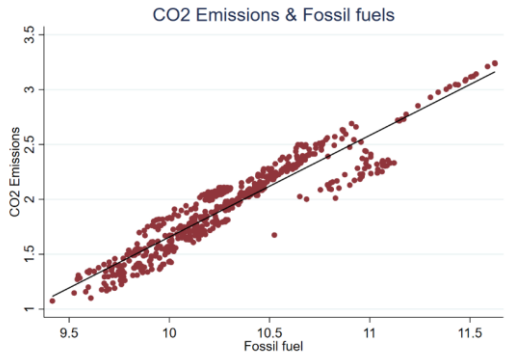

Figure 3 – Relationship Between CO_2 Emissions and Fossil Fuel Energy Consumption

Figure no. 3 illustrates the relationship between CO_2 emissions and fossil fuel use. We observe that there is a positive trend indicating a strong positive correlation between fossil fuel use and CO_2 emissions. This means that as fossil fuel use increases, CO_2 emissions also increase at a steady rate.

4. METHODOLOGY

The methodology of the study was based on the Panel VAR (Vector Autoregressive VAR) model and the analysis of the causal relationship between CO_2 emissions, GDP per capita, renewable energy consumption per capita and fossil fuel consumption per capita. In particular, this model was chosen to investigate the dynamic relationships between multiple endogenous variables. Panel VAR enables these interactions to be studied without requiring

the assumption of unidirectional causality, thus allowing for a more comprehensive understanding of the complex relationships that develop between the variables being examined. Prior to the application of the basic Panel VAR Model, panel-appropriate tests were carried out and a panel regression was performed to show simple correlations of the variables.

4.1 Panel Regression

Before estimating the main model, we conducted a simple panel regression estimation, which is defined as follows:

$$CO_2\ Emissions_{it} = \alpha + \beta_1 GDP\ per\ capita_{it} + \beta_2 Renewables\ consumption\ per\ capita_{it} + \beta_3 Fossil\ fuel\ consumption\ per\ capita_{it} + \varepsilon_{it} \quad (1)$$

where:

- $CO_2\ Emissions_{it}$ is the dependent variable representing CO_2 Emissions for observation i at time t,
- $GDP\ per\ capita_{it}$ is GDP per capita (in constant 2015 US dollars),
- $Renewables\ consumption\ per\ capita_{it}$ is the renewables consumption per capita,
- $Fossil\ fuel\ consumption\ per\ capita_{it}$ is the fossil fuel consumption per capita in 2023,
- α is the constant term of the model,
- $\beta_1,\ \beta_2, \beta_3,$ are the coefficients representing the effect of each independent variable on the dependent variable,
- ε_{it} is the error term.

The theoretical background of the tests, the results of which are presented in the next section, is outlined below.

4.2 Cross-Sectional Dependence Tests

Cross-sectional dependence on panel data is an important issue that can affect the validity of estimates. When residuals from one cross section are related to those of other cross sections, conventional estimates may lead to biased estimates and erroneous conclusions (Pesaran, 2004). For this reason, it is necessary to carry out cross-sectoral dependency tests so that, based on the results, the necessary actions can be taken in subsequent analyses. To test intersectional dependence, we performed four Tests which are represented below:

4.2.1 Pesaran's Test for Cross-Sectional Dependence

Pesaran (2004) test is based on the average of the correlations between the cross-sectional residuals. It is suitable for large panels where the time (T) is significantly greater than the number of cross sections (N). The statistic test is calculated as follows:

$$P_{test} = \sqrt{\frac{2T}{N(N-1)}}\left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \quad (2)$$

where T is the time dimension, N is the number of sections, $\hat{\rho}_{ij}$ is the correlation of residuals between sections i and j. It is proved that under the null hypothesis of no cross-sectional dependence, P_{test} approaches the normal distribution N(0,1) for N→∞ and for sufficiently large T (De Hoyos and Sarafidis, 2006).

4.2.2 Breusch-Pagan LM Test

The Breusch-Pagan LM test (1980) proposed a Lagrange Multiplier (LM) statistic for detecting inter-layer dependence in order to examine the correlation of errors (residuals) between different layered units in a panel of data. The LM statistic follows an asymptotic χ^2 distribution and is mainly used when T (the number of time observations) is significantly larger than N (the number of stratified units). The LM test is particularly useful for testing correlation errors, as its existence can cause problems with the reliability of the estimates. The test is expressed by the following equation:

$$LM_{BP} = T * \left(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{\rho}_{ij}\right) \quad (3)$$

where $\hat{\rho}_{ij}$ is the sample estimate of the pairwise correlation of the residuals:

$$\hat{\rho}_{ij} = \hat{\rho}_{ji} = \frac{\sum_{t=1}^{T}\hat{u}_{it}\hat{u}_{jt})}{(\sum_{t=1}^{T}\hat{u}_{it}{}^{2})^{\frac{1}{2}}(\sum_{t=1}^{T}\hat{u}_{jt}{}^{2})^{\frac{1}{2}}} \quad (4)$$

where $\hat{u}_{it}$ is the estimate of the main model. The null hypothesis is that there is no dependence between sections and it is rejected if the LM statistic is significant, indicating the existence of dependence (Breusch and Pagan, 1980; De Hoyos and Sarafidis, 2006).

4.2.3 Friedman's Test

The test of Friedman (1937) is often used when there is a hypothesis of cross-sectional dependence. More specifically, the test proposed by Friedman is a non-parametric test based on the correlation coefficient of Spearman rankings. The Spearman correlation coefficient is obtained from the equation:

$$\hat{r}_{ij} = \hat{r}_{ji} = \frac{\sum_{t=1}^{T}(\hat{r}_{i,t} - \frac{T+1}{2})\,(\hat{r}_{j,t} - \frac{T+1}{2})}{\sum_{t=1}^{T}(\hat{r}_{i,t} - \frac{T+1}{2})^{2}} \quad (5)$$

Friedman's test is based on Spearman's mean correlation and is given by the equation:

$$R_{ave} = \frac{2}{N(N-1)}\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\hat{r}_{ij} \quad (6)$$

where $\hat{r}_{ij}$ is the estimated correlation coefficient and large values of R_{ave} indicate the existence of non-zero cross-sectional correlations. Friedman showed that:

$$FR_{test} = (T-1)\{(N-1)R_{ave}^2 + 1\} \quad (7)$$

asymptotically follows the x^2 distribution with $T-1$ degrees of freedom, for constant T as N increases (Friedman, 1937; De Hoyos and Sarafidis, 2006).

4.2.4 Frees' Test

The Free's test (1995), takes into account common characteristics of real data, such as heteroscedasticity and non-normality. Specifically, Free's test is based on the sum of the squares of the correlation coefficients of scores and is given by the equation:

$$R_{ave}^2 = \frac{2}{N(N-1)} \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} \hat{r}_{ij}^{\,2} \quad (8)$$

where N is the number of cross-sectional units, $\hat{r}_{ij}$ is the rank correlation coefficient between the residuals of the i and j cross-sectional units.

$$F_{test} = N\{R_{ave}^2 - (T-1)^{-1}\} \xrightarrow{d} Q = a(T)\{x_{1,T-1}^2 - (T-1)\} + b(T)\{x_{2,T(T-3)/2}^2 - T(T-3)/2\} \quad (9)$$

where $x_{1,T-1}^2$ and $x_{2,\frac{T(T-3)}{2}}^2$ are independently x^2 random variables with $T-1$ and $\frac{T(T-3)}{2}$ degrees of freedom, respectively, $a(T) = \frac{4(T+2)}{5(T-1)^2(T+1)}$ and $b(T) = \frac{2(5T+6)}{5T(T-1)(T+1)}$. Thus thenull hypothesis is rejected if $R_{ave}^2 > (T-1)^{-1} + \frac{Q_q}{N}$, where Q_q is the appropriate quantile of the Q distribution.

4.3 Unit root tests

Applying a panel VAR model, is necessary that the variables are stationary and for this reason unit root tests are performed. In our analysis, we performed both first- and second-generation unit root tests, taking cross-sectional dependence into account. The methods we used are Levin-Lin-Chu (LLC) and Im-Pesaran-Shin (IPS) tests for the first generation and Pesaran's CADF and CIPS for the second generation.

4.3.1 Levin-Lin-Chu (LLC) Test

The Levin-Lin-Chu test (2002) is based on the assumption that the autoregressive coefficient, ρ, is common across all cross-sectional units. The equation of the test can be expressed as:

$$\Delta_{y_{it}} = \varphi_{y_{i,t-1}} + z'_{it}\,\gamma_i + \sum_{j=1}^{p} \vartheta_{ij} \Delta_{y_{i,t-j}} + \varepsilon_{it} \quad (10)$$

where y_{it} is the variable under control, $\Delta_{y_{it}}$ is the first difference of the variable, φ is the common coefficient that determines whether a unit root exists, $z'_{it}\,\gamma_i$ are the panel-specific features, which include constants and trends, ϑ_{ij} are the coefficients of the lagged first differences, and ε_{it} is the white noise term. The null hypothesis of the test is that a unit root exists, meaning the series is not stationary. If the value of the test statistic is significant, the null hypothesis is rejected in favor of stationarity.

4.3.2 Im-Pesaran-Shin (IPS) Test

The Im-Pesaran-Shin (IPS) test (2003) allows for differentiation in the autoregressive coefficient χ between panels, in contrast to the Levin-Lin-Chu test which assumes a common coefficient. The IPS test tests for the existence of a unit root in the panel data and is based on separate Dickey-Fuller (ADF) regressions for each panel. The basic equation for each cross section i is as follows:

$$\Delta_{y_{it}} = \varphi_i y_{i,t-1} + z'_{it}\,\gamma_i + \varepsilon_{it} \quad (11)$$

where y_{it} is the variable under control, $\Delta_{y_{it}}$ is the first difference of the variable, φ_i is the panel-specific coefficient, which determines whether there is a unit root, $z'_{it}\,\gamma_i$ includes constants and trends and ε_{it} is the noise term.

The IPS test allows for heterogeneity in the coefficients φ_i between cross sections. This test calculates the average of the t-statistics from the ADF regressions for each cross-section and then tests whether this average deviates significantly from zero. If the value is sufficiently small, then the null hypothesis that all series contain a unit root is rejected.

4.3.3 Cross-sectionally Augmented Dickey-Fuller (CADF) test

The CADF test (Pesaran, 2007) is a second-generation test that takes into account cross-sectional dependence in panel data. This test adapts the traditional Dickey-Fuller test by incorporating a common term for cross-sectional dependence. The model equation used is as follows:

$$\Delta_{y_{it}} = \alpha_i + \gamma y_{i,t-1} + \delta \bar{y}_{t-1} + \sum_{j=1}^{p} \vartheta_j \Delta_{y_{i,t-j}} + \varepsilon_{it} \quad (12)$$

where $\Delta_{y_{it}}$ is the first difference of the variable y , $\alpha_i$is the constant for each cross-section, $\gamma$is the coefficient of the lag of the variable $y_{i,t-j}$,t- , $\Delta_{y_{i,t-j}}$ is the average of the y values for all cross-sections at $t-1$, $\sum_{j=1}^{p} \vartheta_j \Delta_{y_{i,t-j}}$ are the lagged differences of the variable and ϵit is the error term.

CADF takes into account the interactions between the cross-sections through the $\bar{y}_{t-1}$ which represents the cross-sectional averages. The null hypothesis (H_0) is that there is a unit root, while the alternative hypothesis (H_1) is that the series are stationary.

4.3.4 Cross-sectionally Augmented IPS (CIPS) test

Pesaran's Cross-sectionally Augmented IPS (CIPS) Test is an extension of the IPS test that takes into account cross-sectional dependence. Unlike traditional first-generation tests, CIPS adjusts the IPS statistic by including cross-sectional averages of lagged levels. The equation of the CIPS test is:

$$CIPS = \frac{1}{N}\sum_{i=1}^{N} CADF_i \tag{13}$$

where $CADF_i$ is the CADF statistic for each cross-section. The CIPS test is ideal for panel data with a large number of cross-sections (N) and a relatively small number of time observations (T), and takes into account cross-sectional dependence, which makes it suitable for panels with cross-sectional dependence.

4.4 Panel Vector Autoregressive (VAR) model

The key empirical results of this paper were obtained using the main panel VAR model. This model allows simultaneous analysis of different endogenous variables and the study of their interactions. The specification of a basic VAR model can be described by the following equations:

$$Y_{it} = \alpha_1 + \sum_{p=1}^{P} \beta_{1p} Y_{i,t-p} + \sum_{p=1}^{P} \gamma_{1p} X_{i,t-p} + \varepsilon_{it}^{(Y)} \tag{14}$$

$$X_{it} = \alpha_2 + \sum_{p=1}^{P} \beta_{2p} Y_{i,t-p} + \sum_{p=1}^{P} \gamma_{2p} X_{i,t-p} + \varepsilon_{it}^{(X)} \tag{15}$$

where:

- Y_{it} and X_{it} are the endogenous variables for observation i at time t,
- α_1 and α_2 are the constant terms of the equations,
- β_{1p} and β_{2p} are the coefficients of the lags of the variables Y_{it} and X_{it},
- γ_{1p} and γ_{2p} are the coefficients of the lags of the variables Y_{it} and X_{it} respectively,
- P is the number of lags included in the model,
- $\varepsilon_{it}^{(Y)}$ and $\varepsilon_{it}^{(X)}$ are the error terms of the equations.

5. EMPIRICAL RESULTS

The results of the analysis are presented in the tables below. In the first stage a panel regression considers seeing the correlations between the variables. In the panel regression the variables were used in logarithmic form to see the percentage variables. In more detail, the results of the regression are presented in Table no. 3. The results for GDP per capita show that a 1% increase in GDP per capita increases CO_2 emissions by 0.028%, however this variable is not statistically significant. For fossil fuel energy consumption per capita it appears that a 1% increase in renewable energy consumption per capita is associated with a 1.036% increase in CO_2 emissions (statistically significant at the 1% level). Finally, with respect to renewable energy consumption per capita, a 1% increase in fossil fuel consumption per capita is associated with a 0.038% decrease in CO_2 emissions (statistically significant at the 1% level). The model, according to the R^2 result, explains 88.1% of the variation in CO_2 emissions, indicating a good fit.

Table no. 3 – Regression Results (Fixed effect model with robust std errors)

Variable	CO_2 Emissions
GDP per capita (constant 2015 US dollar)	0.028
	(0.025)
Fossil fuel consumption per capita	1.036***
	(0.027)
Renewables consumption per capita	-0.038***
	(0.006)
Constant	-8.711***
	(0.236)
Number of observations	525
R^2	0.881

Notes: * significant at 10%; ** significant at 5%; *** significant at 1%; standard errors in parentheses
Source: authors' calculations

Subsequent to the analysis it was considered necessary to test for cross-sectoral dependence. In panel data it is common for observations to be independent of each other, i.e. changes in one cross-section may affect the others. The existence of cross-sectional dependence indicates that alternative estimation methods (e.g. standard error correction or models that take cross-sectional dependence into account) may need to be applied. As cross-sectional dependence can lead to inaccurate estimates, we have made the necessary tests to identify and account for it.

The tests performed are Pesaran's test, Breusch-Pagan LM, Frees' test and Friedman's test are specifically designed for different situations and assumptions about the distribution of the data. The results of the cross-sectional dependence tests are presented in Table no. 4. We observe that cross-sectional dependence exists in all variables and the results are significant at the 1% level of significance.

Table no. 4 – Cross-sectional independence tests

Test	Statistic
Pesaran's test	12.038***
Breusch-Pagan LM	904.641***
Frees' test	2.150***
Friedman's	86.722***

Source: authors' calculations

Since after the above tests it was shown that there is cross-sectoral dependence, we proceeded to unit root tests. Due to the cross-sectional dependence, it was considered necessary to carry out both first- and second-generation unit root tests. The difference between first- and second-generation tests is that first generation tests assume that there is no cross-sectional dependence between observations, while second generation tests allow and often correct for cross-sectional dependence.

The results of the unit root tests in Table no. 5 show that all variables (CO2 Emissions, GDP per capita, Fossil fuel consumption per capita, Renewables consumption per capita) are stationary at the first differences and do not have a unit root, according to the results of both the first- and second-generation tests. The results are statistically significant at the 1% level, as indicated by asterisks.

Table no. 5 – Unit root tests

	First generation		Second generation	
Variables	**Levin–Lin–Chu**	**Im–Pesaran–Shin**	**Pesaran's CADF test**	**Pesaran's CIPS test**
CO_2 Emissions	-4.017***	-9.229***	-8.383***	-4.406***
GDP per capita (constant 2015 US dollar)	-3.775***	-5.566***	-2.741***	-2.88***
Fossil fuel consumption per capita	-3.262***	-9.334***	-9.912***	-4.814***
Renewables consumption per capita	-10.886***	-11.497***	-9.302***	-4.611***

Source: authors' calculations

After the unit root tests and since all variables are stationary at the level of first differences, we proceeded to apply the main model. More specifically, we run a model VAR panel to look at the interactions between variable CO_2 emissions, GDP per capita, renewable consumption per capita, and fossil fuel consumption per capita. The results of the model are shown in Table no. 6. We observe how CO_2 emissions are negatively affected by their past emissions, but positively by fossil fuel consumption. In addition, CO_2 emissions are negatively affected by their past emissions, but positively by fossil fuel consumption. GDP per capita has a positive and significant effect on CO_2 emissions and renewable consumption, but a negative effect on fossil fuels. Finally, renewable consumption appears to have little effect on the remaining variables, while fossil fuel consumption leads to an increase in CO_2 emissions.

Table no. 6 – Panel Var Model

	CO_2 Emissions	GDP per capita	Renewables consumption per capita	Fossil fuel consumption per capita
L1. CO_2 Emissions	-0.749**	-0.047	-0.389*	0.898**
	(0.298)	(0.107)	(0.210)	(0.445)
L2. CO_2 Emissions	-0.813**	-0.356***	-0.495*	0.504
	(0.346)	(0.125)	(0.263)	(0.465)
L1. GDP per capita	0.719***	0.728***	0.628***	-1.025**
	(0.236)	(0.143)	(0.192)	(0.421)
L2. GDP per capita	0.495***	-0.015	0.423***	0.971***
	(0.165)	(0.110)	(0.140)	(0.339)
L1. Renewables consumption per capita	0.413	-0.023	0.074	-0.650
	(0.284)	(0.114)	(0.220)	(0.459)
L2. Renewables consumption per capita	0.463	0.329**	0.217	-0.327
	(0.319)	(0.135)	(0.258)	(0.477)
L1. Fossil fuel consumption per capita	0.075**	0.021*	0.053**	-0.013
	(0.034)	(0.012)	(0.024)	(0.085)
L1. Fossil fuel consumption per capita	0.055**	0.007	0.038*	-0.110*
	(0.028)	(0.011)	(0.021)	(0.058)
Observations	425	425	425	425

Notes: * significant at 10%; ** significant at 5%; *** significant at 1%; standard errors in parentheses
Source: authors' calculations

For a better understanding of the results, performed the extraction of graphical representations of the impulse responses of each variable (CO_2 emissions, GDP, fossil fuel and renewable energy consumption) to possible shocks, using a Panel VAR system over time. The representations of these impulse responses are shown in Figure no. 4.

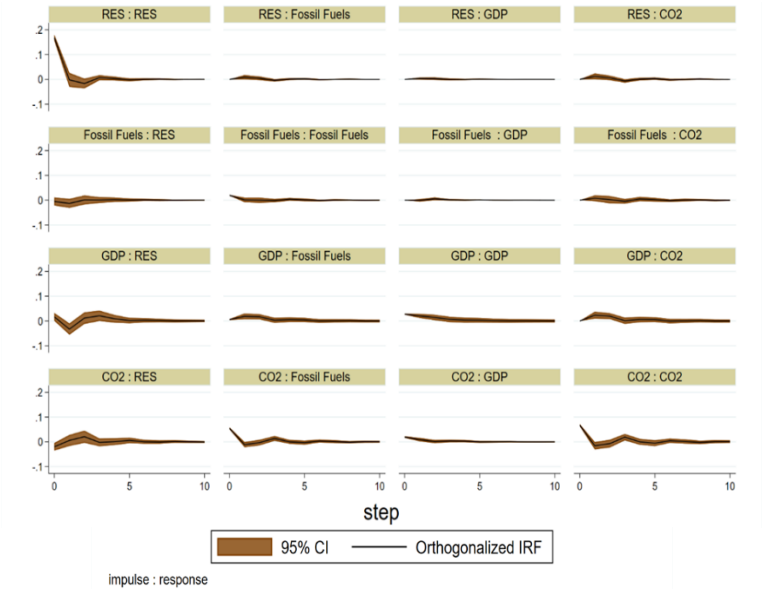

Figure 4 – Impulse Response Functions (IRFs) derived from the Panel VAR model
Source: authors' calculations

More specifically, Figure no. 4 shows that a shock to renewable energy consumption directly and negatively affects fossil fuel consumption, suggesting that an increase in renewable energy use leads to a reduction in fossil fuel dependence. Also, the effect on CO_2 emissions from increased renewable energy consumption is relatively mild, indicating that renewables do not affect emissions as strongly as fossil fuels.

In contrast, fossil fuel consumption causes a significant increase in CO_2 emissions. While the effect on economic growth (GDP) is small, it reveals that fossil fuel consumption is related to economic activity. In terms of GDP, the shock to CO_2 emissions appears to have a positive but weak effect, while the relationship with renewable energy shows little response. Finally, it is observed that a shock to CO_2 emissions has a negative effect on renewable energy consumption, but no significant effect on other variables such as GDP per capita or fossil fuel consumption.

Table no. 7 presents the results of the Wald test for Granger causality testing and examines whether one variable can predict the other. In more detail, we see that important Granger causalities are observed between CO_2 emissions and GDP, fossil fuel consumption and GDP, as well as between CO_2 and renewable energy sources. Fossil fuel consumption significantly affects CO_2 emissions, GDP and renewable sources. CO_2 affects renewable sources and all variables overall and finally renewable consumption affects GDP and all variables overall.

Table no. 7 – Panel VAR-Granger causality Wald test

	X^2		X^2
CO_2 → GDP	18.540***	Fossil → CO_2	5.344*
CO_2 → Fossil	4.080	Fossil → GDP	21.671***
CO_2 → Renewables	6.021**	Fossil → Renewables	5.975**
CO_2 → All	25.248***	Fossil → All	27.519***
GDP → CO_2	8.753**	Renewables → CO_2	4.089
GDP → Fossil	7.143**	Renewables → GDP	12.707***
GDP → Renewables	2.994	Renewables → Fossil	2.051
GDP → All	10.652	Renewables → All	19.343***

Notes: * significant at 10%; ** significant at 5%; *** significant at 1%

Source: authors' calculations

Ensuring the stability of the panel VAR model used to analyze the relationship between CO_2 emissions, GDP per capita and energy consumption (both fossil fuels and renewables) is the focus of the eigenvalue stability condition in Figure no. 5.

Stability is crucial for interpreting impulse response functions (IRFs), which show how variables such as CO_2 emissions react over time to shocks in energy consumption or economic growth. If the model was not stable, these IRF's would not return to their initial value, leading to possibly misleading conclusions about the long-term effects of these shocks. The eigenvalue stability results in Figure no. 5 confirm that the model is stable, allowing valid conclusions to be drawn from the empirical analysis.

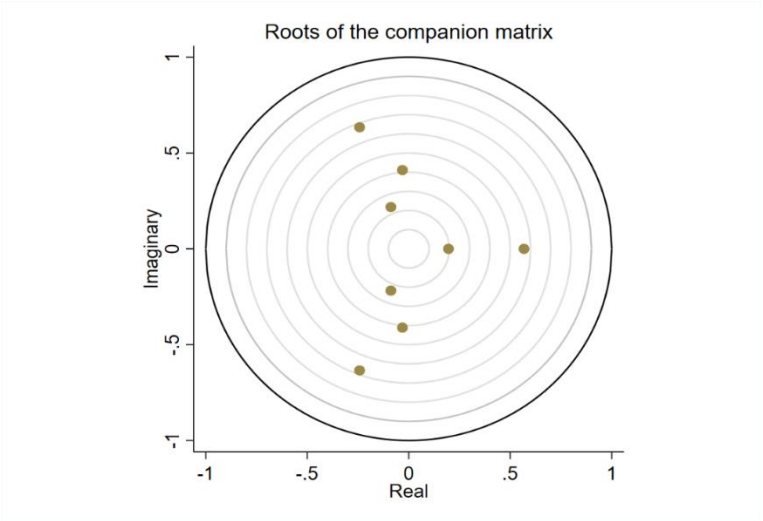

Figure no. 5 – Eigenvalue stability condition

6. CONCLUSION REMARKS

To conclude, exploring the relationship between economic growth, energy consumption and CO_2 emissions in Europe is crucial for climate change mitigation. This paper focuses on the relationship between economic growth, energy consumption and CO_2 emissions for European Union countries. Analyzing the causal relationships between these factors can play a key role in the decision-making process and contribute to the broader effort to reduce CO_2 emissions and achieve sustainable development. The main findings show that fossil fuel consumption has a strong positive effect on CO_2 emissions, indicating that an increase in fossil fuel consumption leads to a significant increase in emissions. This result underlines the need to reduce their consumption, in line with the European Green Deal's targets to reduce emissions by 55% by 2030 and achieve climate neutrality by 2050 and the urgent need to accelerate the transition to cleaner energy sources, as set out in the agreement. At the same time, renewable energy consumption has a negative effect on CO_2 emissions, although its effect remains weaker than that of fossil fuels. GDP per capita also shows a positive effect on CO_2 emissions, confirming the close link between economic growth and increased energy consumption and emissions. It is also apparent that the consumption of fossil fuel contributes much to both the level of emissions and GDP, which evidences that economic activity in the EU still depends greatly on fossil fuel. Logically, therefore, consumption of renewable energy sources has contributed relatively little to economic activity to date, a proxy for the fact that transition to renewable energy sources has so far not managed to replace the dependence on fossil fuels.

Our analysis indicates that there is bidirectional causality between renewable energy consumption and economic growth. The reasoning for this evidence is verified by the conclusions of Apergis and Payne (2010) and Apergis and Payne (2012). Similar results in our analysis indicate that, as in both considered studies, bidirectional causality exists in both short- and long-run frameworks. Also, while the findings of Asiedu *et al.* (2021) showed the strong efficient effect of renewable energy on reducing CO_2 emissions, our results tend to show it to

be milder in the EU, meaning economic growth is still highly dependent on the use of non-renewable energy sources. Also, Al Araby *et al.* (2019) explores the impact of renewable energy on the decrease of CO_2 emission and finds a positive impact; hence supporting our analysis.

The findings indicate that policymakers in the European Union should place greater emphasis on increasing investment in renewable energy and improving energy efficiency. The strong link between fossil fuel consumption and CO_2 emissions highlights the urgent need to reduce fossil fuel use. Likewise, the relatively limited impact of renewables on emissions suggests that more efforts are needed to expand their share in the energy mix. In general, speeding up the transition to a cleaner energy model through innovative policies, green technologies, and energy efficiency is crucial for achieving sustainable economic growth.

Future research will look at how new renewable energy solutions can reduce CO_2 emissions and speed up the transition to a cleaner energy mix. As economic growth has been heavily dependent on fossil fuels, a key issue for investigation will be whether a transition to full decarbonization is possible for individual sectors of the economy or for different EU countries. Further studies should also explore the dynamics of the deployment of technologies, such as energy storage and smart grids, in order to increase the contribution of renewables to energy demand. These findings could help policymakers achieve the 2050 climate neutrality target.

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FDI and Trade Connectivity in EU: New Evidence from a Non-Linear Panel Smooth Transition VECM

Pavlos Stamatiou*, Nikolaos Dritsakis**

Abstract: This study examines the relationship between real gross domestic product (GDP) per capita, trade openness and foreign direct investment (FDI) inflows, for the group of the European Union (EU) countries over the period 1995-2020. Using recently developed panel unit root and cointegration techniques, the empirical results confirm the existence of a long-run relationship among the variables. A structural break in the cointegrating relationship appears in 2009. Taking into account the 2009 regime shift, we estimate a panel smooth transition vector error correction model (PST-VECM) to examine whether real GDP per capita, trade openness, and FDI have non-linear short-term and long-term causal relationships. Our findings demonstrate how crucial it is to consider potential non-linearities when assessing FDI-trade-growth causality nexus and designing macroeconomic policies. Overall, the study's findings suggest that trade is a more effective growth stimulant, than FDI. Policy implications are then explored in the conclusions.

Keywords: FDI; trade openness; panel data; structural break VECM.

JEL classification: B23; C33; C50.

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1. INTRODUCTION

In the international business and economics literature, there has been a growing interest regarding the relationship among FDI, trade openness and economic growth. The global trading system has grown increasingly competitive and open over the last few decades. We can identify two major research directions about the relationship between trade and FDI, based on economic theory. The first research direction argues that foreign direct investments (from multinational corporations operating in a nation) have the potential to replace exports, lower unemployment rates, and overall boost growth rates. Economic openness can have a substantial impact on the size and growth of a national economy, since it fosters the effective distribution of sources, increases competitiveness in both domestic and international markets, and stimulates the transfer of technology and knowledge within the workforce (Chang *et al.*, 2009).

Conversely, the second research direction implies that the link between the openness of trade and FDI is supplementary, resulting in a positive link between them. There are numerous discussions in favor of the possibility of bidirectional causal relationships between FDI and trade. However, to our knowledge, the majority of research tends to conclude that increased FDI inflows result higher growth rates than vice versa. In addition to encouraging private investment and the creation of new jobs, foreign direct investments also transfer knowledge and technology skills within the workforce and generally strengthen the economy of the host countries (Chowdhury and Mavrotas, 2006).

Nevertheless, the impact of trade and FDI are worthy of empirical investigations, as it seems to depend on a set of factors, such as policy and macroeconomic stability, economic freedom/quality of economic institutions, open trade regime, market size, human capital, infrastructure, etc. (Bhatt, 2013; Kumari *et al.*, 2023). In addition, the stage of economic development of the country also depends on the nature of FDI and the sectoral growth that is possible, when the foreign investor invests/or target that particular sector (Kumari *et al.*, 2023).

After the 1990s, Europe saw a notable increase in the share of FDI inflows to GDP. According to UNCTAD (2022), the increase was over 1% in high-income economies throughout the 1980s and over 5% in 2007. However, the growth in FDI inflows was less (almost 2% after 2000) in low- and middle-income economies, indicating a slightly higher relevance of FDI inflows in developing countries in the most recent time period. Regarding the countries of Central and Eastern Europe, considerable increases in FDI inflows occurred as soon as the accession negotiations began (Ozturk, 2007). Open economies have more market prospects, but they also face more competition from enterprises operating in other nations.

FDI is the primary means by which knowledge/technology is transferred from developed to developing nations. Consequently, decision-makers in transitional economies have sought it out (Borensztein *et al.*, 1998). For this reason, transition countries have generally implemented the following reforms (Stejskal *et al.*, 2018):

1. Liberalization: Allowing competitive free markets to decide pricing and removing trade barriers.
2. Macroeconomic stabilization: Monetary and fiscal approaches to control inflation.
3. Restructuring & privatization: Transferring enterprise ownership from the government to private owners and establishing a robust banking sector to assist private businesses.
4. Legal and institution reforms: Bringing democracy to the economy and reducing government meddling.

The purpose of this study is to investigate the potential short-term, long-term and causal relationships between FDI inflows, openness of trade and economic growth with a focus on the European Union (EU) countries. The sample dataset is annual time series data for the period 1995-2020. This research seeks to add to the literature in a number of ways:

1. It augments the literature with empirical proofs related to the links among FDI inflows, trade openness and economic growth. The study aims to revisit the issue of the effects of trade and FDI on growth, for the group of the EU member states.
2. In accordance with the authors' best knowledge there aren't many studies that include these three variables together based on a structural break test and the panel causality analysis, under the non-linear framework. This study considers structural breaks that, if ignored, could lead to an incorrect rejection of the null hypothesis and, thus, inaccurate estimates (Hobbs *et al.*, 2021).
3. The methodology used in the paper relies on recent data and proper econometric techniques for which we support that they are the correct estimation procedures. Since prominent panel unit root tests (first generation tests) have been applied, we continue employing the unit root tests proposed by Im *et al.* (2005) and Lluís Carrion-i-Silvestre *et al.* (2005), Bai and Perron (2003) panel cointegration methodology, as well as FMOLS technique. Finally, the non-linear panel smooth transition vector error correction model (PST-VECM), rather than traditional Granger causality approach, is used to analyze the causal links between the examined variables.
4. Another difference of the study is that, in the current analysis (in contrast to the existing studies), we investigate not only the causal relations among the examined variables but also the potential of short-term, long-term and strong causality relations among FDI inflows, trade openness and economic growth.
5. Findings of this research will give a richer depiction as to whether there exist long run relationships between the involved variables. Our results highlight the significance of considering potential non-linearities in order to analyze the causality nexus, as well as designing macroeconomic policies.
6. Finally, the study presents some conclusions and policy implications that may serve as a debate for further investigation. Furthermore, the study analyzes the trade-growth nexus in the EU, specifically examining both the "trade-led growth" and the "growth-led trade" hypotheses. The results of the analysis will clarify whether export earnings have a major impact on economic development or whether domestic growth dynamics are what first enhance export capacity in the EU.

The structure of the paper is as follows: Section 2 reviews the theoretical and empirical literature. Section 3 presents the data. Section 4 presents the econometric approach and the discussion of the results. Concluding remarks and policy implications are given in the Section 5.

2. A THEORETICAL AND EMPIRICAL LITERATURE REVIEW

Given that production parameters are globally immobile, the relationship between trade and foreign direct investments is not clearly defined in neoclassical trade theories, such as those of Heckscher-Ohlin and Ricardo. According to these models, international commodity trade involves an indirect exchange of factors between countries (Anthony, 2013). In developing nations, the Heckscher-Ohlin-Samuelson model is a crucial tool for increasing real wages and promoting economic growth (Erkisi and Ceyhan, 2019).

Solow (1956), in his fundamental study of the neoclassical growth model, analyzed the aggregate production function which is connected to the labor force and overall output of the

economy. He concluded that, because FDI brought new technologies to the manufacturing process, it had a positive impact on economic growth.

Krueger (1978) and Balassa (1985), who made a great contribution to neo-classical economics, developed models emphasizing export-based development and asserting that increased exports positively impacted real GDP growth.

Mundel (1957) used the neoclassical Heckscher-Ohlin and Samuelson models' presumptions to investigate the relationship between trade and FDI. His analysis's findings showed that flows of FDI depend on the differences in financing and prices of each country. Nevertheless, given the quick capital movement, these differences seem to be smaller. Finally, Mundel (1957) argued that mobility of capital, which is driven by foreign direct investments, constitutes a perfect substitute for exports for each country.

Schmitz and Helmberger (1970), a few years later, supported that trade and FDI have a complementary connection. They stated that when capital mobility is imported into a nation, trade volume rises.

The dynamic advantages obtained as a result of openness to international trade constitute the primary features of the endogenous growth theories led by Romer (1986) and Lucas (1988). In endogenous growth models, it is feasible to demonstrate long-term relationships between trade liberalization and economic development. According to the theory, sophisticated capital goods will accelerate technology transfer via imports concurrently with liberalization.

2.1 Technological Diffusion, through FDI, as a Key Factor for Economic Growth

As endogenous growth theories suggest (Romer, 1986), FDI can boost economic growth through mechanisms including innovation and knowledge transfer from foreign to domestic companies. Using data from 1987 to 1996, Keller and Yeaple (2009) examined the technology transfer from FDI to manufacturing firms in the United States (US). Their results showed that FDI spillovers accounted for 11% of productivity growth in US firms. The authors' conclusion was that high technology industries had stronger FDI spillovers, which highlights the variability of FDI effects across industries.

However, the effects of FDI seem to depend on the host country’s characteristics, such as technological innovation, human development index, financial development and financial institution quality, as well as openness to trade (Borensztein *et al.*, 1998).

Using data from 25 Eastern European countries between 1990 and 1998, Campos and Kinoshita (2002) found a strong positive correlation between FDI and economic growth through technology (and know-how) transfer to the host country industries. Furthermore, the authors claimed that the impact of FDI inflows is not determined by human capital.

On the other hand, Li and Liu (2005) argued that FDI boosts economic growth both directly and indirectly (via human capital), using a panel dataset of 84 developed and developing economies from 1970 to 1999. However, the developing countries (the host countries) saw a decline in economic growth as a result of their weaker absorptive capacity (which is a result of their low level of human capital development).

A similar study was carried out by Curwin and Mahutga (2014). They claimed that FDI decrease economic growth rates over the long and short terms, using data from 25 Eastern European economies between 1990 and 2010. This could be explained due to rapid share of FDI inflows, in these economies. Privatization schemes resulted in large budgetary shocks, because of poor institutional frameworks in competition policy and governance.

Furthermore, Islam *et al.* (2020) investigated the relationship between FDI and financial development, given the significance of FDI inflows for a host country's long-term economic development. Their empirical study suggests that financial institutions are more attractive to FDI than financial markets. Therefore, governments should support reputable financial institutions in order to make the country more appealing to foreign investors.

2.2 Trade Liberalization and Economic Growth

Countries gain from foreign trade in a number of ways. Trade improves the efficiency of global resource allocation (by equating the values of products and services), as well as allows countries to specialize in areas where they are most effective (in the creation of commodities and services) (Tupy, 2005).

A dynamic panel model of growth was examined by Greenaway *et al.* (2002), for 73 developing economies in the context of various measures of liberalization. They discovered that whereas trade liberalization initially has a negative effect on GDP per capita, over time this effect fades as economic development increases. The results of the study show a relationship between the variables in the shape of a "J" curve: evidence that holds true for different samples and liberalization levels.

Using panel data from 22 emerging economies over the period 1972-1997, Santos-Paulino and Thirlwall (2004) discovered that the increase in exports, brought about by trade liberalization, had an impact on wage inequality, income distribution, unemployment rate, and economic devlepoment. Authors argued that increased imports have weaker effects on these variables, and that trade liberalization affects the balance of payments by boosting imports.

Kilavuz and Topcu (2012) examined the effects of different classifications of trade on economic growth, in 22 developing countries from 1998 to 2006. The main finding of the study is that exports, investments, and imports of high-technology manufacturing firms have a major and beneficial impact on economic development.

A recent study conducted by Erkisi and Ceyhan (2019) in order to investigate the relationship between economic growth and trade liberalization, for the case of 13 transition countries in Europe using data covering the period 1995-2016. The results indicate that trade liberalization positively affects economic growth in mutual way between exports, imports and economic growth according to the feedback hypothesis.

2.3 Interrelationship between FDI, Trade Openness and Economic Growth

The relationships between FDI, trade openness, and economic development have been the subject of several studies. The literature on the interrelationship between FDI, trade openness and economic growth has been quite varied and often inconclusive.

Using Granger causality approaches and panel data analysis, Hsiao and Hsiao (2006) investigated the link between exports, FDI, and GDP for 8 East and Southeast Asian economies from 1986 and 2004. Their study's findings demonstrated that FDI affects GDP both directly and indirectly (via exports). Furthermore, the authors found a bidirectional causal relationship between the group of countries' GDP and exports.

Ciftcioglu *et al.* (2007) investigated the effects of FDI inflows on unemployment, trade openness and economic growth, in 9 Central and East European countries using data covering the period 1995-2003. The analysis's key conclusion is that an increase in FDI inflows has a

negative effect on the unemployment rate. Authors came to the conclusion that these economies ought to prioritize measures that boost FDI inflows' beneficial effects on technical progress and therefore on economic growth.

Between 1994 and 2008, Acaravci and Ozturk (2012) examined the connections among FDI, exports and economic growth for 10 European countries. They found that there is a causality relation between exports, FDI, exports and economic growth in four out of the ten economies.

Dritsakis and Stamatiou (2014) used annual panel data covering the years 1970-2011 to investigate the relationships between exports, FDI, and GDP in five Eurozone countries. Their findings support that there is a bidirectional causal relationship between exports and economic development, but not between FDI and growth nor exports and FDI. Authors concluded that a rise in these nations' domestic output volumes would drive their export volumes and growth rates.

Cinar and Nulambeh (2018) examined the effects of trade liberalization and foreign direct investments on economic growth in 34 Sub-Saharan African countries from 2006 and 2015. Their results showed that trade openness and foreign direct investments play important roles in explaining economic growth. The authors came to the conclusion that governments should keep up their efforts to foster a business-friendly environment and design macroeconomic policies that promote infrastructure development and economic openness.

Banday *et al.* (2021) examined the causal relationship between FDI, trade openness and economic growth in BRICS countries using data for the period of 1990-2018. Their analysis's principal finding is that FDI and trade openness have a positive impact on long-term growth rates. The causality results of the study reveal bidirectional causalities between FDI and economic growth and between trade openness and FDI, as well as a unidirectional causality running from trade openness to FDI.

In this paper, we go a few steps further related to the existing literature in the field, by focusing on EU countries, viewed as group. More importantly, we apply modern econometric techniques, for which we support that they are the correct estimation procedures within the non-linear panel framework.

3. DATA

The following variables were measured annually for the 27 member states of the European Union: GDP per capita in current US dollars (GDP), trade openness in current US dollars (TO) expressed as the sum of imports and exports divided by GDP per capita, and inflows of foreign direct investments in current US dollars per capita (FDI). To convert current prices into constant prices, each country's GDP deflator (2015=1) was used (to deflate all variables). The selection of the sample is based on the data availability. All data needed, collected from WDI (2022) and UNCTAD (2022).

4. METHODOLOGY AND RESULTS

4.1 Panel Unit Root Tests

To find the integration order of the corresponding variables, we begin our analysis with the panel unit root tests. The tests by Breitung (2001) and Levin *et al.* (2002) pre-suppose that the dynamics of the autoregressive coefficients are homogeneous for every unit of the panel.

However, Phillips and Sul (2003) show that this idea frequently results in the null hypothesis being rejected mistakenly.

The unit root test of Im *et al.* (2003) permits heterogeneity in the panel's autoregressive coefficients' dynamics. Furthermore, based on the Fisher-ADF and Fisher-PP tests, Maddala and Wu (1999) presented a non-parametric technique that permits heterogeneity between panel units.

Finally, Hadri (2000) proposed a Lagrange Multiplier test based on residuals to test the null hypothesis that the time series are stationary around a deterministic trend for each *i*, while contrasting it with the alternative of a unit root in panel data. In all cases except Hadri (2000), the null hypothesis is that the variable contains a unit root.

The results of these panel unit roots are displayed in Table no. 1. The results show that all three variables are non-stationary in their levels, with an intercept and trend. Evidently, the results indicated that all variables are stationary in their first differences.

Table no. 1 – Unit Root Results

Level			
	GDP	**TO**	**FDI**
LLC	2.545	-1.471	-0.312
Breitung	1.841	-1.613	-0.554
IPS	2.328	-0.972	0.744
ADF	4.517	9.687	2.338
PP	0.039	5.711	2.439
Hadri	4.447***	4.441***	1.728**
First Difference			
	GDP	**TO**	**FDI**
LLC	-4.446 ***	-7.574 ***	-3.009 ***
Breitung	-4.156 ***	-2.720 ***	-2.308 **
IPS	-2.074 **	-4.244 ***	-2.619 ***
ADF	18.903 ***	36.093 ***	16.846 ***
PP	13.538 **	48.267 ***	29.188 ***
Hadri	0.713	-0.005	1.209

Notes: Panel data include all countries. ***, **, denotes rejection of null hypothesis at the 1% and 5% level of significance, respectively. Lag length selection automatic based on Schwarz criterion.

To further investigate the validity of the first generation panel unit root tests, we additionally employ the tests proposed by Im *et al.* (2005) and Lluís Carrion-i-Silvestre *et al.* (2005) that allow endogenous determined structural breaks. More precisely, the above mentioned approaches permit one break in the level of each series, as well as an arbitrary number of breaks, respectively. In Im *et al.* (2005) test, the null hypothesis is that the series contain a unit root (non-stationarity), whereas the null hypothesis for the Lluís Carrion-i-Silvestre *et al.* (2005) test is stationarity.

The findings of the approaches used by Im *et al.* (2005) and Lluís Carrion-i-Silvestre *et al.* (2005) are presented in Table no. 2. The null hypothesis pertaining to non-stationarity in levels is not rejected by the Im *et al.* (2005) technique. However, at 1% level of significance, the null hypothesis is rejected when the variables are converted to first differences. Furthermore, at the 1% level of significance, the Lluís Carrion-i-Silvestre *et al.* (2005) test rejects the null hypothesis of stationarity in levels. Nevertheless, the null hypothesis cannot

be rejected once the variables have been converted to first differences. We conclude that GDP, TO and FDI are integrated of order one (i.e. *I*(1)), with a structural break occurring in 2009.

Table no. 2 – Unit Root Results (Break Included)

Level	**GDP**	**TO**	**FDI**
Im *et al.* $\Gamma_{LM}^{B}(p)$	-2.90	-2.60	-2.50
Carrion-i-Silvestre *et al.* $LM(\lambda)$	24.40***	35.30***	25.60***
First Difference	**GDP**	**TO**	**FDI**
Im *et al.* $\Gamma_{LM}^{B}(p)$	-28.40***	-38.50***	-28.60***
Carrion-i-Silvestre *et al.* $LM(\lambda)$	1.50	1.40	1.30

Notes: The critical value for the $\Gamma_{LM}^{B}(p)$ test is -4.26 at 1% level of significance. In addition, for the $LM(\lambda)$ test the critical value is 10.63 at 1% level of significance. Break location 2009. *** denotes rejection of null hypothesis at the 1% level of significance. The maximum number of common factors and structural breaks in the Lluís Carrion-i-Silvestre *et al.* (2005) test are set equal to five according to the literature.

4.2 Non-linear Panel Cointegration

The economic literature states that one of the most important factors determining long-term economic growth is investment or capital accumulation. This is especially true when determining an economy's long-run productive capacity because investments produce new capital products and causes the capital stock to grow quickly (Romer, 2001).

Additionally, Chakraborty and Mukherjee (2012) provided evidence supporting the idea that FDI inflows will assist recipient countries economically in a number of ways, potentially spurring economic growth through positive externalities and spillover effects. Furthermore, trade openness is included in this study's analysis as an explanatory variable within the sources of growth equation. International commerce may lead to a significant elasticity of substitution, as determined by Mankiw *et al.* (1992). In accordance with Hsiao and Hsiao (2006), we define the model's generic form as follows:

$$GDP_{it} = f(TO_{it}, FDI_{it}) \tag{1}$$

After defining the integration order, we proceed by using the panel cointegration methodology, taking any structural breaks into account. Equation (2) specifies the overall form of the model within a break augmented panel regression framework.

$$GDP_{it} = a_{ij} + \beta_{1i} TO_{it} + \beta_{2i} FDI_{it} + \varepsilon_{it} \tag{2}$$

where: a_{ij} *(j=1,...,m_i+1)* represent the country specific intercept that is subject to m_i structural breaks, β_{1i} are the country specific slopes that are assumed to be constant over time and ε_{it} is assumed to be independent and identically distributed over time periods and across cross-sectional units.

With regard to equation (2), the traditional cointegration techniques can be used assuming that the series has no structural breaks. The relationship in equation (2) is no longer linear in the case that there are structural breaks, so the conventional panel cointegration tests do not yield reliable findings. Westerlund (2007) recommends applying Bai and Perron (2003) least squares method, which is predicated on resolving the following minimization problem:

$$(\tau_{i1...}\tau_{\min}) = \arg\min_{\tau_{i1}...\tau_{\min}} \sum_{j=1}^{m_i+1} \sum_{t=\tau_{ij-1}+1}^{\tau_{ij}} \varepsilon_{it}^2 \quad (3)$$

where: ε_{it} stands for the residuals in equation (5) based on the partition τ_{ij} with $j = 1...m_i$ and a trimming parameter of $\tau_{\min}$, with the minimum length of each subsample to be $\tau_{ij} - \tau_{ij} - 1 > \tau_{\min}$.

This approach's primary benefit is its ability to test for numerous breaks at arbitrary dates. To reliably calculate the number of breaks, it estimates each break point using a specific-to-general technique (Esteve and Requena, 2006). The process operates as follows: For each break number $m_i = 1...m_{\max}$, we first calculate the minimum of the sum of the squared residuals related to structural breaks τ_{ij}. The Schwarz criterion is used to estimate the number of structural breaks for each i in the second phase.

The first step in the Bai and Perron (2003) process is to minimize the objective function with respect to a_{ij} and τ_{ij}, and while maintaining β_{1i} and β_{2i} fixed. The objective function of a pure structural change is minimized given that β_{1i} and β_{2i} stay fixed. In the second phase, the objective function is minimized in relation to a_{ij}, β_{1i} and β_{2i}, and while maintaining the τ_{ij} fixed (Apergis and Payne, 2014).

The following table shows the results of the cointegration test conducted by Bai and Perron (2003). For the group of the selected EU countries, Table's no. 3 results validate a cointegrating vector among the variables under examination. At the panel level, the null hypothesis of cointegration is accepted. Put otherwise, the findings indicate that, over time (long run), GDP, TO, and FDI are all moving together.

Table no. 3 – Cointegration Results

Bai and Perron		
	Statistic	**P-Value**
Intercept Break	9.503	0.550

Notes: The p-value is based on the bootstrap distribution.

After cointegration is established, we use the fully modified OLS (FMOLS) technique for heterogeneous cointegrated panels to estimate the long-run relationship. This FMOLS estimator permits more flexibility in the case that heterogeneity exists in the cointegrated vectors (Pedroni, 2001b, 2001a). Furthermore, in addition, the superior estimator consider

both serial correlation and endogeneity problems, so it is preferable than the OLS estimator (Phillips, 1995). The following equation displays the estimator's formula:

$$\beta_{FM} = \left[\sum_{i=1}^{N} \sum_{t=1}^{T} (x_{it} - \overline{x_i})(x_{it} - \overline{x_i})' \right]^{-1} \left[\sum_{i=1}^{N} \left(\sum_{t=1}^{T} (x_{it} - \overline{x_i}) y_{it}^{*} + T\Delta_{EM}^{*} \right) \right] \quad (4)$$

where: y_{it}^{*} is the transformed variable of y_{it} in order to achieve the endogeneity correction and Δ_{EM}^{*} is the serial correlation error correction term.

We continue by estimating the long-run equilibrium relationship's parameters. The following table presents the findings from Pedroni (2001a)'s FMOLS estimations.

Table no. 4 – FMOLS Results

	Independent Variables	
	TO	**FDI**
Coefficient	0.212	0.375
	(0.016**)	(5.140***)
Pesaran (CD)	0.644 [p-value = 0.289]	

Notes: The numbers in parentheses denotes t-statistic, *** and ** denotes significant at 1% and 5% level of significance.

Trade openness (TO) and foreign direct investments (FDI) are significant contributors to economic growth, as demonstrated by the FMOLS estimator. More specifically, at the 5% and 1% significance levels, respectively, TO and FDI are two significant factors that boost growth rates. A 1% increase in TO tends to lead GDP in the group of selected European Union countries increasing by 0.212%. In addition, a 1% increase in FDI tends to lead GDP increasing by 0.375%. The study's findings are consistent with those of Hsiao and Hsiao (2006), who argued that, among a group of industrialized economies, exports and FDI combined play the most significant role in the process of economic growth. The Pesaran (2004) cross-sectional dependence (CD)[1] is likewise shown in Table no. 4 and provides reliable values for both small and large samples. The results of the test fail to reject the null hypothesis of no cross-sectional dependence, indicating that the residuals (in the cointegrating vector) are not cross section dependent.

4.3 Panel Causality Analysis

We continue using a non-linear panel smooth transition vector error correction model (PST-VECM) to analyze the causal links between the variables under investigation. The PST-VECM takes into account potential non-linear dynamics, in addition to the long term relationship adjustment.

Following Gonzalez *et al.* (2005), as well as Omay and Öznur Kan (2010), the equations of the PST-VECM are given below:

$$\Delta GDP_{i,t} = a_{1,i} + \lambda_{1,i} ECT_{i,t-1} + \sum_{k=1}^{p} \beta_{1,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \beta_{1,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \beta_{1,3,i,k} \Delta FDI_{i,t-k}$$
$$+ G(S_{it};\gamma,c)\left[\lambda_{1,1,i} ECT_{i,t-1} + \sum_{k=1}^{p} \delta_{1,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \delta_{1,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \delta_{1,3,i,k} \Delta FDI_{i,t-k} \right] + u_{1,i,t} \quad (5)$$

$$\Delta TO_{i,t} = a_{2,i} + \lambda_{2,i} ECT_{i,t-1} + \sum_{k=1}^{p} \beta_{2,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \beta_{2,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \beta_{2,3,i,k} \Delta FDI_{i,t-k}$$
$$+ G(S_{it};\gamma,c)\left[\lambda_{2,1,i} ECT_{i,t-1} + \sum_{k=1}^{p} \delta_{2,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \delta_{2,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \delta_{2,3,i,k} \Delta FDI_{i,t-k} \right] + u_{2,i,t} \quad (6)$$

$$\Delta FDI_{i,t} = a_{3,i} + \lambda_{3,i} ECT_{i,t-1} + \sum_{k=1}^{p} \beta_{3,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \beta_{3,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \beta_{3,3,i,k} \Delta FDI_{i,t-k}$$
$$+ G(S_{it};\gamma,c)\left[\lambda_{3,1,i} ECT_{i,t-1} + \sum_{k=1}^{p} \delta_{3,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \delta_{3,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \delta_{3,3,i,k} \Delta FDI_{i,t-k} \right] + u_{3,i,t} \quad (7)$$

where: $a_{j,i}$ (j = 1, 2, 3, 4) represents the fixed individual effects, $G(S_{it};\gamma,c)$ is the transition function bounded between 0 and 1 (depends on the transition variable S_{it}), γ is the transition parameter that describes the slope of the transition function, c is a threshold parameter, $u_{j,i}$ is the error term assumed to be a martingale difference with respect to the history of the vector of variables with mean zero and variance, $ECT_{i,t-1}$ is the error correction term (ECT) derived from the long run cointegration equation.

In the above equations (5), (6), and (7), the transition between regimes is addressed using the next logistic and exponential functions:

$$G(S_{it};\gamma,c) = \left[\frac{1}{1+\exp\left(-\gamma \prod_{j=1}^{m}(S_{it}-c)\right)} \right] \quad (8)$$

where: $\gamma > 0$ and $c_1 \le c_2 \le \ldots \le c_m$

According to Gonzalez *et al.* (2005), it is adequate to take into account only the cases in which *m = 1* or *m = 2*. A logistic transition function is present when *m = 1*. In the other case *(m =2)*, the transition function is an exponential type.

In equations (5), (6), and (7), the short run causal relationship between the variables depends on:

1. For the causal relationship between GDP and TO:

$\beta_{1,2,i,k} + \delta_{1,2,i,k} G(S_{it};\gamma,c)$ and $\beta_{2,1,i,k} + \delta_{2,1,i,k} G(S_{it};\gamma,c)$ for $k = 1,..,p$

2. For the causal relationship between GDP and FDI:
$\beta_{1,3,i,k} + \delta_{1,3,i,k} G(S_{it};\gamma,c)$ and $\beta_{3,1,i,k} + \delta_{3,1,i,k} G(S_{it};\gamma,c)$ for $k = 1,..,p$

3. For the causal relationship between GDP and TO:
$\beta_{2,3,i,k} + \delta_{2,3,i,k} G(S_{it};\gamma,c)$ and $\beta_{3,2,i,k} + \delta_{3,2,i,k} G(S_{it};\gamma,c)$ for $k = 1,..,p$

In addition, the long run causalities depend on:

$$\lambda_{1,i} + \lambda_{1,1,i} G(S_{it};\gamma,c),\ \lambda_{2,i} + \lambda_{2,1,i} G(S_{it};\gamma,c) \text{ and } \lambda_{3,i} + \lambda_{3,1,i} G(S_{it};\gamma,c).$$

As we see, the transition variable S_{it} is a key variable in the causality relation among GDP, TO and FDI.

The following steps are part of the smooth VECM estimation technique. First, we compare the alternative of non-linearity (smooth transition) to the null hypothesis of linearity. In the case that linearity is rejected, we proceed to determine the shape of the transition function. Luukkonen *et al.* (1988) state that the transition function can be replaced with the k^{th} order Taylor expansion around γ in the next auxiliary equations (5), (6), and (7). In the end, we estimate the parameters in the smooth panel VECM that we have chosen.

$$\begin{aligned}\Delta GDP_{i,t} &= \psi_{1,i} + \lambda_{1,i} ECT_{i,t-1} + \sum_{k=1}^{p} \pi_{1,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \pi_{1,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \pi_{1,3,i,k} \Delta FDI_{i,t-k} \\ &+ \lambda_1' S_{it} ECT_{i,t-1} + \sum_{h=1}^{k} \left(\sum_{k=1}^{p} \pi'_{1,1,i,k} S_{it} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \pi'_{1,2,i,k} S_{it} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \pi'_{1,3,i,k} S_{it} \Delta FDI_{i,t-k} \right) + u_{1,i,t}\end{aligned} \tag{9}$$

$$\begin{aligned}\Delta \mathrm{TO}_{i,t} &= \psi_{2,i} + \lambda_{2,i} ECT_{i,t-1} + \sum_{k=1}^{p} \pi_{2,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \pi_{2,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \pi_{2,3,i,k} \Delta FDI_{i,t-k} \\ &+ \lambda_2' S_{it} ECT_{i,t-1} + \sum_{h=1}^{k} \left(\sum_{k=1}^{p} \pi'_{2,1,i,k} S_{it} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \pi'_{2,2,i,k} S_{it} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \pi'_{2,3,i,k} S_{it} \Delta FDI_{i,t-k} \right) + u_{2,i,t}\end{aligned} \tag{10}$$

$$\begin{aligned}\Delta FDO_{i,t} &= \psi_{3,i} + \lambda_{3,i} ECT_{i,t-1} + \sum_{k=1}^{p} \pi_{3,1,i,k} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \pi_{3,2,i,k} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \pi_{3,3,i,k} \Delta FDI_{i,t-k} \\ &+ \lambda_3' S_{it} ECT_{i,t-1} + \sum_{h=1}^{k} \left(\sum_{k=1}^{p} \pi'_{3,1,i,k} S_{it} \Delta GDP_{i,t-k} + \sum_{k=1}^{p} \pi'_{3,2,i,k} S_{it} \Delta TO_{i,t-k} + \sum_{k=1}^{p} \pi'_{3,3,i,k} S_{it} \Delta FDI_{i,t-k} \right) + u_{3,i,t}\end{aligned} \tag{11}$$

Testing $\gamma = 0$ in equations (5), (6), and (7) is equivalent to testing the hypothesis H_0: ω1=ω2=ω3=0 in equations (9), (10), and (11) (where $\omega_i \equiv (\lambda', \pi')$). This test can be undertaken using an LM test statistic approximated by and F-distribution as shown below:

$$LM = [(SSR_0 - SSR_1) / mk] / [SSR_0 / TN - N - mk] \rightarrow F(mk, TN - N - mk) \quad (12)$$

where: SSR_0, SSR_1 are the sums of squared residuals under the null and the alternative hypothesis, k is the number of explanatory variables.

The following tables provide the panel smooth VECM estimate results. Since we have selected the appropriate transition variable S_{it}, we apply a sequence of F tests as suggested by Terasvirta (1994) in order to choose the type of the transition function. The choice of trade openness as the transition variable was made in light of the literature's theoretical and empirical support for the idea that economic openness can affect both FDI and economic growth at the same time. Despite this, Chaboud and Wright (2005) argued that alternative transition variables can have the same policy implications in specific situations.

Table no. 5 – Selection of the Transition Function break date 2009

	F1	F2	F3
GDP	0.055	0.095	0.189
TO	0.040	0.123	0.177
FDI	0.039	0.112	0.411

Notes: Reported numbers are prob. values. Order Taylor approximation equals to 3.

The findings indicate that F_1 has the smallest p-value among the F tests, indicating that F_1 is a suitable logistic function to utilize as the transition function. Since the estimated value of c is extremely near to zero (-0.001), extreme regimes are associated with both positive and negative growth values prior to and following the structural break.

We now proceed with the regime-wise Granger causality analysis to examine the short and long term correlations among the variables for each regime (pre-2009, post-2009 periods), as we have chosen both the suitable transition variable and the transition function. Additionally, we test for the strong causality based on the joint significance of the error correction term and the long term coefficients.

We proceed with regime-wise short and long term Granger causalities. The lagged values of the first-difference of the relevant variables are used to test for short run causalities. Furthermore, depending on the statistical significance of the corresponding error correction terms, the long term causalities are perfumed. Finally, we use the joint significance of the lagged values of the variables' first-difference and the error correction term, to assess the strong-form of causality.

Tables no. 6 and no. 7 present the results of the regime-wise Granger-causality tests, for the pre-2009 and the post-2009 period, respectively.

The short-run causality results show that trade openness and economic growth have a bidirectional causal relationship for the pre-2009 period, in addition to two unidirectional causalities that flow from trade openness to FDI and from FDI to economic growth. Furthermore, there may be long-term convergence of dynamic equilibrium based on the statistical importance of the error correction terms in the corresponding equations (5), (6), and (7). Value of the estimated coefficient of the *ECT* shows the speed of adjustment (convergence). Finally, the aforementioned causality links are validated in terms of the joint test of the long-run and short-run (strong causality).

Table no. 6 – Causality Results (pre-2009 period)

	Short-run F-values			Long-run t-values	Joint (short-long-run) F-values		
	ΔGDP	**ΔTO**	**ΔFDI**	**ECT**	**ΔGDP ECT**	**ΔTO ECT**	**ΔFDI ECT**
ΔGDP		0.719	-0.870	-0.350		3.371	-2.155
		(0.023)**	(0.017)**	(0.040**)		(0.043)**	(0.036)**
ΔTO	0.630		0.192	3.630	0.114		2.124
	(0.025)**		(0.316)	(0.034)**	(0.030)**		(0.131)
ΔFDI	-0.069	-0.710		-0.667	0.080	1.850	
	(0.843)	(0.069)*		(0.063)*	(0.922)	(0.089)*	

Notes: Partial F-statistics with respect to short run changes in the independent variables. The optimal lag lengths were selected by using the Akaike information criterion, The numbers in parenthesis are p-values calculated under the null hypothesis of no causality, ***, ** and * show significant at 1%, 5% and 10% levels respectively.

Table no. 7 – Causality Results (post-2009 period)

	Short-run F-values			Long-run t-values	Joint (short-long-run) F-values		
	ΔGDP	**ΔTO**	**ΔFDI**	**ECT**	**ΔGDP ECT**	**ΔTO ECT**	**ΔFDI ECT**
ΔGDP		0.593	0.035	-0.411		1.049	0.838
		(0.025)**	(0.855)	(0.084)*		(0.198)	(0.438)
ΔTO	1.850		0.081	-0.405	3.428		0.342
	(0.091)*		(0.963)	(0.089)*	(0.072)*		(1.115)
ΔFDI	0.227		-0.160	-0.039	0.460		0.900
	(0.299)		(0.150)	(0.697)	(0.211)		(1.234)

Notes: Partial F-statistics with respect to short run changes in the independent variables. The optimal lag lengths were selected by using the Akaike information criterion, The numbers in parenthesis are p-values calculated under the null hypothesis of no causality, ***, ** and * show significant at 1%, 5% and 10% levels respectively.

The short-run causality results for the post-2009 period show that trade openness and economic growth have a bidirectional causal relationship, but there is no causal relationship between trade openness and FDI nor between FDI and economic growth. Furthermore, the statistical significance of the error correction terms in the corresponding equation (5) implies the presence of long-term convergence of dynamic equilibrium. The value o the estimated coefficient of the *ECT* shows the speed of adjustment (convergence). Finally, in terms of the joint test of the short-run and long-run (strong causality), the above mentioned causality relation is confirmed.

The study's primary conclusion is that there is no correlation between economic development and foreign direct investments throughout the post-crisis period. FDI does not appear to have a direct or indirect impact on GDP (via trade openness). This result is supporting of the study of Dritsakis and Stamatiou (2014). Dritsakis and Stamatiou (2014) used a panel data sample spanning 42 years for 5 Eurozone economies to find that there is no causal relationship between exports and FDI nor between economic growth and FDI. The main explanation for this is the global financial crisis of 2008. FDI inflows have been significantly impacted by the great recession of 2008-2009 in all European countries. After 2009, FDI inflows into the EU decreased dramatically (57%). From 3.25 (% GDP) in 2009 decreased to 1.38 (% GDP) in 2019 (WDI, 2022).

5. CONCLUSION

This study investigates the relationship among FDI inflows, trade openness and economic growth, within a panel framework for the group European Union (EU) countries during the period 1995-2020. We excluded before 1995s due to a lack of dataset.

By examining a panel of 27 EU countries, this research adds to the growing body of knowledge regarding the factors that affect economic development, within a non-linear panel smooth transition vector error correction model (PST-VECM). Findings show a structural break in the cointegrated vector that occurred in 2009, which coincides with the launch of the recent global financial crisis. The results also confirm positive and statistically significant estimates of long-run elasticity with respect to real GDP per capita, FDI inflows, and trade openness.

Overall, the study's findings suggest that trade is a more effective growth stimulant than FDI. As a result, policy makers seek to assist EU companies in breaking into new markets. The European community should place greater focus on encouraging export-oriented behavior through trade-capacity building programs, aid-for-trade, and further policy initiatives to support the expansion of export-oriented manufacturing businesses (Tekin, 2012). Trade promotion will enable businesses to grow and benefit from economies of scale. Furthermore, more jobs will be created in the economy resulting in higher income levels.

A non-linear PST-VECM, which acknowledges the 2009 regime shift, highlights the significance of obtaining FDI under the trade promotion regime in the pre-2009 period compared to the post-2009 period. Increased FDI is correlated with higher trade levels. While it is true that host country exporting activity reflects local firms' international competitiveness, a higher level of export in a host country signals to foreign investors that there is a potential market in these countries (Pourshahabi *et al*., 2013).

Trade openness may promote technological development, which may in turn lead to long-term growth that is permanent. Nowak and Lehmann (2000) asserts that the promotion of technical progress is related to the attraction of more and better FDI, incentives for innovation in industries where trade liberalization is strongly correlated and stronger capital goods imports. Therefore, FDI can lead to higher growth rates. This can be done through boosting industrial and political security, promoting exports based on industry, growing free trade economic zones, lowering trade barriers, increasing training, and strengthening quality control programs (Saleem *et al*., 2020).

Currency depreciation might be an extra tool for the non-Eurozone economies. By promoting trade and maintaining a stable exchange rate together may create an atmosphere that supports these European countries continued development. However, there are number of factors that go into creating a favorable environment for foreign direct investments, including financial market regulations, tax incentives, trade regimes, free trade zones, the quality of the financial system and infrastructure, the host nation's human capital base, and trade regimes (Bhatt, 2013). Any form of investments still requires the host nation's economies to be politically and macroeconomically stable.

The research findings surprisingly show that there is no causality relation between FDI and economic development nor between trade openness and FDI for the post-2009 period. The global crisis of 2008-2009 had a significant impact on macroeconomic indicators that might change the nomenclature of economic activity in respect to trade and FDI inflows. The region's capital inflows were significantly impacted by the economic crisis, although the exact impact varied widely depending on the kind of inflows and the receiving nation. The sharp

decline in EU foreign direct investment inflows, which were 57% lower than pre-2009 levels (WDI, 2022), was substantive enough to dampen the FDI-growth led relationship. By means of this research, governments could make the decisions associated with the investments in foreign investments after embracing more openness to trade.

5.1 Limitations and Future Research

The current analysis is not without limitations: i) For the variables under investigation, there were just 26 observations available. Due to the fact that 16 of the EU's 27 members entered the union after 1995, subsequent studies utilizing an unbalanced panel data analysis may be used (withdrawal of the UK should also be taken into account). However, most of the time, balanced datasets are generally preferred over unbalanced panels, as they reduce the noise introduced by unit heterogeneity (Baltagi and Song, 2006). ii) Another constraint is the adoption of a proxy for trade openness that was not strategy initiated. Further investigation using trade policy as a metric of a trade openness measures may provide us with increasingly strong results (Kumari *et al.*, 2023). iii) As already mentioned, the influence of foreign investments on economic development is established by the characteristics of the host economy and the capacity of domestic companies to absorb. This paper does not take into account the features of European regions that may have made FDI less effective in promoting economic development. So, firm-level microeconomic research may help policymakers determine the sectors and types of businesses that gain from FDI (Hobbs *et al.*, 2021).

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Notes

[1]The Pesaran (2004) cross sectional statistics is: $CD = \sqrt{\frac{2T}{N(N-1)}}(\sum_{i=1}^{N-1}\sum_{j=i+1}^{N}\rho_{ij}) \rightarrow N(0,1)$, where ρ_{ij} are the correlation coefficients obtained from the residuals of the model as described in equation (2).

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Environmental Convergence in the Context of Integration between Ukraine and the EU: Empirical Evidence and Policy Implications

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Abstract: The European Green Deal will play a key role in the development of the environmental policies of the EU and its neighbouring countries (i.e. Ukraine). Accordingly, the implementation of environmental policies will contribute to the development of national economies on a convergent basis of Ukraine and the EU. The aim of this study is to analyse environmental convergence between the EU and Ukraine, taking into account the complex specificities of combining economic growth and reducing environmental impacts. In addition to the classical models of beta, sigma, gamma and delta convergence, we use methods to study environmental convergence that are based on increasing the level of economic development of less developed countries rather than reducing the unevenness of their development and include club convergence and distributional dynamics approaches. Such methodologies emphasise the importance of efforts and policies aimed at bringing countries closer together and creating favourable conditions for them to achieve higher levels of development. The result of the empirical analysis of the environmental convergence of economies using different methodologies shows that the Ecological Footprint is characterised by different results. In this context, a narrowing of the Ecological Footprint gap between countries is shown, indicating common development trends and that countries with lower levels of development are on a faster growth path to catch up with countries with higher levels of development. Another finding is that Russia's armed invasion has affected Ukraine's convergence with the EU and will continue to have a negative impact on the country's economic development and influence on convergence processes.

Keywords: environmental convergence; green growth; Ukraine-EU integration; catch-up.

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1. INTRODUCTION

The European Union is based on economic, social and territorial unity, balanced economic growth and convergence. As noted by Eurofound (2018), "convergence trends between member states have been achieved in recent decades in both economic and social dimensions". With the adoption of the European Green Deal by the European Commission, significant attention has been paid to environmental issues in the development of member states. This approach confirms the importance of joint action by Member States towards sustainable development (Fetting, 2020). On the other hand, according to the official documents of the European Commission, convergence is the basis for new member states and therefore for countries whose goal is European integration (European Commission, 2023), which Ukraine is.

In connection with the European integration vector of Ukraine's development, we emphasize that Ukraine has chosen the path of European integration by signing the Association Agreement between Ukraine and the EU in 2014 and has embarked on the path of implementing ambitious and complex reforms, the overall goal of which is to achieve economic growth. The model of European integration is based on the process of convergence, and the economic growth on which this process is based is accompanied by a negative impact on the environment. Therefore, the Association Agreement, one of the parts of which is devoted to environmental and economic aspects, is not only a fundamental tool for socio-economic convergence of Ukraine and the EU, but also a strong incentive for reforming environmental and economic policy on a European basis and ensuring its integrated character.

Numerous empirical studies on this topic by researchers from all over the world now form a strong basis for the development of relevant regional economic policies by the governments of countries. The period since the 1980s has been characterized by an increased interest of researchers in the processes of convergence of regions and countries, since such processes have important positive consequences for the well-being of the population, economic growth and are the basis for the development of effective regional polices. At the same time, the impetus for such an increase in the interest of economists in this topic was undoubtedly related to the development of powerful statistical data sets created by Maddison (1980), Summers and Heston (1988), which activated precisely the empirical research on convergence processes. It should be noted that the idea of convergence and the emergence of its basic hypothesis, as well as the first empirical studies, appeared in the academic literature much earlier. Kuznets (1973), Abramovitz (1986) and Raup (1963) were the first to study the theoretical and methodological foundations of regional socio-economic convergence.

A review of the classical economic literature on convergence shows that this concept covers a wide range of processes, including environmental ones. Since the 1972 United Nations Conference on the Environment in Stockholm, where the concept of sustainable development was first discussed, numerous events have been held and international agreements have been adopted to address environmental issues, notably the Kyoto Protocol (United Nations, 1997), the Sustainable Development Goals (United Nations, 2016) and the Paris Agreement (Centre for International Law, 2015). However, despite the existence of a large number of environmental policies and initiatives, the processes of environmental and economic convergence, their contents, signs, characteristics and functions have only been partially studied.

This article is devoted to the comprehensive analysis of the nature and content of the convergence processes between the EU and Ukraine, taking into account the environmental component. The environmental modernization and post-war reconstruction of Ukraine in the

context of its integration into the EU is particularly complex, as it involves deep institutional transformations in various spheres, which is primarily related to the process of achieving compliance with European regulations and legislation, standards and requirements for environmental protection, energy efficiency and sustainable development.

Drawing an analogy with socio-economic convergence, we note that environmental convergence is possible when countries with low per capita emissions of pollutants increase their emissions, and a country with high per capita emissions reduces them.

The research is divided into five sections: Section 2 presents detailed literature review. Section 3 represents methodology and Section 4 the data. Section 5 shows the empirical results. Section 6 concludes the study.

2. LITERATURE REVIEW

There are numerous empirical studies in the scientific literature on environmental convergence, which is considered as a key goal of emission reduction efforts in different countries. Environmental convergence is the basis of many scientific schools of climate change research (Barassi *et al.*, 2018). In addition, converging countries can jointly address environmental threats and coordinate their emission reduction commitments.

The analysis of Scopus and WoS sources on the term "environmental convergence" allowed us to conclude that the subject of numerous empirical studies based on the methodology of the theory of economic growth is the convergence of CO2 emissions (Table no. 1).

Table no. 1 – Research on environmental convergence: analysis of Scopus and WoS

Source	Countries/period	Indicator	Type	Result
(Strazicich and List, 2003)	100 countries/1960-1997	CO2 emissions	β, stochastic convergence	Stochastic convergence
(Nguyen Van, 2005)	100 countries/1966-1996	CO2 emissions	β, distributional dynamics	Exists in 26 developed countries
(Rui *et al.*, 2019)	Provinces of China/1995-2015	CO2 emissions	σ, β - convergence	Exists
(Panopoulou and Pantelidis, 2009)	128 countries/1960-2003	CO2 emissions	Club convergence	There are 2 clubs
(Herrerias, 2013)	Developed countries/1980-2009	CO2 emissions	Distributional dynamics	Exists
(Ordás Criado *et al.*, 2011)	25 EU countries	SOx and NOx emissions	Non-parametric method	Convergence exists
(Camarero *et al.*, 2013)	22 OECD countries/1980-2008	CO2 emissions	Club convergence	There are 2 clubs
(Solarin, 2014)	African countries	CO2 emissions	β - convergence	Exists
(Zhao *et al.*, 2015)	30 provinces of China/1995-2011	CO2 emissions	β - convergence	Exists
(Acaravci and Erdogan, 2016)	South Asia, East Asia, EU, Latin America, Middle East, North America, Sub-Saharan Africa /1960-2011	CO2 emissions	Stochastic convergence	Exists
(Runar *et al.*, 2017)	124 countries/1885-2010	CO2 emissions	β - convergence	Exists

Source	Countries/period	Indicator	Type	Result
(Apergis and Payne, 2017)	50 US states	CO2 emissions	β - and σ-convergence	Both types exist
(Barassi *et al.*, 2018)	28 OECD countries/1950-2013	CO2 emissions	Stochastic convergence	Poor results
(Rios and Gianmoena, 2018)	141 countries/1970-2014	CO2 emissions	β - convergence	Mixed
(Yu *et al.*, 2019)	74 cities of China/2005-2015	CO2 emissions	β - and σ - stochastic convergence	Exist, except stochastic
(Fernández-Amador *et al.*, 2019)	66 countries/1997-2014	CO2 emissions	β - convergence	Exists (weak)
(Apergis *et al.*, 2020)	6 countries of Central America	CO2 emissions, energy use	Club convergence	Exists

It should be noted that the CO2 emissions indicator reflects only part of the cumulative impact of extensive energy use. In addition to CO2 emissions, the use of resources such as forests, soils, oil, gas and mining reserves also has a significant impact on the environment. For example, in developed countries, the number of specific pollutants per unit of output has decreased as a result of technological progress and the implementation of strict environmental legislation, bur wastewater pollution has simply shifted from nitrogen oxides and sulphur to solid waste, so that total waste remains high and per capita waste may even remain constant (Stern, 2004). This point means that the theoretical basis of environmental convergence lies in the concept of the Kuznets curve, which operates when the most developed countries (and also the biggest polluters) reduce their emissions. While this situation is observed, the process of economic growth in the poorer and developing countries will bring their per capita emissions closer to the level of the developed economies. This concept, first introduced by Grossman and Krueger (1991), describes an inverted U-shaped relationship between pollutants and GDP per capita, the idea being that in the early stages of economic growth, the state of the environment deteriorates, but after a certain level of income (tipping point) is reached, per capita pollution starts to decline.

The evidence for the interdependence of the Kuznets curve is rather weak and, as Stern (2004) notes, most of the estimates in the available empirical studies are not statistically significant. Another study (Prebisch, 1950), on the other hand, argues that the concept of the Kuznets curve is of theoretical importance, but that technological progress and the effects of globalization make the curve more equal across developing countries.

The relationship between pollution, per capita income and the catching-up process is explained by three theses (Panayotou, 1993; Stern, 2017). First, the composition of manufactured products determines the environmental impact of economic activity, i.e. countries that specialize more in agricultural production or tertiary activities pollute less than countries that mainly produce other types of products. It follows that the concept of the Kuznets curve is closely linked to the transition from a manufacturing to a service-based economy, since the tertiary sector leads to changes in the structure of production costs that are less harmful to the environment. Second, technological progress can promote the diffusion of the changes in the structure of production costs between countries, as well as the diffusion of less polluting production technologies, thereby promoting energy efficiency. Third,

changes in individual preferences, together with appropriate government policies, increase the demand and supply for environmentally friendly goods and services.

On the basis of such interpretations, the following limitations to the use of the Kuznets curve concept in the development of environmental policy can be highlighted:

1) the assessment of pollution commonly used in Kuznets curve analysis is based on a limited set of pollutants; studies have found negative empirical assessments of the Kuznets curve based on the ecological footprint, which is a comprehensive indicator of the impact of human activity on the environment. Studies of CO2 emissions, for which the impact is global, show a tendency to increase with rising per capita income, even in developed countries;

2) statistical estimates of the concept vary considerably depending on the method and indicators chosen;

3) the existence of hysteresis may reduce the relevance of the Kuznets curve concept for environmental policies, as the costs of repairing damage and improving environmental quality after a tipping point has been reached may be significantly higher than the costs of preventing pollution.

In addition, several mechanisms create environmental convergence when it comes to emissions, such as CO2. First, while international agreements (such as the Kyoto Protocol) aim to reduce emissions in high-income countries, there are no commitments for developing countries. Second, as noted by Requate (2005); Vine and Hamrin (2008), economic instruments such as emission taxes and environmental legislation contribute to emission reductions only in developed countries. In addition to these two mechanisms, the development of the tertiary sector of the economy and technological progress slow down pollution in high-income countries and contribute to the growth of CO2 emissions in low-income countries (Payne, 2020).

In the context of the theoretical study of environmental convergence, it is important to carry out a detailed literature analysis of the catching-up process in the green economy, similar to its "traditional" counterpart. For example, Baumol (1986), in a well-known publication, demonstrated a significant effect of socio-economic convergence in the process of regional catching-up. The analysis of convergence as a process of achieving well-being, based on indicators with different initial conditions, is the subject of research by a wide range of economists in the field of economic growth theory. Today, there is a large number of studies on different states of convergence, whose theoretical and methodological basis is σ-convergence, which is a measure of the level of economic "reserves", and β-convergence, which is a measure of the growth rate of the economy. These two concepts allow an empirical assessment of the catching-up process achieved by combining the relevant economic indicators. However, such convergence is usually considered as conditional and territorial, due to the different possibilities of resource allocation in each country/region. In fact, this condition directly affects the convergence coefficient through the influence of the independent variables on the coefficients of the production function (Barro and Sala-i-Martin, 1992).

Some studies prove the existence of club convergence, where economic growth occurs in a group of countries/regions with similar development conditions; countries converge to a territorial steady state, thus receiving a significant impact of territorial distribution and different convergence conditions (Quah, 1996). In addition, the role of technological efficiency in the formation of long-term convergence, based on the leapfrogging effect in less developed regions, has been studied in the literature. The catching-up process triggered by technological backwardness and regional innovation capacity has been integrated into a single conceptual framework in order to identify more ways of accelerating the convergence of key

economic drivers (Fagerberg, 1994). Further acceleration of technological catching-up in less developed countries may depend to a large extent on the emergence of new technological innovations, involving technological demonstration, imitation and diffusion.

In the projection of the environmental economics, the object becomes "green" well-being and not the efficiency of the economy. There are numerous studies in the scientific literature that have carried out convergence analysis and found that the catch-up problem is not only economic but also environmental. The relationship between convergence analysis and sustainable development in different fields (sustainable lifestyles, sustainable agriculture, sustainable energy, etc.) has been explored by several scholars (Pugliese, 2001; Markandya *et al.*, 2006; Farges, 2015). To address the problem of ensuring sustainable economic growth in less developed countries, as well as their efforts to catch up with more developed countries with lower levels of pollution, factors of the green economics have been added to the convergence analysis paradigm (Brown *et al.*, 2009). Thus, environmental convergence reflects resource-dependent economic convergence with negative environmental impacts.

3. METHODOLOGY

The analysis of environmental (and other types) convergence between Ukraine and EU countries has a significant problem, which is that classical convergence studies consider homogeneous systems of countries/regions (US states, Chinese provinces, EU countries, etc.), which cannot be said about Ukraine and EU countries. In addition, there are other bottlenecks related to different methodologies and standards of statistical reporting, political and social challenges, cultural and historical differences. One of the methods used to overcome such bottlenecks can be the selection of countries based on characteristics such as geographical proximity (e.g. Poland, Slovakia, Hungary, Romania and Bulgaria), similarity of economic characteristics (e.g. Bulgaria, Romania, Latvia and Lithuania), institutional proximity (e.g. Bulgaria, Romania, Croatia), the formation of a representative sample (e.g. Germany, France, Spain, Italy and Poland) or the use of an approach consisting in the evaluation of club convergence, the theoretical foundations of which were developed by Baumol (1986).

Indeed, it is in this case that club convergence has the greatest theoretical and practical value and can be used in this study. According to this concept, countries with the same level of income or economic development tend to form an "economic club" in which the economic indicators and policies of these countries converge. Club convergence occurs as a result of the influence of two factors. The first factor is that high-income countries become more economically similar to each other, which may be due to similar market conditions, technological innovation or the spread of best practices. The second factor is that countries with a lower levels of income or economic development will try to catch up with countries with a higher levels and move closer to their economic indicators. This can be done by implementing relevant reforms, attracting foreign investment, transferring technology or other mechanisms that contribute to economic growth.

It follows from the above that the assessment of the clusters of the EU countries and Ukraine for the purpose of their convergence analysis is of particular importance. For this purpose, the approach of Phillips and Sul (2007) was used, which includes the following steps:

1) for panel data, the corresponding indicator for the most recent observation period is sorted in descending order;

2) the formation of the main cluster, which involves the estimation of logistic regression for the first k countries $(2 < k < N)$ with maximization k with condition that t-statistics $t > 1,65$; i.e. the size of the main cluster k^* is defined as $k^* = \arg\max_k \{t_k\}$ if $\min\{t_k\} > -1,65$; if this condition is not met for $k = 2$ (the first two countries), then the first country is discarded and the iteration is repeated; if condition $\min\{t_k\} > -1,65$ is not met for any of the values, then there is a divergence characteristic of all countries.;

3) the logistic regression is re-estimated with the gradual addition of the country not included in the main cluster; if t_k greater than the critical value c^*, then this country is included in the convergence club; countries included in the main cluster k^* and added in this step form the first convergence club;

4) if the condition is not met in the previous step, i.e. $t_k < c^*$, then these countries are then placed in a separate group and a further logistic regression analysis is carried out to check the condition. $\min\{t_k\} > -1,65$; if the condition is met, a second club is formed and steps 1-3 are repeated to identify other clubs.

The range of convergence methods and models is quite broad, depending on the type of convergence being studied and on the field of research: social policy, fiscal policy, environmental policy, trade, banking regulation, telecommunications, health care, monetary policy, migration policy, infrastructure, competition, justice and data protection policy, agricultural policy, education policy, foreign policy (Heichel *et al.*, 2005).

The vast majority of economists use two well-known concepts of σ- and β- convergence, based on the neoclassical theory of economic growth by Solow (1956), Ramsey (1928) and Cass (1965), as a methodological basis for studying convergence/ divergence processes. In neoclassical models of economic growth, the process of convergence describes trends in per capita income equalization between economies, i.e. countries, regions, provinces, states, etc. As noted by Quah (1990), income is a generalized concept in these models and is used, for example, as an indicator of convergence: GDP or GRP per capita, return on assets, inflation rate, wage per employee, pollutants and even political sentiment.

The concept of convergence is that economies with low levels of per capita income (relative to their steady-state levels) tend to grow faster in key per capita indicators. This dynamic is often confused with another meaning of convergence, which is that the dispersion of real income per capita for a given group of regions decreases over time. All measures of income inequality (Gini, Theil, Atkinson, etc.) are distributional statistics that give some indication of variance. And one of them is the standard deviation of the logarithm of income $\sigma_t = \sigma(\ln y_t)$, where income at a given time t is a direct characteristic of the distribution, which has been called σ-convergence. This is possible if the inequality $\sigma_{t+T} < \sigma_t$ holds for some time interval T. At the same time, β-convergence provides a direct assessment of the economic hypothesis that countries with lower income levels will develop faster than countries with higher income levels (Barro and Sala-i-Martin, 1992).

A condition for σ-convergence is the presence of β-convergence, so the analysis should begin with the evaluation of the last (Barro and Sala-i-Martin, 2004). Thus, the beta-convergence equation, which, as mentioned above, is based on neoclassical models of

economic growth, the purpose of which is to formalise and substantiate the factors of uneven development of regions (countries, provinces), as well as to find the reasons that lead to the convergence of income levels per capita of the region over time. The main thesis of classical studies of economic growth (Ramsey, 1928; Solow, 1956; Cass, 1965) is that regions with a lower level of economic development grow faster than regions with a higher level of economic development. In neoclassical growth models, the convergence effect is enhanced by the movement of capital and technology from economically rich to poor regions, and of labour from poor to rich regions.

The analysis of β-convergence has a strong applied value in studies that examine the processes of differentiation in the socio-economic and environmental development of countries/ regions. Today, a large number of scientists from all over the world publish research results every year, which are based on the use of β-convergence and its modifications. Empirical studies use a statistical analogue of the neoclassical Solow-Swan growth model. To account for these modifications, we write the unconditional β-convergence equation in the form:

$$\gamma_i = \alpha + \beta y_{i,o} + \varepsilon_i \tag{1}$$

where $\gamma_i = t^{-1}\left(\log y_{i,t} - \log_{y_i,0}\right)$ - per capita income growth rate (or other indicator), and unconditional convergence occurs if $\beta < 0$, $i = \overline{1,n}$ - region (country), ε - error.

The conducted detailed critical analysis of the β-convergence methodology leads us to the conclusion that the corresponding empirical analysis of the unevenness of the development of countries should be carried out in a complex manner with other methods, which are used to conceptualize the quantitative assessment of convergence (Heichel *et al.*, 2005).

Thus, the second most common method is σ-convergence, which reflects a reduction in the differences in the corresponding statistical indicator between the countries concerned. Obviously, the quantitative measures of this type of convergence are the coefficients of standard deviation and variation. The latter is considered to be the most appropriate for assessing homogeneity, as it allows the trends of variability between the different indicators studied to be examined (Boyle and McCarthy, 1999). Accordingly, if the coefficient of variation decreases over time, this reflects the σ-convergence process. The main advantage of using this type of convergence is that it basically corresponds to the conceptual understanding of convergence, i.e., the degree of homogeneity achieved by countries. At the same time, the main disadvantage of using the coefficient of variation in this case is that its decrease may be caused by an increase in the average value of the indicator being studied, and not by a decrease in the standard deviation. Therefore, if comparing indicators is not the goal of the study, it is desirable to calculate σ-convergence using a "pure" measure of variability, such as standard deviation.

It is worth noting that the analysis of β-convergence is covered exclusively in academic literature, but σ-convergence is widely used in practice at the state level for the development of relevant policies (European Commission, 2016).

Another concept, called γ-convergence, consists in studying the "movements" of countries and was developed as a variant of β-convergence, which, as we have already seen,

does not reflect the dynamics between countries (Holzinger *et al.*, 2014). The γ-convergence analysis compares country ratings at different points in time to assess the "mobility" of countries. If there is a catching-up process between countries with higher rankings, then convergence will be observed. The change in the level of the resulting indicators can therefore be measured by a simple association measure, such as the Kendall's rank consistency index, which measures the degree of consistency or similarity between two rankings or ratings of the same set of objects:

$$KI_t = \frac{Var\left[\sum_{t=0}^{T} raiting\left(Y\right)_{i,t}\right]}{\left(T+1\right)^2 Var\left(raiting\left(Y_{i,0}\right)\right)}, \tag{1}$$

where KI_t - the Kendall index at a given time t, $-1 \le KI_t \le 1$, Var - dispersion, $raiting\left(Y\right)_{i,t}$ - current rating of the country i at the time t, $raiting\left(Y\right)_{i,0}$ - current rating of the country i at the initial moment of time, T - number of periods.

A corresponding positive value of the index (2) indicates agreement between the ratings, while a negative value indicates the exact opposite or inverse agreement between the ratings. A value of 0 indicates no statistical agreement between the rankings. The Kendall index is calculated by comparing a pair of ranks for each item in the two rankings. If the order of the rank pairs is the same in both rankings, they are considered consistent, and if the order of the rank pairs is opposite, they are considered inconsistent.

The γ-convergence methodology described makes it possible to obtain additional quantitative characteristics of the convergence of countries over time. Although the use of this type of convergence is not widespread in the academic literature, it can be effective in the development of relevant policies, as it allows countries and governing bodies to gain insight into trends in the equalisation of economic indicators and the effectiveness of policies aimed at ensuring more equal development. Thus, the corresponding application of γ-convergence has been carried out by Holzinger *et al.* (2014), where the authors study the convergence of national environmental policies of OECD member countries.

Finally, the concept of δ-convergence has been proposed by Heichel *et al.* (2005) to quantify the distance of a country from an exemplary model, in particular countries with the highest level of development. δ-convergence can be calculated as the sum of the distances between the maximum and the minimum values of a given indicator for countries:

$$\delta_t = \sum_{i=1}^{N}\left(MAX\left(x_{i,t}\right) - x_{i,t}\right), \tag{3}$$

where $x_{i,t}$ - the value of the corresponding indicator for the country i at time t.

Accordingly, the closing of the gap between a given country and the leading country over time represents convergence (3). δ-convergence is a measure of the extent to which countries are becoming similar to countries at a higher level of development. Although the calculations in (3) may be imprecise due to the presence of outliers, delta convergence is an effective quantifier of convergence towards a given policy objective. The first studies

(Heichel *et al.*, 2005) of delta convergence were concerned with examining changes in costs in a small group of countries, which became the basis for developing appropriate mechanisms for improving policies over time.

In the context of the study of methodological approaches to the analysis of environmental convergence, it is worth adding that, based on the interpretations of the neoclassical theory of economic growth, the dynamics of development depends on one or more structural characteristics of the economy of each country, regardless of the initial conditions. Contrary to approaches based on endogenous models of economic growth (the formation of convergence clubs), such dynamics may be the result of differences in the initial conditions of different economies with similar structural characteristics. In other words, β-convergence does not allow us to identify the true factors that determine the environmental growth of a given country, since it is well known that a positive coefficient β in ratio (1) is a necessary but not sufficient condition for reducing interregional dispersion (Barro and Sala-i-Martin, 1991). Barro and Sala-i-Martin (1992) emphasize that the study of β-convergence must necessarily be complemented by the assessment of σ-convergence. On the other hand, the analysis of σ-convergence uses only one indicator, which is a major drawback in the study of environmental convergence as a set of indicators and therefore provides insufficient information on convergence dynamics. It is not able to detect cases of cluster convergence, which can be accompanied by both an increase and a decrease in unevenness. It is therefore more informative to examine the form of the distribution of the values of the relevant indicators over time (Magrini, 2007). The method of analysing the dynamics of income distribution over time, first proposed by Quah (1993), makes it possible to detect interregional asymmetries based on the mathematical evaluation of a stochastic kernel (e.g. Gaussian). Such a technique is appropriate for assessing the environmental and economic convergence of the EU countries and Ukraine, as it allows specific effects for each country to be taken into account. Accordingly, denote by $y_i(t)$ the level of the corresponding indicator in the country *i* at time *t*, and by $\bar{y}(t)$ - the average level of this indicator for all countries; then we consider its normalized value in the form of: $x_i(t) \equiv y_i(t) / \bar{y}(t)$; by $F_{x(t)}$ denote the density of the distribution $x(t)$, by $f_{x(t)}$ - a probability measure associated with $F_{x(t)}$.

Let us consider the dynamics of the distribution of the indicator y in the following form (Magrini, 2007):

$$f_{x(t+s)}(A) = \int_{-\infty}^{\infty} M_{t,s}(x, A)\, f_{x(t)} dx \qquad (4)$$

where $M_{t,s}$ - the stochastic kernel, on which you must focus your attention when analyzing the dynamics of the distribution of the corresponding indicator, the period between *t* and $t+s$; estimation of $M_{t,s}$ will provide information on the shift of countries from one part of the distribution to another.

In this study, the stochastic kernel was estimated by dividing the estimate of the joint distribution function $f_{x(t),(t+s)}$ by the estimate of the partial (separate) distribution function:

$$p_{t,s} = f_{x(t+s)|x(t)} = \frac{f_{x(t),x(t+s)}}{f_{x(t)}} \tag{5}$$

The stochastic kernel estimate shows where different parts of the original distribution are headed over time. The line $x_{t+s} = x_t$ is a mobility line, peaks (local maxima) along which indicate the presence of convergence clusters.

Assuming that for all $t \geq 0$ stochastic process $x(t)$ is Markov, and the matrix of transition probabilities is $P_{t,s}$ does not depend on time, model (5) can be considered as a finite state Markov chain. Therefore, the stochastic kernel can be interpreted as a transition matrix, and the distribution densities in equation (4) can be estimated by kernel density estimation.

Convergence in this case is analysed on the basis of the appearance (geographical shape) of the three-dimensional graph of the stochastic kernel or the corresponding contour plot. Conclusions are drawn from the placement of data relative to the main diagonal in such graphs. The conclusion of convergence therefore follows from the concentration of most of the graph around the value 1 on the time axis $t+s$ in parallel to the time axis *t*. On the other hand, if the formation of two or more modes (peaks) is observed, we can speak of polarization. The bimodal distribution of indicators in countries indicates polarization, similar to the result of income convergence among poor countries and convergence among rich countries. The presence of two or more modes in the distribution density can indicate the polarization of countries by indicator, and their formation in a time sequence $F_{x(t)}$ about cluster convergence.

Based on this, the monomodal or multimodal ergodic distribution can be used to conclude that there is environmental convergence between the EU countries and Ukraine.

Thus, as a counterpart to the classical beta, sigma, gamma and delta convergence models, this study includes alternative methodologies that focus on enhancing the economic development of less developed countries rather than merely reducing disparities. These approaches emphasise policy efforts, institutional changes and economic mechanisms that create favourable conditions for sustainable growth.

One key approach is club convergence, which considers groups of countries with similar economic structures and levels of development, allowing for differentiated convergence trends rather than assuming uniformity across countries. This method provides insights into how countries progress towards environmental and economic convergence based on their specific conditions.

Another important methodology is the distributional dynamics approach, which goes beyond traditional convergence measures by analysing the evolution of the entire distribution of environmental and economic indicators over time. Unlike classical models, this approach allows the identification of patterns within sub-groups, helping to assess whether less developed countries are gradually catching up with wealthier nations or whether divergence persists. By applying stochastic kernel estimation, this technique provides a more detailed perspective on the structural changes that influence environmental and economic convergence across regions.

These methods provide a more distinct understanding of convergence by taking into account country heterogeneity, structural change and the role of policy interventions in shaping economic and environmental trajectories.

4. DATA

When analysing the convergence of environmental development in Ukraine and EU countries, it is important to choose appropriate indicators. For example, the Kyoto Protocol defines six indicators for assessing harmful emissions: CO2, methane, nitrous oxide, hydrofluorocarbons, perfluorocarbons and sulphur hexafluoride (United Nations, 1997). The Kyoto Protocol requires countries to reduce their emissions of these gases, of which CO2 emissions account for the largest proportion (70%) of greenhouse gas emissions. In addition, these emissions have been identified as the largest man-made environmental pollutant (United Nations, 1997).

In the scientific literature, CO2 emissions are used to study the convergence of indicators of negative environmental impact (Table no. 1). Since the publication of the first study (Strazicich and List, 2003), in which the authors used the unit root criterion to confirm the convergence of 22 industrialized countries for the period 1960-1997, the discussion on the convergence of CO2 emissions has been extensively explored in the scientific literature on energy and environmental economics. Recent studies on environmental convergence have addressed different types and characteristics of convergence, as well as numerous econometric methods (in particular unit root tests, clustering algorithms, cross-sectional and distributional analysis). Due to the use of different econometric approaches and data sets, the results of these studies are ambiguous, with some authors finding convergence in per capita CO2 emissions and others finding divergence. An analysis of the publications shows (Table no. 1) that the authors of most of them focus on the national convergence of emissions between countries, with limited research at the sectoral and regional levels. With regard to the latter, due to the availability of qualitative statistical information, the main focus of research is on the regions of China and the states of the USA.

The environmental catching-up hypothesis assumes that poorer countries are more polluted than rich countries, and that pollution diverges between rich and poor countries over time. The reason for this differentiation is the capital level of countries at the initial point in time. As developing countries begin to adopt environmental technologies and their income levels rise, the gap between the quality of the environment in rich and poor countries will narrow and their pollution indicators will converge. Although economic growth initially causes environmental damage, it eventually leads to an improvement in environmental quality over time. According to the study by Stern (2004), the convergence hypothesis shows that pollution decreases faster in countries with a high level of pollution than in countries with a low level of pollution. If rich countries start with a high level of pollution, while poor countries start with a low level of pollution, the result will be similar to the Kuznets curve hypothesis. However, unlike this hypothesis, which has been extensively explored in many studies, the literature on pollution convergence is quite limited. This means that it is a major disadvantage if countries focus only on reducing CO2 emissions and ignore other sources of pollution (Lin *et al.*, 2018). Therefore, the relevant indicators of negative environmental impact, including CO2 emissions, should be complemented by complex cumulative indicators. For example, the study (Ozcan *et al.*, 2019) highlights the following key indicators for analysing the impact on sustainable development: analysis of energy consumption, analysis of electricity consumption (i.e. the amount of energy used directly in direct and indirect transformations for the production of goods or services), environmental input-output tables, ecological footprint, carbon footprint, environmental pricing, Life Cycle Assessment (i.e. the assessment of the

environmental impacts associated with all stages of the life cycle of a commercial product, good or service).

However, in many studies, in particular in (UNEP/SETAC, 2009), it is noted that the most appropriate method for assessing the impact of human activity on global sustainability is the footprint itself. At its core, the Ecological Footprint reflects human demand on natural resources and has six components: fields, pastures, forests, fisheries, built-up areas and carbon footprint. The use of the Ecological Footprint in the study of environmental convergence is not so common and is present in several papers (Table no. 2).

Table no. 2 – The use of the Ecological Footprint in the study of environmental convergence

Source	Period	Countries	Main result
(Ulucak and Apergis, 2018)	1961-2013	EU	The empirical results confirm the existence of certain convergent clubs. The empirical results show differences in the quality of the environment as well as in the strategy of each EU member according to the assigned club.
(Bilgili *et al.*, 2019)	1961-2014	All	Ecological and economic convergence is observed in 15 countries from each continent. The results showed the presence of ecological footprint convergence for African, American and European countries, while the null hypothesis of convergence was rejected for Asian countries.
(Solarin *et al.*, 2019)	1961-2014	92	The results showed the existence of 10 clubs of convergence. At the same time, there are five clubs for the level of CO2 emissions, seven for the footprint of cultivated areas and two for the footprint of fisheries. It was concluded that the environmental protection policy should take into account the unique ways of convergence of each of the countries of the cluster according to the indicator of ecological footprint, as well as its components.
(Yilanci and Korkut Pata, 2020)	1961-2016	ASEAN	It was found that the Ecological Footprint is non-linear, with divergence in the second regime and absolute in the first. The second regime represents about 80% of the sample. It was concluded that there is an absolute convergence of the Ecological Footprint in the region studied.
(Erdogan and Okumus, 2021)	1961-2016	All	Main conclusions: a) dependency exists for all income groups; b) the methods used show clear convergence; c) there are several convergence clubs. The existence of club convergence implies that the environmental policy of each country studied should be developed according to its membership in a particular club.

As environmental convergence is a system of complex interactions between environmental and economic processes, we have used the Ecological Footprint (Global Footprint Network, 2022) for its empirical analysis, which allows a more complete assessment of the interrelationship between these processes. Using indicators separately leads to a one-sided assessment, distorts the real situation and does not take into account other factors that may affect environmental and economic convergence.

Based on the above, an empirical analysis of the environmental convergence of the national economies of the EU countries and Ukraine was conducted for the period from 2000 to 2022, divided into two sub-periods: 2000-2013 and from 2014 onwards, in order to identify the trends of the Russian armed invasion from 2014 and its impact on environmental convergence in the conditions of war. This can allow appropriate forecasting and strategic planning of policy implications for the period after 2022 and, in particular, after the war.

5. EMPIRICAL RESULTS

The assessment of club convergence using the methodology of Phillips and Sul (2007) did not reveal any club convergence and the following results were obtained: the negative β coefficient of -0.4889 indicates that the economies in this group are diverging over time and the magnitude of the beta suggests a moderate degree of divergence; the small standard error and the high absolute *t*-value indicate that the estimate of divergence is accurate and statistically significant, so that a *p*-value of 0 confirms that the evidence for divergence is robust. These results indicate that the group of economies under consideration is experiencing significant divergence. The strong statistical significance of the negative beta coefficient suggests that the divergence is not due to random variation but reflects a real and substantial divergence trend among these economies. Taking into account the results obtained, as well as qualitative features such as geographical proximity and similarity of economic characteristics, we formed a convergence club consisting of such countries as Ukraine, Romania, Bulgaria, Greece, Poland, Croatia, Hungary and the Baltic States. Despite the low statistical significance of the calculations, the Baltic countries are included on the basis of the results of the qualitative analysis, because the experience of these countries can also be useful for Ukraine, as all three Baltic states are now successful economies and nations that have integrated into the European Union. Ukraine went through a similar historical experience, but could not follow the same path.

The next step was to assess β-, σ-, δ- та γ-convergences. β-convergence calculations were carried out according to relationship (1), which indicates that the higher β parameter, the faster the level of average growth responds to the difference between $\log\left(\hat{y}^{*}\right)$ and $\log\left[\hat{y}(0)\right]$, and therefore there is a higher rate of convergence to the steady state. The graph of β-convergence (Figure no. 1) helps to visualize the degree of convergence of the economic indicators of the countries studied.

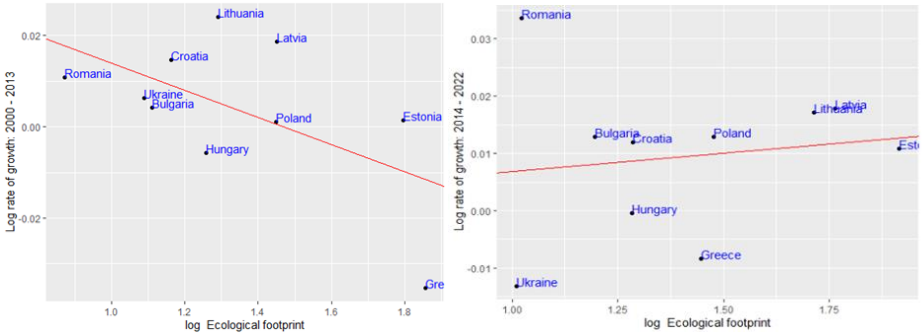

Figure no. 1 – β-convergence: subperiods 2000-2013 and 2014-2022

The downward trend (Figure no. 1) for the 2000-2013 sub-period indicates the presence of beta convergence for the club of countries studied, and therefore they have a faster pace of Ecological Footprint, although the gap between them tends to decrease over time. This proves the theoretical thesis that countries with a lower level of development have the potential for faster growth and catching up with countries with a higher level of development; for the sub-

period 2014-2022 there is an upward trend and therefore a divergence. Detailed quantitative estimates are presented in Table no. 3.

Table no. 3 – Summary of beta convergence results

Period	Coefficient	Estimate	Std. Error	t-statistic	p-value	Adj. R-squared	Result
2000-2013	Intercept	0.04380	0.0211	2.08	0.0715	0.23271	Convergence
	Initial income (indic)	-0.02982	0.0154	-1.93	0.0896		
2014-2022	Intercept	0.00053	0.0222	0.0237	0.982	-0.10143	Divergence
	Initial income (indic)	0.00636	0.0154	0.414	0.690		

The comparison in Table no. 3 shows a remarkable change in the patterns of environmental convergence before and after 2014. The earlier period (2000-2013) showed weak signs of convergence, while the latter period (2014-2022) suggests a shift towards divergence, although not statistically significant. This shift could be attributed to the geopolitical and economic impact of the Russian invasion of Ukraine, which may have disrupted the convergence process among the economies analysed. Further analysis with additional variables and robustness checks would be beneficial to fully understand the underlying factors driving these changes. However, it is important to note that the beta convergence analysis gives a general idea of the trends, but does not take into account all the possible factors affecting the green growth of countries.

Another important feature is sigma convergence, which shows how similar countries are becoming to each other on a given indicator. To assess sigma convergence, we calculated the coefficients of standard deviation and variation. Recall that beta convergence is a necessary but not sufficient condition for sigma convergence. As an example, let's visualise sigma convergence graphically (Figure no. 2). The results of sigma convergence show the main disadvantage of using this type of convergence: the reduction in the coefficient of variation is caused by an increase in the mean instead of a reduction in the standard deviation. In such a case, it is desirable to use a "pure measure of variability", in particular the standard deviation, to compare indicators.

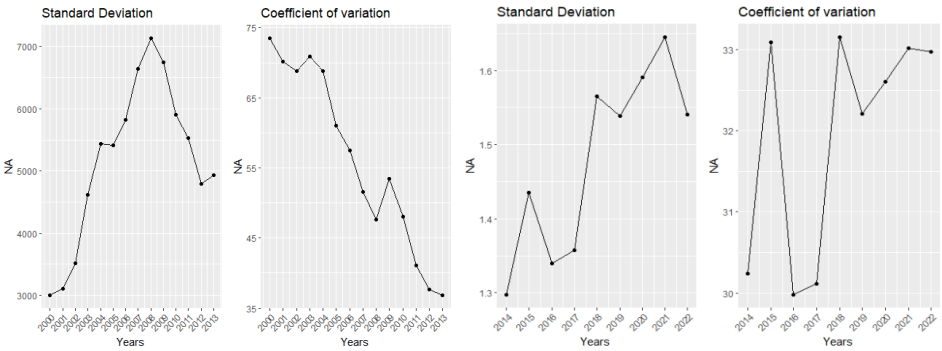

Figure no. 2 – σ -convergence: subperiods 2000-2013 and 2014-2022

For the period 2000-2013, there is a slight decrease in the standard deviation and the coefficient of variation of the Ecological Footprint, suggesting a small sigma convergence. This indicates that the dispersion of the Ecological Footprint across regions has slightly decreased over this period. While there were some years (e.g., 2003 and 2007) where dispersion increased, the overall trend is towards decreasing inequality in environmental impact. For the period 2014-2022, the increasing trend in both the standard deviation and the coefficient of variation indicates sigma divergence, meaning that the dispersion of the Ecological Footprint across regions increased. This suggests that environmental inequality between regions has risen over this period. The results show that regional disparities have increased in post-2014, which may be partially attributable to the invasion of Ukraine by Russia and its subsequent economic and geopolitical ramifications. This divergence suggests that the invasion may have exacerbated regional environmental inequalities, possibly due to economic disruptions, shifts in trade patterns, political instability, and differing regional responses to these challenges. Overall, the findings highlight that while there was some movement towards environmental convergence before 2014, the period following the invasion saw a reversal of this trend, with growing disparities in ecological footprints across regions.

The next type of γ -convergence uses country rankings to compare their "mobility" and measures the degree of convergence based on changes in rankings over time. If countries with higher rankings gradually move closer to countries with lower rankings, this indicates a process of convergence. At the same time, the analysis of gamma convergence was carried out according to the relationship (2), where a positive value of the Kendall index indicates consistency between ratings and a negative value indicates the complete opposite or reverse consistency between ratings. A value of 0 indicates no statistical consistency between the rankings. The results of the Kendall's index analysis are shown in Figure no. 3.

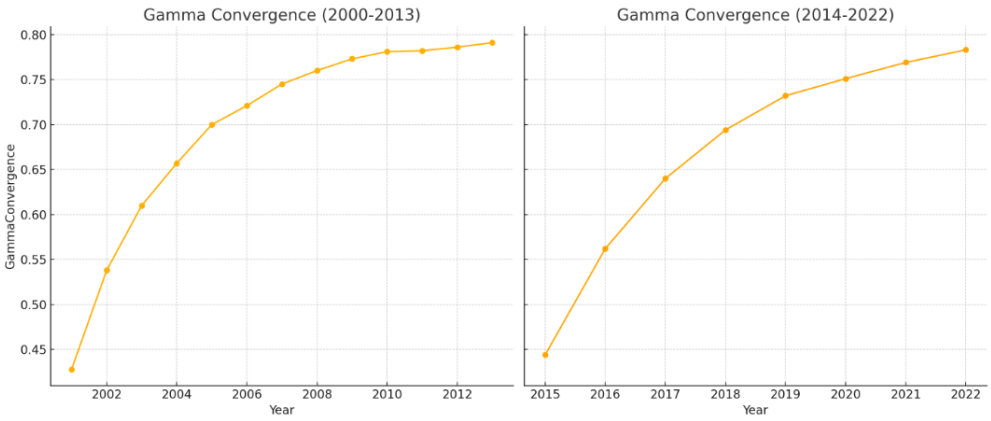

Figure no. 3 – γ -convergence: subperiods 2000-2013 and 2014-2022

The continued upward trend in gamma values (Figure no. 3) indicates even less mobility between countries in their Ecological Footprint rankings than in the previous period. This suggests that the rankings of countries have become more entrenched, with less movement between higher and lower rankings. The very high and increasing gamma values suggest a

strong process of environmental convergence. The rankings of countries in terms of their ecological footprint became even more stable and consistent, reinforcing the trend observed in the earlier period. This suggests that countries with initially higher Ecological Footprints may have continued to move closer to countries with lower Footprints, albeit at a slower pace due to the increasing stability. In 2000-2013, there was a trend of environmental convergence, with increasing consistency in country rankings and decreasing mobility, indicating that countries were moving towards similar ecological footprints. In 2014-2022, the trend towards environmental convergence continued, with even higher consistency in rankings and further reduced mobility, suggesting entrenched positions and potentially greater stability in ecological footprints. The geopolitical instability since 2014, in particular the Russian invasion of Ukraine, may have contributed to this trend by increasing regional disparities and reducing the movement towards convergence.

In the study of γ-convergence, the ratings can be used to determine the change in the level of the indicators and to observe the process of convergence or divergence of countries. In general, a higher rating indicates more "mobile" or more developed countries. A lower rating indicates less mobility or a lower level of development. In other words, the general idea of the γ-convergence ratings is to compare the level of the indicators between countries at different points in time. The corresponding ratings are shown in Table no. 4.

Table no. 4 – γ- convergence: the average ranking of countries from the convergence club

Period	Average rank									
	Bulgaria	**Croatia**	**Estonia**	**Greece**	**Hungary**	**Latvia**	**Lithuania**	**Poland**	**Romania**	**Ukraine**
2000-2013	2	5	10	6	4	9	8	7	1	3
2014-2022	2	4	10	6	3	9	8	7	5	1

The results of the γ-convergence analysis between Ukraine and the EU (Tables no. 3 and no. 4) show that Ukraine is characterized by a high level of "mobility" or growth compared to EU countries. This indicates that Ukraine has achieved positive changes in relevant environmental, which is the result of effective economic reforms, environmental policies and other factors contributing to environmental and economic growth.

Accordingly, the δ-convergence provides a quantitative assessment of the distance of the country from an exemplary model, in particular the country with the highest level of development. Delta convergence has been estimated according to relationship (3). First, the dynamics of change in the Ecological Footprint are presented for the whole period under consideration (Figure no. 4).

According to Figure no. 4, convergence is visualised in the period 2000-2009; the period 2009-2016 is characterised by the presence of delta divergence, caused by the 2008 crisis. In addition, we see an increase in the level of divergence after 2014, which also logically explains the impact of Russia's military invasion on Ukraine's economic development. Finally, the period 2016-2022 is characterised by an increase in the level of environmental growth, which led to the convergence of the club of countries studied.

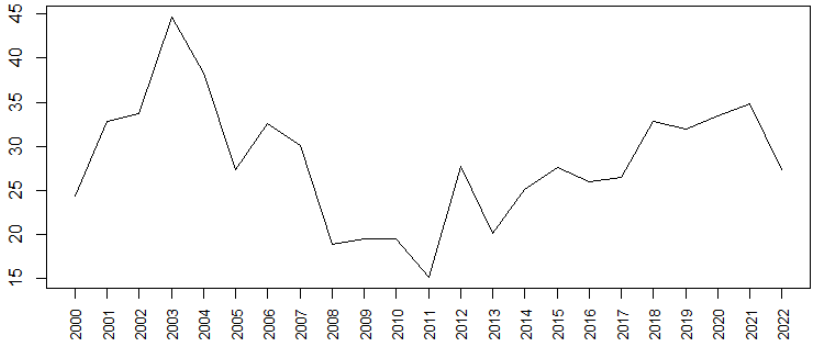

Figure no. 4 – δ -convergence of the ecological footprint for the convergence club

When analysing delta convergence, it is also important to assess how much a particular country's indicator differs from the average of a group of countries. For example, let's consider the sum of the increase and decrease in the Ecological Footprint compared to the average for the club of countries (Figure no. 5).

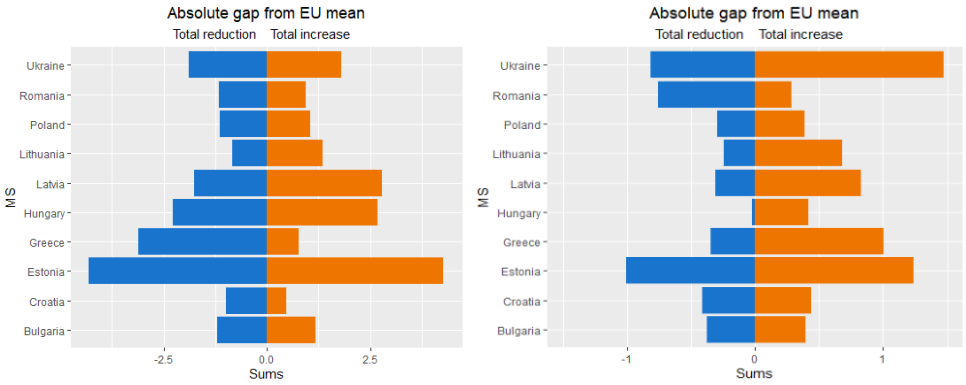

Figure no. 5 – Cumulative change in Ecological Footprint from the average of the club of countries: subperiods 2000-2013 (left) and 2014-2022 (right)

The graphical visualisation (Figure no. 5) provides an opportunity to observe the approach or distance of the respective indicator to/from the reference country (benchmark). In particular, in the period 2000-2013 we can speak about a high degree of divergence between Ukraine and the studied countries, which slightly decreased in the second subperiod. A more detailed analysis of the delta convergence is presented in Table no. 5.

Let's move on to the analysis of the form of income distribution over time according to the method (4-5), which allows us to analyse changes in the distribution of indicators. This approach considers not only the average values of the indicators, but also their distribution, taking into account the differences in development between countries. It also makes it possible to determine whether inequality in the distribution of indicators is increasing or decreasing over time and to identify which groups of countries are performing better or worse.

Table no. 5 – Cumulative change in indicators from the average for the club of countries: delta-convergence

Period	Convergence (k) / divergence (d)									
	Bulgaria	**Croatia**	**Estonia**	**Greece**	**Hungary**	**Latvia**	**Lithuania**	**Poland**	**Romania**	**Ukraine**
2000-2013	k	k	k	k	d	d	d	k	k	k
2014-2022	d	d	d	d	d	d	d	d	k	d

In order to detect the biomodality (the distribution of a random variable has two distinct peaks) of the distribution of the Ecological Footprint, we will construct appropriate graphs: a three-dimensional graph of the stochastic kernel and the corresponding contour plot (Figures no. 6 and no. 7).

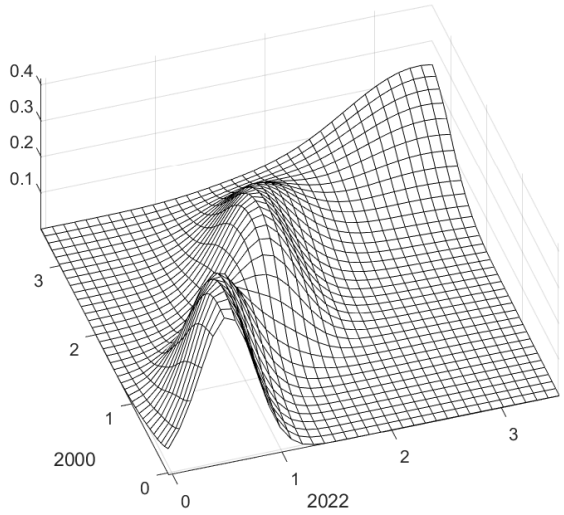

Figure no. 6 – Stochastic core: distribution of footprint relative to the 2000-2022 mean

The graphical form of the plane in Figure no. 6 allows us to draw additional conclusions compared to the previous analysis. Thus, two local maxima are clearly visible in both the poor and rich parts of the distribution of the density of the Ecological Footprint of Ukraine and the EU countries; in addition, a bulge in the centre of the graph is clearly visible, i.e. the density of the distribution of the average values of the indicator studied. The density clustering around the maxima is sharper and around the averages - softer, i.e. regions with average income levels are not distinguished. Looking at the 3-dimensional diagram allows us to draw a preliminary conclusion about the biomodality of the distribution and the presence of cluster convergence.

This conclusion is confirmed by the analysis of the percentage contour plot in Figure no. 7: Two peaks of the density of the distribution of high and low levels of the indicator are traced, and the density of the distribution of regions with an average level of Ecological Footprint is not traced.

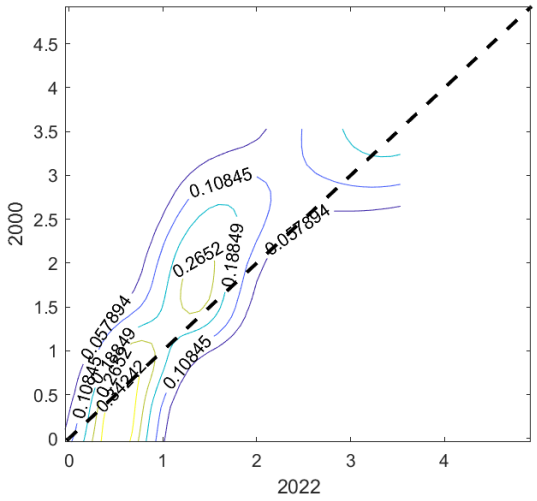

Figure no. 7 – Percentage contour plot of Ecological Footprint distributions: 2000-2022, Ukraine - EU

Figure no. 7 allows us to draw a conclusion: the peaks of the density of the distribution of high levels of the ecological footprint are below the 45-degree diagonal in comparison with similar peaks of low levels, which indicates a decrease of their difference in the years 2000-2022, i.e. there is a convergence of Ukraine and EU countries. The assessment of the distribution itself (Figure no. 8) allows us to conclude that we do not reject the hypothesis of divergence, since the studied distribution is moving in time to unimodal (the random variable has only one pronounced peak point or maximum): ergodic (statistical properties of the system in time or space are preserved when the mean values or other characteristics can be calculated as averages over all possible paths or realisations of the system).

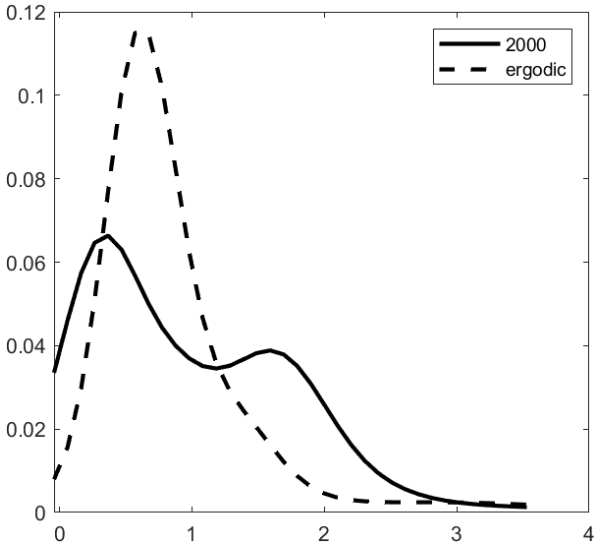

Figure no. 8 – Ergodic distribution of the Ecological Footprint: 2000-2022, Ukraine – EU

Despite the complexity of the practical application of such a technique, it will be useful for the analysis of environmental and economic convergence because it will allow the effectiveness of policies, programmes and reforms aimed at reducing the gaps between countries to be assessed. It makes it possible to visualise in more detail the distribution of development outcomes and to determine whether it is possible to achieve greater uniformity in the achievement of convergence objectives.

In order to improve clarity and to track the contribution of each output to the final objective, the following Table no. 6 provides a centralised summary of the main empirical findings:

Table no. 6 – Summary of Ecological Footprint convergence results and their implications

Period	Beta Convergence	Sigma Convergence	Gamma Convergence	Delta Convergence	Interpretation
2000-2013	Weak Convergence	Declining Variability	Moderate Mobility	Some Convergence	Initial signs of catching up due to economic and policy alignment
2014-2022	Divergence	Increasing Dispersion	Limited Mobility	Widening Gaps	Geopolitical instability and economic shocks reversed previous convergence trends

The table above provides a structured overview of convergence patterns specifically for the Ecological Footprint, helping to understand how different time periods have influenced environmental convergence trends.

Furthermore, the analysis of the distributional form of the Ecological Footprint provides additional insights into convergence over the whole period (2000-2022). Traditional models struggle to detect cluster convergence, which can involve both increasing and decreasing inequalities. The use of stochastic kernel estimation allows an in-depth examination of interregional asymmetries over time. The results indicate that while some initial convergence was observed, the distribution has widened over time and shows signs of increasing divergence in recent years. These findings support the conclusion that geopolitical instability has negatively affected environmental convergence trends in Ukraine and its peer group.

The results of this study have significant implications for Ukraine's environmental and economic policies. Given the observed divergence in the ecological footprint between Ukraine and the EU, the increasing differences in environmental indicators call for a structured approach to policy adaptation. In order to achieve environmental convergence, Ukraine should focus on the following strategies:

- legislative adaptation and policy alignment. Ukraine must continue to align its environmental policies with EU standards, particularly in the areas of emissions control, green energy development and biodiversity conservation. Strengthening environmental governance and enforcement will be key to achieving sustainable convergence;

- investment in green technologies and infrastructure, as the divergence observed after 2014 highlights the need for significant investment in renewable energy, waste management and sustainable transport. International cooperation and foreign direct investment can play a crucial role in financing these initiatives;

- post-war economic recovery and environmental sustainability because the war has severely disrupted Ukraine's economic activities and environmental policies. Reconstruction efforts should integrate green development strategies to ensure that post-war recovery supports long-term sustainability and resilience;

- reducing regional disparities, as disparities in environmental convergence across Ukraine's regions suggest the need for targeted interventions. Strengthening local governance, improving environmental monitoring and increasing resource allocation to underdeveloped areas will contribute to more balanced growth;

- leveraging EU integration for sustainable development: Ukraine's European integration process provides an opportunity to accelerate environmental convergence through access to EU funding, knowledge-sharing initiatives and collaborative research projects on sustainability.

6. CONCLUSIONS

This study has shown that environmental convergence follows similar principles to socio-economic convergence. Countries with lower per capita emissions can increase their emissions while high emitting countries reduce their emissions, leading to a balanced environmental trajectory. However, approaches to analysing environmental convergence must take into account the complexities of combining economic growth with reducing environmental impacts. In addition to classical beta, sigma, gamma and delta convergence models, distributional dynamics and stochastic kernel estimation provide a more comprehensive perspective by identifying structural shifts and regional asymmetries.

Our empirical findings show mixed results in terms of environmental convergence between Ukraine and the EU. While some methodologies point to convergence, others highlight divergence, suggesting that Ukraine's integration into the EU environmental framework is a complex and multifaceted process. Some dimensions of cooperation promote convergence, while others increase divergence.

Geopolitical instability has played an important role in shaping convergence trends. The Russian armed invasion in 2014 altered Ukraine's trajectory towards EU alignment, negatively impacting economic stability, environmental policies and institutional development. The full-scale invasion in 2022 further exacerbated these challenges, disrupting key policies that could have facilitated convergence.

To reduce divergences and improve environmental integration with the EU, Ukraine needs to adopt a multi-pronged approach, including regulatory reforms, investments in sustainable technologies and adjustments to regional policies. A continued focus on cooperation with EU countries, drawing on international expertise and funding opportunities, will be essential to strengthen Ukraine's environmental and economic resilience in the long term.

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A Catering Perspective of the Banking Sector Markets: Evidence from a Cross-Country Analysis

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Abstract: In this paper, we attempt to analyze and better apprehend the nature, structure and dynamics of connections between bank stock indices of different countries in G7 and BRIC regions during the outbreak of tremendous events. For this end, we apply the bi- and multi-variate wavelet method on banking sector indices during the period 1/1/2016 to 4/28/2023. The empirical findings show that the banking sector indices' comovement between the US and other markets tends to change in both short- and long-term and depend on region/country. Such connections are highly affected by the outbreak of tremendous events (crisis/pandemic). In particular, the impact of the SVB collapse on such connections seems to be dissimilar among countries and regions. The findings could have insightful information for investors and portfolio managers and call for stronger emphasis on the suitable banking regulatory environment.

Keywords: comovement; multivariate wavelet analysis; the SVB collapse.

JEL classification: G15; G20.

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1. INTRODUCTION

Overall, the banking industry is a substantial part of the economy around the world (Pandey *et al.*, 2023). It is characterized by specific features in comparison to other economy's sectors (Baumöhl *et al.*, 2022) as banks successfully perform important functions to better foster the economy's performance (Allen, 1990). Notwithstanding its far-reaching importance, the banking sector still remains fragile. That is why any bank bankruptcy could have tremendous and adverse effects (Cowan *et al.*, 2022) on other financial institutions in the sector through interbank connections from different perspectives (e.g. counterparty linkages related to liability/asset liability positions). Even if such connections are important for the stability of the financial system, they intensify the systemic risk during turbulent times. Not only that, but it can also imply risk contagion from such sector to other financial markets and even the real economy. Many events including the global financial crisis, the European sovereign debt crisis and the Covid-19 pandemic have increasingly shaken the national and international financial markets (Foglia *et al.*, 2022) and adversely impacted investor confidence. In this regard, the failure of Silicon Valley Bank (SVB) which is the 16th greatest bank in the United States led to the financial losses ($billions) in deposits and investments and arose against the backdrop of a changing tech industry during the health crisis (Yadav *et al.*, 2023). According to Vo and Le (2023), greater debt investments, small equity investment and a strongly concentrated depositor base. The collapse of the Silicon Valley Bank and then two other US banks (Signature Bank and Silvergate) implied a strong reaction among financial stress indicators given that depositors and investors were worried about downturn which may transform into global financial crisis (Dosumu *et al.*, 2023).

From an academic standpoint, many researchers have started to examine the effect on the SVB fall on the banking system and financial markets. For instance, Dosumu *et al.* (2023) investigate how social media increases bank runs using the recent bank turmoil in the United States. They display that social media offer a conduit through which an immediate adverse and substantial effect of the bank crisis transmits among global investor sentiments and market outcomes. They also show a substantial (resp. insignificant) spillover effect of the turmoil on G7 and European (resp. Asian and African) economies. Pandey *et al.* (2023) analyze the effects of Silicon Valley Bank failure on global stock markets. The magnitude of such effect is well-documented in developed markets. They also report that such collapse seems to be dissimilar among all countries. Yousaf and Akhtaruzzaman *et al.* (2023) study the effect of the SVB collapse on US market sectors based on event study approach. They report significant and negative abnormal returns on the event date only for the real estate, materials and financial sectors. They also display that the financial sector records the most important effect. Yadav *et al.* (2023) explore the influence of SVB failure on the top nine global equity indices. They report that the steep sell-off of equities can be attributed to the bank run on March 10, 2023. They afterwards indicate the substantial effect of SVB fall on the global equity markets with contagion effects of such crisis.

On the other hand, and leafing through literature on financial contagion and cross-border linkages, it is worth noting to mention that bank collapses could substantially and negatively influence national and international stock markets (Bellia *et al.*, 2022). It could be well-documented for community/small banks (e.g., Toussaint-Comeau *et al.*, 2020) and amid economic stressful times. Some studies report that factors (e.g. the kind of bank asset holding) impact the effect of bank bankruptcy on financial markets (Caiazzo and Zazzaro, 2023)

whereas other ones (e.g. interbank loans, liquidity and market factors) could contribute to the degree of systemic risk (e.g., Brunnermeier *et al.*, 2020; Meuleman and Vander Vennet, 2020). Strikingly, the interconnection among markets has been investigated using various approaches and techniques. As a matter of fact, many researchers have interestingly tried to apprehend a great degree of dependence and contagion across bank sectors within and among countries and regions during crisis periods (e.g., Black *et al.*, 2016; Toussaint-Comeau *et al.*, 2020; Zedda and Cannas, 2020).

Based on this crux, the purpose of this study is to analyze the structure and dynamics of connections between bank stock indices of different countries in G7 and BRIC regions during the outbreak of tremendous events such as the Covid-19 pandemic and the SVB collapse. Herein, it seems to be relevant to analyze the context of BRIC and highly industrialized (G7) countries given that BRIC countries are emerging economies along with opportunities for growth and investment (Sawal and Anjum, 2023) and not much is known about how connections between bank stock indices of different countries in G7 and BRICS regions. The regulators of BRIC countries have implemented more liberal financial policies with the aim of deleting regulatory obstacles to competition which produces efficiency gains, restricts bank fragility and fosters financial stability (IBRD, 2020). On the other hand, the regulatory practices (e.g. the banks operating systems) in G7 countries seem to be the benchmark for the other economies to follow (Chortareas *et al.*, 2012). Oredegbe (2022) analyzes the banking industry stability in G7 and BRICS during the period 2005-2014 and displays that stability level in a previous period influences stability during the subsequent period. They show that competition enhances stability. Economic growth improved stability in BRICS. Interestingly enough, the advent of unexpected and adverse events such as the Covid-19 pandemic and the SVB collapse have revived the debate on the interaction of banking sector, financial stability, and financial markets. By doing so, we try not only to offer insights into the time-varying magnitude of potential contagion impacts of tremendous events (e.g. a bank fall) on financial markets but also the dynamic connectedness among financial institutions. Together, it can help different stakeholders to establish an insightful picture of contagion dynamics within national/international financial system. From a methodological standpoint, we use the wavelet approaches which allow us to better apprehend the lag-lead relationship, phase difference and correlation framework in the frequency-time domain. Indeed, such methods are considered as frequency-time domain approaches based on frequency-time decomposition. They distinguish from other methods such as (A)DCC models by offering more interesting information based on time and frequency domains (Rua and Nunes, 2009). Therefore, they offer some insights into investor behavior and investment horizons. In particular, the wavelet methods help to analyze the comovements among indicators through time and frequencies (high, medium and low).

This study contributes to literature in different ways. First, we investigate the potential connections among banking sector stocks for different regions (developed and emerging countries). As a matter of fact, delving into the available literature on the cross-country analysis of international banking sectors seems to be narrow; nevertheless, some studies have endeavored to investigate return transmission and volatility spillover effects in international sector stocks. Second, we analyze the nature and dynamics of banking sectors' comovements during a crisis/pandemic. Despite other previous studies which particularly analyze the impact of specific adverse event (e.g. the Covid-19 pandemic), we try to the behavior of comovements with the outbreak of different events. This allows us to foster insights into the connectedness of banking sectors in different regions and enhance financial regulations.

Third, this study can provide insightful information to understand the resilience/fragility of banking systems to the intensity of unprecedented events. Finally, the research lacks studies explicitly investigating bank failures' effect on cross-border linkages. That is why this paper contributes to the literature by providing fresh evidence of the dynamics and magnitude of the effect of the SVB bank run on the connectedness between banking sectors in different regions.

Overall, foreshadowing the main empirical findings, one might document that exploring the time-varying frequency-time connectedness of US bank stocks and bank stocks in different regions in multi(bi)-variate structure show insightful empirical results. First, the linkages between assets seem to vary both long- and short-run. Some cross-correlations tend to be higher due to the advent of SVB fiasco and Ukraine-Russia war. So, the nature of negative events affects significantly the asymmetric dynamics of comovements through assets.

The structure of this paper is as follows. A set of studies exploring the effect of adverse events on the banking sector stocks' comovements is reported in Section 2. Section 3 clearly presents the methodology. Data description and descriptive statics are reported in Section 4. The estimation results and interpretations are presented in Section 5. Finally, Section 6 concludes and discusses.

2. LITERATURE REVIEW

Many researchers have interestingly investigated the connectedness among banking sectors in different regions, particularly with the outbreak of tremendous events such as the Covid-19 pandemic and the SVB failure. As a matter of fact, Rua and Nunes (2009) use the wavelet analysis to clearly depict how international stock returns relate in the frequency and time domains. Tiwari *et al.* (2016) tend to evaluate the level of contagion, comovements and rolling correlation among the PIIGS and those of Germany and the UK by using the wavelet method. They show that, in the short-term, the correlation level is stronger during financial distress episodes. However, in the long-term, the comovements exist for different time horizons. Albulescu *et al.* (2017) analyze the contagion and comovement among six international stock index futures markets by using a frequency-time method. The empirical results show that comovements among the international markets manifest in the long term. However, the contagion phenomenon linked to the very short-term horizon exists in the case of the European markets due to their level of integration. Jokipii and Lucey (2007) profess that the comovements between the Eastern and Central European banking sectors are greatly attributed to the contagion effect. Bouvatier and Delatte (2015) display the international banking integration outside the Euro zone has increasingly reinforced after the financial crisis. Mensah and Premaratne (2018a) study how the banking systems in different countries can commove with each other. They report that the banking sector returns connections changes during bull and bear markets. They also indicate that average dependence achieve moderate levels, even if dependence among the banking sectors of the developed Asian markets are quite greater than the emerging ones. Mensah and Premaratne (2018b) investigate the degree of integration for ASEAN and global markets during the period 2000-2012. They find high correlation between markets over time.

Arreola Hernandez *et al.* (2020) show that the most substantial emerging market spillover receivers and transmitters appear to be banks from Brazil. They also indicate that comovements between developing market banks seems to be more significant than the American institutions. Hanif *et al.* (2021) investigate the effects of Covid-19 pandemic on

spillovers among the Chinese and U.S. stock sectors. They display that such event amplifies the risk spillovers for different markets during 03/2020-04/2020. Laborda and Olmo (2021) report that the banking sector seems to be an essential shock transmitter to the rest of the economy. Tabak *et al.* (2022) analyze the impact of the Covid-19 pandemic on changes in the forms and intensity of banking sector connections across various countries. They display that the changes in the classification of receiving and transmitting spillover during the Covid-19 pandemic. They also show interesting acquaintances about systemic integration among banking markets in different countries, particularly during tremendous times. Foglia *et al.* (2022) investigate the volatility connectedness of banking sector in the Eurozone during the period 2005-2020. They report that thirty banks are increasingly interrelated. They also reveal the high effect of Covid-19 pandemic on the volatility dynamics. They afterwards display that small-medium banks play a substantial role in the contagion effect. By using Dynamic Factor Model (DFM) with time-varying loading parameters and stochastic volatility, Kapinos *et al.* (2022) to develop a new measure of comovement in the banking sector which takes into consideration the dynamic nature of interlinkages in the net chargeoffs (NCO) and return on assets (ROA) among banks. They show that the degree of comovement in NCO and ROA peaked during the 2009 financial crisis, indicating a substantial increase in sector-wide stress. Shabir *et al.* (2023) analyze the impact of Covid-19 pandemic on the stability and performance of the banking sectors in 106 countries during the period 2016 Q1-2121 Q2. They indicate that the advent of Covid-19 pandemic has substantially lowered bank stability and performance. They also report that the negative effect of Covid-19 pandemic is related to the features of the market and bank framework.

With the outbreak of the recent bank crisis, many researchers have endeavored the impact of SVB on national stock markets and cross-border linkages. For instance, Aharon *et al.* (2023) analyzes the effect of the SVB collapse on the financial markets. Based on an event study, they show that stock markets responded negatively to the SVB collapse. They also display that stock markets in Latin America, Europe and the Middle East and Africa experienced a substantial and negative reaction on the day of the event. Such impact spent in the aftermath of the SVB collapse. Yousaf *et al.* (2023) analyze the impact of the SVB bankruptcy on financial markets. They display that abnormal returns seem to be negative and significant for US equities, global banks, Bitcoin and GCC equities. Nevertheless, abnormal returns seem to be insignificant for most metals, fiat currencies and energy markets. Akhtaruzzaman *et al.* (2023) examine if the SVB collapse can catalyze financial contagion in India, Brazil, South Africa and the G7 countries. They report that contagion seems to be well-documented within global banks but lower in other areas. They also show that the contagion is short-lived, being most widespread during the week following the SVB failure. Pandey *et al.* (2023) investigate the effect of SVB collapse on financial markets using an event study. They show that the collapse triggered uncertainty and panic, implying substantial and negative returns. The level of the effect is well-documented within developed marks due to the greater level of interdependence and integration with the global economy, along with significant and high abnormal volatility. They also display the effect of the SVB collapse seems not similar among countries.

Yousaf *et al.* (2023) analyze the potential effect of the SVB collapse on US market sectors. They report substantial and negative abnormal returns on the event date uniquely for the real estate, materials and financial sectors. They show that the most substantial effect is recorded for the financial sector. Yadav *et al.* (2023) analyze the effect of SVB fall on stock indices during the period 06/09/2022-22/03/2023. They show that the significant sell-off of

stocks could explain such movement. They also report that the SVB failure significantly affect stock markets, coupled with contagion effects spreading among markets. Azmi *et al.* (2023) analyze the effect of SVB collapse on global assets. They report that no substantial reaction is detected, except for US Treasury Bills and gold. They also display little evidence of spillover/reputation contagion from the SVB fall to other asset classes. Dosumu *et al.* (2023) investigate how social media increases the effect on bank collapse on financial markets. They show that the important role of social media which contributes to the immediate, significant and negative impact of the bank crisis on stock markets. They also report a relevant spillover effect of the bank crisis on G7 and European economies. Nevertheless, no significant effect is documented for markets in Asia and Africa.

Aharon *et al.* (2023) examine the possible impacts on different financial markets of a banking shock by exploring the recent collapse of SVB and its repercussions on technological and banking companies in the Europe, China and US and its impacts on gold, oil and cryptocurrency markets. Using event study method, the empirical results display that assets (e.g. gold, cryptocurrencies and oil) show positive returns, indicating that investors search for refuge in these perceived safe-haven assets. They also display that the SVB's financial distress has a significant impact on the stocks of banking firms in Europe and US whereas it has a positive effect on the stocks of technology firms in these regions. Mehdian *et al.* (2024) show that the reactions of financial markets to the failure of some banks seem to be mixed. The banks' collapses lead to stronger market volatilities than positive news for Dow Jones Equity Real Estate Investment Trust Index and Bitcoin. Galati and Capalbo (2024) use BEKK model to analyze contagion effects among digital assets during the SVB collapse. The results show that the presence of contagion effects among Bitcoin and major stablecoins. Sarmiento (2024) assesses how the market stress is linked to the failure of one of the most interconnected NBFIs in emerging market economy impacted the availability and pricing of unsecured interbank funding. The findings display that the market stress conducted to a reallocation of money mutual funds deposits within the banking sector, which impacted the banks' liquidity provision in the unsecured interbank market.

3. METHODOLOGY

To investigate the effect of the momentous events such as the collapse of SVB bank on the interdependence of bank stocks of different countries with US bank stocks, this article uses the wavelet coherency (WTC) and wavelet local multiple correlation (WLMC) approaches.

According to the advantages of wavelet transforms, techniques such as cross-wavelet analysis (CWT) and wavelet coherence (WTC) have emerged as powerful tools to investigate the interdependence of financial indices (Gençay *et al.*, 2001).

We use WTC and phase analysis to examine the interdependence and causality of two indices in the time-frequency domain. Furthermore, we use WLMC to investigate the multiple correlations between the US banking stock and G7 and BRIC banking stock indices at different time horizons. One of the most advantages of using the wavelet approach in financial analysis is to examine the correlation at the time and scale. Although econometric methods such as the DCC-GARCH also show a correlation in the time, but they are not able to analyze the correlation at scale.

In the following parts, we briefly illustrate WTC and WLMC concepts.

3.1 Wavelet Coherency (WTC)

The co-movement between two series over time and frequencies is measured by using coherence. Wavelet coherence coefficient defines as follows (Torrence and Compo, 1998; Torrence and Webster, 1999):

$$R_t^2(s) = \frac{|S(S^{-1}W_t^{AB}(s))|^2}{S\left|\left(S^{-1}\left|W_t^A(s)\right)\right|^2 S\left|\left(S^{-1}|W_t^B(s)\right)\right|^2|} \quad (1)$$

In equation (1), S is a smoothing operator for both time and scale. $R_t^2(s)$ is similar to the correlation coefficient. Since its value is positive, the values close to 0 show weak dependence, and the values close to 1 reveal strong dependence. However, this coefficient does not indicate the direction of causality. To illustrate the direction of causality and negative or positive correlation, we use wavelet coherence phase difference analysis. The wavelet coherence phase can be expressed as equation (2):

$$\Phi_{xy}(\mathrm{s}) = \tan^{-1}\left(\frac{I\left\{S\left(S^{-1}W_t^{AB}(s)\right)\right\}}{R\left\{S\left(S^{-1}W_t^{AB}(s)\right)\right\}}\right) \quad (2)$$

where I and R show the imaginary and real parts of the smooth power spectrum, respectively.

3.2. Wavelet Local Multiple Correlation (WLMC)

WLMC is an extended wavelet approach in which dynamic correlations of multivariate are investigated. In other words, this type of multiple correlation is variated over time. Fernández-Macho (2018) introduced the estimated WLMC:

$$\tilde{\rho}_{X,s}(\lambda_j) = \mathrm{corr}\,(\theta(t-s)^{\frac{1}{2}}w_{ijt}, \theta(t-s)^{\frac{1}{2}}\widehat{w}_{ijt}) = \frac{\mathrm{cov}\,(\theta(t-s)^{\frac{1}{2}}w_{ijt}, \theta(t-s)^{\frac{1}{2}}\widehat{w}_{ijt})}{\sqrt{\mathrm{Var}(\theta(t-s)^{\frac{1}{2}}w_{ijt})\mathrm{Var}(t-s)^{\frac{1}{2}}\widehat{w}_{ijt})}} \quad (3)$$

where $s = 1, \ldots, T$ and $\theta(\cdot)$ is a moving average weight function. In this research, the Gaussian function considered in Fernandez's article is used.

4. DATA AND DESCRIPTIVE STATISTICS

In this article, KBW Bank (BKX), S&P/TSX Canadian Financials, FTSE 350 Banks (FTNMX301010), CAC Financials (FRFIN), DAX Banks (CXPBX), FTSE Italia All-Share Banks (FTITLMS3010), Nikkei 500 Banking (NBKS), Financials (IFNC), MOEX Financials (MOEXFN), Nifty Bank (NSEBANK), and FTSE China A 600 - Banks (FTXIN4301010) data are used during the period from 1/1/2016 to 4/28/2023, containing a total of 1890 available daily observations. The return for the banking stock index (R_{it}) is defined as $R_{it} = \frac{P_{it}-P_{it-1}}{P_{it-1}}$, where P_{it} and P_{it-1} represent the price of the bank stock index i at time t, and time $t-1$, respectively. Annex 1 indicates plots on these returns.

Table no. 1 – Descriptive statistics

Index Code	MAX	MIN	Mean	Std. Dev	Kurtosis	Skewness	JB	ADF
KBW Bank (BKX)	13.82	-17.67	0.0046	1.93	11.393*** (0.000)	-0.547*** (0.000)	8422.023*** (0.000)	-45.080*** (0.000)
S&P/TSX Canadian Financials	13.93	-13.71	0.019	1.14	43.704*** (0.000)	-0.689*** (0.000)	122924.069*** (0.000)	-42.474 *** (0.000)
FTSE 350 Banks (FTNMX301010)	11.54	-11.12	-0.0026	1.61	7.042*** (0.000)	-0.220*** (0.000)	3200.292*** (0.000)	-42.107 *** (0.000)
CAC Financials (FRFIN)	11.17	-15.11	0.006	1.52	15.765*** (0.000)	-0.954*** (0.000)	16212.848*** (0.000)	-38.634*** (0.000)
DAX Banks (CXPBX)	11.99	-20.38	-0.014	2.43	6.892*** (0.000)	-0.690*** (0.000)	3176.077*** (0.000)	-39.736*** (0.000)
FTSE Italia All Share Banks (FTITLMS3010)	11.03	-24.94	-0.013	2.22	9.952*** (0.000)	-1.044*** (0.000)	6647.654*** (0.000)	-40.825*** (0.000)
Nikkei 500 Banking (NBKS)	7.76	-8.36	-0.018	1.5	2.119*** (0.000)	-0.230*** (0.000)	302.210*** (0.000)	-37.092*** (0.000)
Financials (IFNC)	12.36	-14.25	0.05	1.84	9.155*** (0.000)	-0.615*** (0.000)	5486.049*** (0.000)	-42.520*** (0.000)
MOEX Financials (MOEXFN)	12.29	-24.66	0.017	1.67	40.470*** (0.000)	-3.149*** (0.000)	107847.398*** (0.000)	-36.645 *** (0.000)
Nifty Bank (NSEBANK)	7.98	-18.31	0.049	1.44	19.630*** (0.000)	-1.324*** (0.000)	25223.573*** (0.000)	-42.072*** (0.000)
FTSE China A 600 - Banks (FTXIN4301010)	44.62	-65.35	0.002	2.19	440.551*** (0.000)	-8.536*** (0.000)	12496773.861*** (0.000)	-50.621*** (0.000)

Notes: *** indicates significance at 1%; Std. Dev and JB denotes standard deviation and Jarque-Bera test, respectively. ADF denotes Augmented Dickey and (1979).

Table no. 1 displays the descriptive statistics of the returns of bank stock markets in G7 and BRIC countries. The average returns of all indicators except the bank stock in the UK, Germany, Italy, and Japan are all positive. This reveals that in these countries, on average, the returns of banking stocks have been positive. The highest and lowest returns are related to the China index. Also, based on the standard error deviation, the highest and lowest dispersion are assigned to Germany and Canada indices, respectively. All the series display a leptokurtic distribution and are negatively skewed. More precisely, all the distributions are characterized by a longer tail on the distribution's left part. The high values of kurtosis indicator indicate heavier tails and reveal the impact of extreme events. The FTSE China A 600-Banks index has the highest kurtosis and skewness, indicating the presence of large shocks. In contrast, NBKS has the lowest kurtosis and skewness compared to other indices, indicating that it is less volatile. The statistical properties of these time series, such as high kurtosis, skewness, and non-normal distribution, can significantly influence the analysis and the selection of appropriate methods. Therefore, it is crucial to employ a method that does not rely on assumptions about the underlying distribution of data. Wavelet analysis, which is free from distributional assumptions, is particularly effective in managing the inherent statistical

complexities. This approach is well-suited for analyzing financial data, which may exhibit non-linear fluctuations or extreme shocks.

Table no. 1 afterwards presents the estimation results from applying Augmented Dickey-Fuller (ADF) unit root test on different time series. One might reject the null hypothesis of a unit root. This finding is also confirmed by accepting the null hypothesis of stationary process.

Table no. 2 – Correlation between bank stock indices in G7 and BRIC countries

		US	UK	CA	FR	GE	IT	JP	CH	RU	IN	BR
G7	**US**	1										
	UK	0.59	1									
	CA	0.76	0.54	1								
	FR	0.65	0.80	0.63	1							
	GE	0.57	0.74	0.54	0.81	1						
	IT	0.53	0.68	0.50	0.82	0.78	1					
	JP	0.17	0.26	0.20	0.27	0.25	0.20	1				
BRIC	**CH**	0.04	0.09	0.06	0.8	0.06	0.05	0.08	1			
	RU	0.23	0.31	0.30	0.36	0.30	0.30	0.08	-0.001	1		
	IN	0.33	0.35	0.40	0.43	0.31	0.31	0.18	0.09	0.26	1	
	BR	0.44	0.31	0.49	0.37	0.30	0.30	0.09	0.03	0.18	0.23	1

Table no. 2 presents the correlation between the bank stock indices. According to Table no. 2, it can be observed that the highest and the least correlations are associated with France-Italy and China-Russia, respectively. Also, in G7 countries, Canada and Japan have the highest and the least correlation with the US bank stock index, respectively. Moreover, in BRIC countries, there are the highest and the least correlation with the US bank stock in Brazil and China, respectively.

5. RESULTS AND INTERPRETATIONS

This section investigates the interdependence and causality between the banking stock indices in BRIC and G7 counties with the US bank stock index, at different time scales using wavelet coherency and phase difference. In this section, we use coherency wavelet heat figures. The horizontal and vertical axis represent time and scale, respectively. Also, the color shows the amplitude of coherency. According to the vertical bar on the right-hand axis, the warmer red color represents a stronger correlation. In contrast, the blue color represents a region with a lower correlation. A black line that is drawn around some regions shows the intensity and significance of the correlation. The periods are 4, 16, 64, and 256, daily. The value of wavelet coherence is always positive. The value of wavelet coherence is always positive. So, we couldn't distinguish between positive and negative co-movements without employing additional techniques such as the phase difference approach. By analyzing the phase difference, one can gain a better understanding of the nature of the relationship between the variables and determine which one is causing changes in the other. In the phase difference approach, the direction of causality between two variables is represented by arrows. When the arrows are pointing to the right (→) or left (←), it indicates that the two variables behave in phase or anti-phase, respectively. On the other hand, when the arrows are pointing (↑), (↗), or

(↙), it signifies that the first variable is leading. Conversely, when the arrows are pointing (↓), (↖), or (↘), it shows that the second variable is leading.

Our results can be summarized across three sections as follows.

5.1 The interdependence between US bank stock return and G7 bank stock returns

Figure no. 1 presents the correlation between the US banking stock return and six banking stock returns in G7 region. The most interdependence exists between the US banking stock and Canadian banking stock. Also, the interdependence between the US banking stock and Japanese banking stock is lower than in other countries. Panels a, b, and c (Figure no. 1) show the co-movement between the USA banking stock and the UK, Canadian, and France banking stocks. Based on this crux, there are stronger correlations in these markets with the US. The phase difference analyses show that they are in phase. In addition, in the short term, the co-movement between US-Canada is higher after the Covid-19 pandemic. Such findings are in line with those of Baranova *et al.* (2022) who showed that UK and Canadian banking stock indices have a relative correlation with the USA banking stocks. The degree of correlation between the USA banking stock and the UK, Canadian, and France banking stocks makes diversification benefits between such assets practically impossible, especially during the post-Covid-19 pandemic. This implies that investors and portfolio managers cannot find hedge, safe-haven benefits and diversification benefits when including such assets together.

As shown in Figure no. 1, at the beginning of the period, the correlation between bank stock indices in the G7 countries and the United States increased. In this period, the correlation between bank stock indices in the G7 countries and the USA increased. The German banking crisis and issues related to non-performing loans in Italy had a great impact on the European stock markets during this period. As a matter of fact, the International Monetary Fund warned about the possible future uncertainty of global financial stability and risk spillover among the 28 banks in the global systemically important banks (IMF, 2016). Although the correlation between the banking indices of the investigated countries and the United States has relatively decreased during the years 2017 to 2018, with the formation of the Turkish currency crisis and then the Covid-19 pandemic, this relationship has been relatively intensified. Overall, the Covid19-pandemic is the one of most factors that caused the interdependence between markets after 2020. Even though, after 2021 these correlations were declining. After 2022, these relationships are increasing. Ukraine war and bank crises such as the SVB collapse are the significant factors that cause this increase.

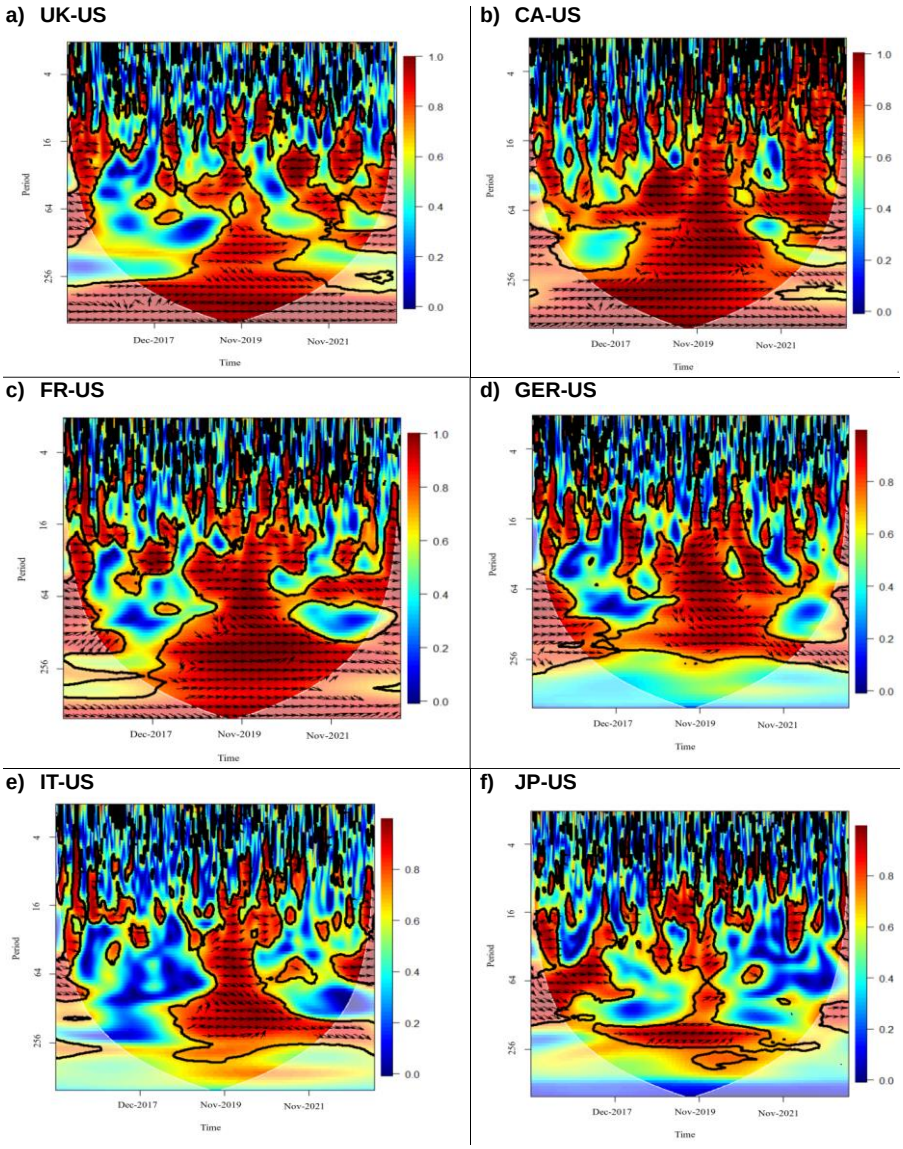

Figure no. 1 – The interdependence between US bank stock return and G7 bank stock returns, using wavelet coherency

5.2 The interdependence between US bank stock return and BRIC bank stock returns

Figure no. 2 presents a wavelet coherency between the US banking sector stock returns and the four BRIC country's banking sector stock returns. In Figure no. 2, the Indian banking stock sector has the highest correlation with the US banking stock. This correlation is higher in the long term. In general, the correlation between the banking stock sector of BRIC

countries and the US banking stock sector has increased in the medium term since mid-2018. This correlation has been higher in Brazil, India, and Russia. However, since 2021, this correlation has declined in BRIC countries. The results of the phase difference analysis in Figure no. 2 show that the returns are generally in-phase. It also reveals that US banking stock drives the co-movements of Brazilian and Indian banking stocks in the long term. Such finding displays that investors cannot gain diversification benefits from holding US banking stock at long term. Specifically, most right-pointing arrows in the long term are upward after 2018. On the other hand, Figure no. 2 clearly shows that the co-movement between US banking stock and BRIC countries often is little in the short-term. As such, BRIC banking stock markets can provide rewarding grounds for investors in short-term.

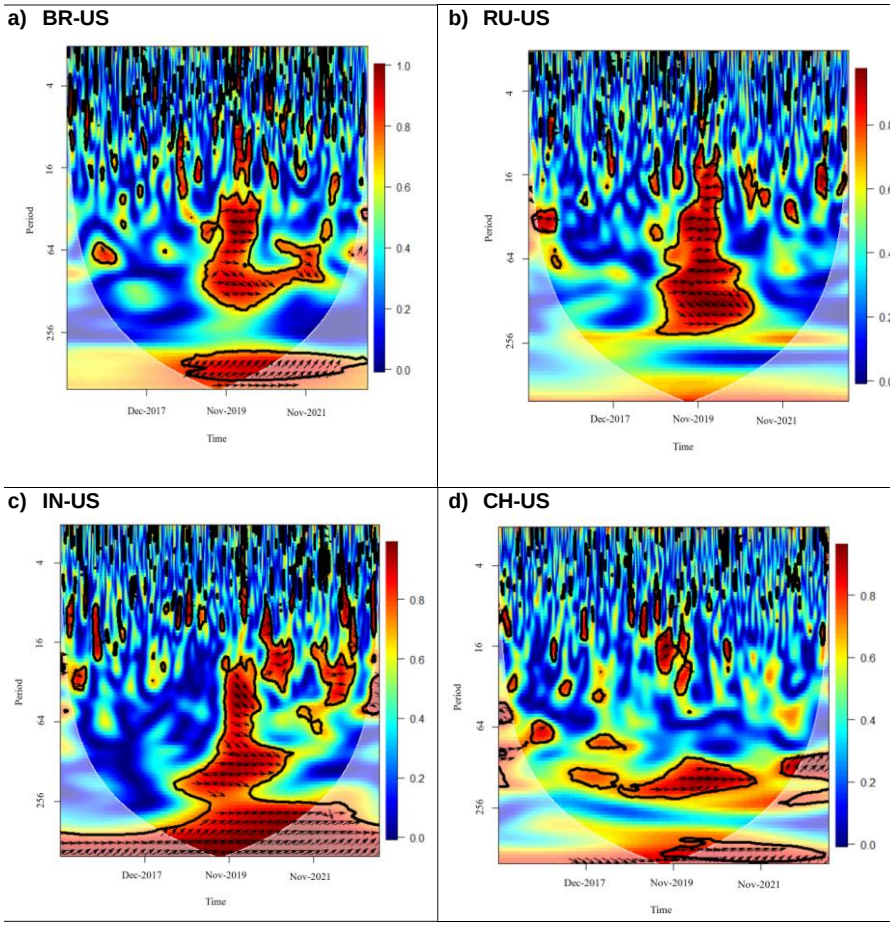

Figure no. 2 – The interdependence between US bank stock return and BRIC bank stock returns, using wavelet coherency

Comparing Figure no. 1 and Figure no. 2 reveals that the interdependence between the banking stock market in G7 and USA is more important than the BRIC and USA. The banking

crises before 2018 or after 2021 increased the correlation between markets in G7 countries but this correlation declined in BRIC countries. It seems that the most important factor that has caused greater correlation between the American banks index and the BRIC countries is the Covid-19 pandemic crisis. It is worth noting that investors cannot gain diversification benefits from holding of such assets and develop effective risk management strategies.

5.3 The interdependence between US- BRIC and US-G7 bank stock market: A comparative analysis

This section examines the wavelet local multiple correlations (WLMC) between G7 and BRICS countries' banking stock with the US. Figure no. 3 and Figure no. 4 illustrate the WLMC for the G7 and BRIC countries respectively. As mentioned earlier, the vertical bar on the right side of the figure shows the colors that represent the correlation of the markets. In Figure no. 3, the range of this correlation is determined from 80 to 100 percent. So, the blue color indicates 80, and the red color indicates the highest correlation. According to Figure no. 3, the correlation between bank stock indices in the G7 countries and the United States is high during the period under study. However, this correlation has increased at times. In other words, this interdependence seems to be intensified during crises, including the banking crisis of 2016, the Covid-19 pandemic, the war in Ukraine, and the recent economic and banking problems in 2023 such as the bankruptcy of SVB.

These findings align with the bi-directional analysis in Figure no. 1, emphasizing that crises amplify correlations between banking stocks in G7 countries. Similarly, the results show that the correlation between the G7 countries' bank stock indices and the United States is also high. This increasing interdependence significantly reduces investors' ability to achieve diversification benefits when constructing portfolios that include these assets.

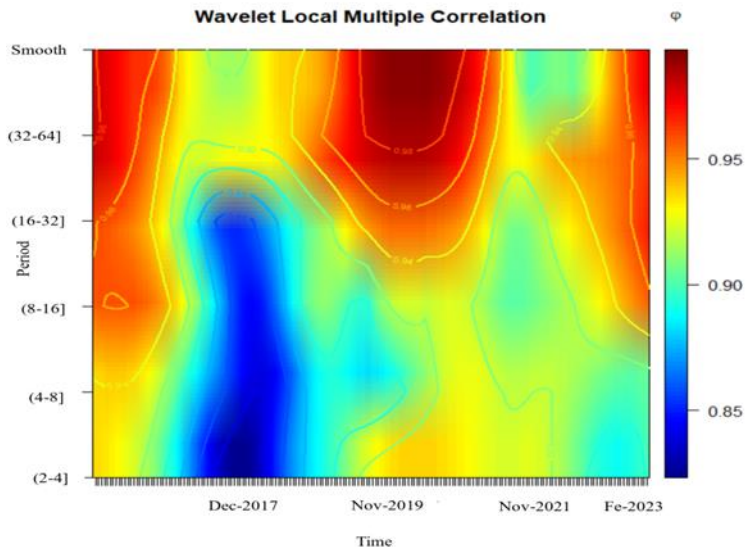

Figure no. 3 – The interdependence between US-G7 bank stock market using WLMC

In Figure no. 4, the range of the correlation is determined from 30 to 100 percent. The blue color represents a correlation of 30 percent or less, while the red color indicates the highest correlation of 100 percent. As shown in Figure no. 4, the correlation of banking stocks in BRIC countries with the United States has increased in all frequencies during the Covid-19 pandemic. Comparing Figure no. 2 and Figure no. 4 shows that the correlation between the US banking stock market and the BRIC countries has increased significantly during 2019 and 2020, especially in the medium and long term. Furthermore, a comparison of Figure no. 3 and Figure no. 4 reveals that the correlation between the banking stock markets of G7 countries and the United States is higher than that of the BRIC countries.

During the COVID-19 pandemic, the correlation pattern between the BRIC countries and the United States is similar to that of the G7 countries. However, the correlation between the G7 countries and the United States is more significant during 2016 and 2023. The beginning of the analyzed period coincides with the onset of the banking crisis in the European Union. Additionally, it appears that the war in Ukraine and the SVB collapse have further intensified the interdependence of the banking stock markets in the G7 countries with the United States. In contrast, the banking crises of 2016, the recent banking crisis, and the war in Ukraine have had a lesser impact on the correlation of the banking stock markets in the BRIC countries. This suggests that BRIC countries can attract the attention of investors seeking to diversify their portfolios. Therefore, they can be considered a safe investment haven at the international level, particularly during periods of banking crises or political uncertainty.

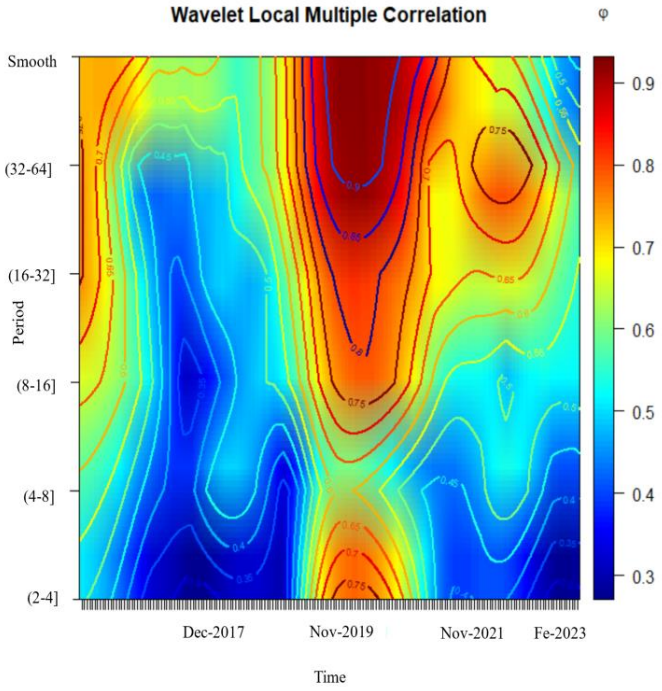

Figure no. 4 – The interdependence between US-BRIC bank stock market, using WLMC

6. CONCLUSIONS AND DISCUSSIONS

As mentioned earlier, many researchers have increasingly attempted to investigative the potential impact of bank runs and failures and other unexpected events on the behavior and dynamics of financial markets and cross-border linkages. Most of them report the significant and negative effects of bank crisis on national and international financial markets. With the outbreak of Silicon Valley Bank fiasco, the debate of its impact on global stock markets has increasingly revived by analyzing the potential ramifications for stock dynamics. In this regard, Pandey *et al.* (2023), among others, focus on the short-lived or immediate of such event on global asset classes using the event study event approach. Based on this crux, we attempt to analyze the structure and dynamics of connections between bank stock indices of different countries in G7 and BRICS regions during the outbreak of tremendous events. To this end, we use the wavelet coherency (WTC) and wavelet local multiple correlation (WLMC) approaches during the period from 1/1/2016 to 4/28/2023. Such approaches enable to analyze and better apprehend the nature and duration of the nexus between asset classes. This could help to better emphasize the behavior and dynamics of such nexus with the advent of exceedingly adverse and unexpected events such as the Covid-19 pandemic. Not only that, the WLMC approach seems to be useful statistical and computational method which could assess correlation across multivariate, non-stationary, financial time series (Fernández-Macho, 2018).

Overall, analyzing the dynamic time-frequency connectedness of US bank stocks and bank stocks in different regions in both bivariate and multivariate framework reveals interesting findings. First, the connection among assets tends to change both short- and long-term. For instance, the empirical results show that US bank stock drives the comovements of the Indian and Brazilian banking stocks in the long-term. Second, some cross-correlations become stronger and higher due to the outbreak of SVB collapse and the Ukraine-Russia war. In this regard, it is noteworthy that the effect of the SVB fiasco is not similar and uniform among countries and regions. For example, such adverse event seems to have a lesser effect on the correlation of the banking stock markets of the BRIC countries. Such result is consistent with those of Pandey *et al.* (2023) who explain it by the difference in banking system development and financial stability. The nature of tremendous events has an incredibly impact on the asymmetric dynamics of comovements among assets. Our findings also corroborate those of Yadav *et al.* (2023) which report the contagion and spillover effects disseminating across borders. The bi- and multi- wavelet analysis clearly also shows that relevant comovements across different banking sector stocks and such connections vary over time due to unexpected events such as the Covid-19 pandemic. The intensity and level of comovement seem to relate not only to the geography of country but also the resilience/fragility of banking sector to the advent of adverse events. Such findings seem to corroborate those of Baumöhl *et al.* (2022) who show that connections across seem to be affected by adverse events.

Our empirical findings could offer insightful implications for policymakers and portfolio managers. The effects of unanticipated shocks on financial markets and particularly banking system stocks can spill over and could vary substantially among countries/regions according to the market microstructure and banking system development. In this respect, financial markets in some countries can attract the attention of investors to diversify their portfolios. Therefore, they can be considered a safe investment haven at the international level, especially in a banking crisis or political uncertainty. Interestingly enough, the behavior and degree of correlation among different banking stocks in the G7 and BRIC countries both frequency and

time domains provide insightful signals to undertake portfolio rebalancing in a timely fashion to attain safe-haven, diversification and hedging benefits. Such findings also invite stakeholders to re-consider the spatial spillover transmission effects of stressful events when investigating the markets dynamics in sector perspective. In particular, investors could be aware of the idiosyncratic shocks related to such events across different markets and regions and the potential arbitrage opportunities which could last in the banking stock markets in order to guarantee relevant trading decisions and adjust portfolio allocations among different investment horizons. This also invites policymakers to strategically think about the (dis)advantages of such connections to effectively regulate the banking ecosystem to alleviate the contingency of price gouging, which could influence the decision-making of investors. Further studies could extend our work by incorporating other developing markets to analyze the pattern of potential connections among them.

Declaration of competing interest

The authors declare that they have no competing financial interests or personal relationships that could have appeared to affect the work reported in this paper.

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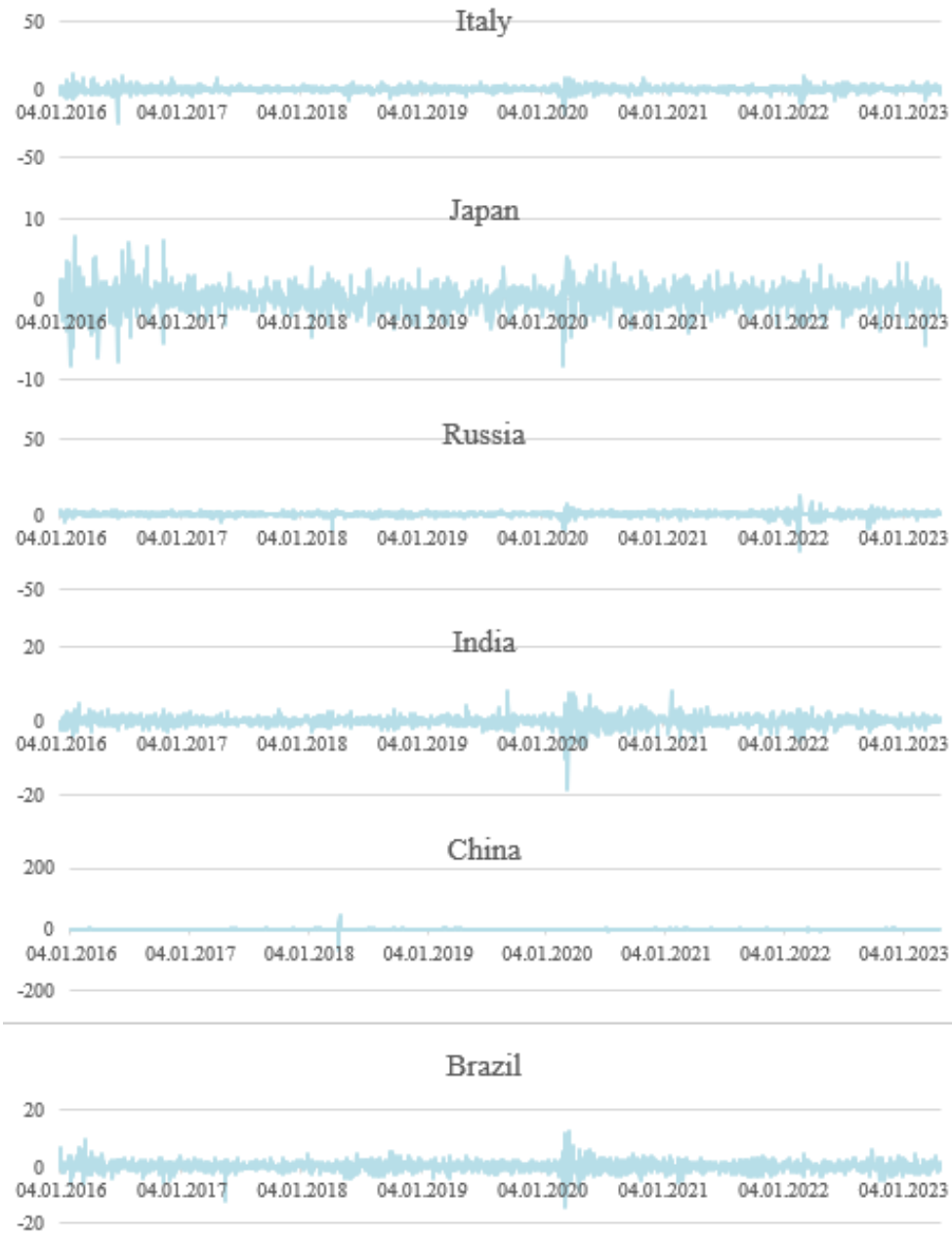
ANNEX 1

Plots of returns


Italy
50
0
-50
04.01.2016
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04.01.2022
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Japan
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Russia
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India
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China
200
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Brazil
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Impact of Macroeconomic Factors on S&P Europe 350 ESG Index During the Russo-Ukrainian War

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Abstract: The Russo-Ukrainian War, which began on February 24, 2022, has introduced significant economic and geopolitical instability. This study aims to investigate the specific impact of key macroeconomic variables - interest rates, exchange rates, inflation, oil, and gas prices—on the S&P Europe 350 ESG Index (SPEESEP) during this conflict. By analyzing daily data spanning 20 months from April 20, 2021, to November 30, 2022, encompassing both pre-war and post-war periods, we employ the Wavelet Coherence Transformation (WCT) method to examine these relationships. Our findings reveal that exchange rates, oil, and gas prices significantly impact the ESG index, while interest rates and inflation exhibit a moderate influence. These results underscore the importance of understanding macroeconomic fluctuations during geopolitical crises for informed investment decisions. The broader significance of this study lies in its potential to guide investors in navigating the complexities introduced by geopolitical conflicts, thereby aiding in better financial decision-making and risk management. By developing appropriate regulations for the ESG industry, this research can contribute to minimizing risks and maximizing profits in volatile environments. As geopolitical risks are a persistent factor in investing, this study emphasizes the necessity for investors to meticulously evaluate these risks when devising investment strategies.

Keywords: Russo-Ukrainian War; S&P Europe 350 ESG index; inflation; exchange rate; oil & gas; EURIBOR; Wavelet Coherence transformation (WCT) method.

JEL classification: F51; N4; G41; O16.

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1. INTRODUCTION

It's doubtful whether the COVID-19 outbreak has totally abated at this point, despite the fact that it began a little more than two years ago. However, the impacts of the crisis in Ukraine must be taken into account as businesses and countries adjust their operations, creating an unexpected new challenge. Corporate executives, entrepreneurs, and government policymakers need to be familiar from the possible consequences of ongoing conflict on the financial system and business in order to achieve this.

The Russo-Ukrainian War, which began on February 24th, 2022, has brought considerable economic and geopolitical instability. As businesses and countries adjust their operations to this unexpected challenge, it is essential for corporate executives, entrepreneurs, and government policymakers to understand the potential consequences of this ongoing conflict on the financial system and business environment.

ESG (Environmental, Social, and Governance) considerations have gained prominence in investment strategies, with research suggesting that ESG-compliant companies may exhibit lower systemic risk exposure (Cerqueti *et al.*, 2021). Studies by Billio *et al.* (2012) and Tobias and Brunnermeier (2016) the importance of identifying key economic players and assessing their systemic risk. Analyzing the impact of sustainability on systemic risk is a crucial extension of this research.

According to Cerqueti *et al.* (2021), ESG investments may help lower systemic risk, with companies adhering to ESG criteria being less vulnerable to systemic shocks. They suggest that firms with higher ESG scores tend to have better stakeholder relations due to more transparent governance. Additionally, investors in ESG assets are less likely to liquidate their investments during market crises, viewing these investments as long-term commitments. However, there is evidence that ESG components might qualify as systemic risk factors (Leterme, 2020). Apergis *et al.* (2022) suggests that the relationship between a company's financial success and ESG scores can be neutral or even negative, while others have identified a positive correlation. This conflicting evidence underscores the need for further research to clarify these relationships.

The Russo-Ukrainian War, as proposed by Lim *et al.* (2022), affects businesses through reduced access to capital, decreased purchasing power, threats to sustained development, increased inflation, and trade restrictions due to economic sanctions. Furthermore, the current COVID-19 crisis has adversely impacted private enterprises, leading to a sudden decline in profitability and issues with timely shifting expenditures (ECB, 2022b). These dual crises highlight the importance of understanding how macroeconomic variables influence financial markets, particularly ESG indices.

This study aims to fill existing gaps by analyzing the impact of macroeconomic factors on the S&P Europe 350 ESG Index (SPEESEP) during the Russo-Ukrainian War. Specifically, we examine the influence of interest rates, exchange rates, inflation, oil, and gas prices on the SPEESEP index returns, utilizing wavelet coherence transformation for data analysis. By elucidating the relationship between these macroeconomic variables and the SPEESEP index, this research seeks to provide valuable insights for investors, analysts, and policymakers.

Understanding the economic ramifications of the conflict in Ukraine and its implications for the ESG sector can inform strategic decision-making and risk management practices, ultimately enhancing the sustainability and competitiveness of businesses in the face of evolving challenges. This study aims to benefit analysts and the general public by providing

comprehensive information on the impact of macroeconomic risk factors on the ESG sector. The insights gained can help investors identify and mitigate the effects of macroeconomic fluctuations on their investments, thereby minimizing risk and maximizing profits through informed policy implementation within the ESG industry.

In conclusion, this research not only addresses the immediate impact of the Russo-Ukrainian War on the SPEESEP index but also contributes to the broader understanding of how geopolitical crises can influence financial markets. By developing appropriate regulations for the ESG industry, this study can help minimize risks and maximize profits, ensuring that businesses remain sustainable and competitive in the face of ongoing and future challenges.

1.1 Background Studies

1.1.1 Russia-Ukraine War

Russia started invading Ukraine on 24, February 2022. In connection with this invasion, there were strikes that caused deaths and destroyed buildings, including homes, schools, and hospitals. The laws of war have been broken by indiscriminate, maybe war crime-level attacks. By the end of the first week of conflict, over a million people had left their homes in Ukraine, many of them were fleeing for safety abroad. Popular independent media outlets in Russia were forced to close as a result of the government limiting access to various independent media websites because of their stories about the conflict. Numerous anti-war protesters were wrongfully imprisoned during the first week of the war all over Russia. The EU and its allied nations ought to grant each refugee from Ukraine a fair shot for travel and treatment.

1.1.2 S&P Europe 350 ESG Index

Acknowledging the S&P Europe 350 is the first step to understanding the SPEESEP index. The S&P Europe 350 ESG Index is a broad-based, real-world index that consists of stocks from all sectors of the European equity market. It is designed to reflect the performance of the entire stock market with a large number of international companies and consider their sustainability and social characteristics in addition to their financial aspects. The index can be viewed as a European version of the global S&P 500 index.

The SPEESEP Index provides information on a variety of sustainability issues, including governance, the environment, tax strategy, risk culture, human rights, gender diversity, cyber security, and many more, rather than concentrating on just one component of ESG. The index incorporates ESG ratings from each organization's 600 to 1,000 sample points on particular subjects.

1.1.3 ESG Repercussions of the Russo-Ukrainian War

It is difficult to predict the exact effects at this time, but the region will become de facto uninvestable due to the sanctions in place and the fact that, as was already mentioned, Russia is anticipated to be excluded from many policy benchmarks. From the standpoint of foreign investors, this will have disastrous effects on Russian businesses. Although it is still too early to tell, it will be interesting to watch if Russia exposure is ever considered when calculating ESG scores.

We think that one long-term effect of the conflict is the acceptance rate of natural gas and nuclear as long-term bridge fuels. This outlook is not specifically determined by a choice to alter the EU energy taxonomy; rather, it is determined by economic and energy security considerations. Another potential side effect is a loosening of regulations with regard to the timelines for decarbonization.

However, the desire for greater autonomy from fossil fuels may ultimately enhance decarbonization measures. Keep in mind that more than 90% of the world's GDP comes from net energy consumers, and almost 90% more of the world's emissions are already met by zero commitments. These commitments will help the renewable energy sector; thus, this crisis may speed up the geopolitical benefits for renewables. This might allay some concerns about potential excess investment in and potential oversupply of renewable energy sources, which are essential to a net zero pathway.

Particularly in light of the European LNG shock, the US shale sector may emerge as a significant and long-term victor from the crisis. Similar to LNG, non-Russian natural gas is expected to experience a boom period along the full value chain.

A review of the world energy market is necessary. Although Russian production growth has been slowing, the reduction will probably be far more severe now that sanctions are in effect (even accounting for potential Chinese investment). The disagreement might push the floor price for crude oil further higher.

1.1.4 Macroeconomic Risk Factors

A country will take the macroeconomic indices into account when comparing the economies of different Countries. Each macroeconomic component produces important data to promote a nation's development depending on its internal activity and global connections. By allowing us to determine which activities have the greatest potential and which components are the weakest, macroeconomic analysis empowers us to take actions that are advantageous to the citizens of the nation and grow the economy.

Following are the few macroeconomic indicators that are being considered in this study for the EU are: Exchange rates, Interest rates, Inflation, Oil Prices and gas price.

2. LITERATURE REVIEW

Increased access to fossil fuels was made more dubious by the unplanned invasion of Ukraine by Russia, but it also may have opened up new opportunities for developing alternative energy sources and making investments in the green energy sector. In order to diversify the risk associated with financial markets, investors will be urged to shift their investment portfolios toward alternative assets. However, it is still difficult to predict how the war will ultimately affect the entire economy, which is currently reflected in rising energy costs and the response of global financial markets (Lo *et al.*, 2022).

According to Deng *et al.* (2022), stocks are more sensitive to the significant compliance of the shift to a low-carbon society fared better in reaction to the Russia-Ukraine conflict, indicating that investors anticipate a general slowing in this transition. In the US, these effects on stock prices were particularly potent. The impacts were less evident or possibly the opposite in Europe. It may be argued that market participants initially anticipated more aggressive policy measures in favor of renewable energy sources in Europe. Investors

believed that the US Inflation Reduction Act and the REPowerEU approach would boost the worth of companies with prospects in the renewable energy sector. They additionally anticipated a rise in the value of US companies that benefit from a moratorium on the regulation of harmful technologies. Overall, the results indicate that there will likely be differences in decarbonization intensity between countries, putting the accomplishments won so far in the fight against climate change at risk due to geopolitical tensions.

The appeal of sustainable investments, according to Kick and Rottmann (2022), is unwavering and draws both investors and scholars. In their theoretical model for simulating the characteristics of such "green" enterprises, Pástor *et al.* (2021) take a precaution against climate hazards. Similarly, it might be believed that organizations with high social ratings might provide protection from similar occurrences. One of the largest events imaginable occurred when Russia invaded Ukraine. They examined whether and how the cumulative anomalous returns during various event windows are affected by Refinitiv's ESG ratings in addition to the CO2 intensity. They discover that the pre-and post-event timeframe has a positive impact on the anomalous returns of businesses with high ecological ratings. However, the consequences have no bearing on the economy. They concluded that the data did not entirely support the idea of an "ESG-hedge" against such a rare occurrence. If such a phenomenon exists, additional traits that account for consistency and defensiveness have superimposed it.

Basdekis *et al.* (2022) try to use daily data to investigate whether there are any relationships between particular crude oil prices, foreign exchange rates, and stock market indexes from January 2021 to July 2022. The COVID-19 post-vaccination phase and the Ukraine War are covered during the time frame we have selected. This makes it easier for us to refer to the time during the Ukraine War and energy crisis as the extent of unstable situation. The research's findings show that there are significant correlations between all of the variables over a range of frequencies and time scales over the study period. The fact that the RTSI strongly influences the American and European stock markets, as well as the development of the Russian ruble, during the crisis is particularly intriguing. Additionally, it appears that the dependency among crude oil and RTSI is influenced by capital restrictions on the Russian stock market as well as rising demand for the commodity. The analysis also discovered an intriguing negative association in low-frequency bands between crude oil and the US stock index as well as the Eurostoxx and RTSI at the time of the pre-war and post-vaccination periods. Investors and asset managers can both use these results to reduce risk and make more certain investment decisions. Additionally, policymakers might utilize these insights to create regulatory strategies for limiting systemic risks in the capital markets.

How the Russo-Ukrainian dispute impacts the European financial markets is examined by Ahmed *et al.* (2023). The objective is to ascertain why these markets respond badly to this crisis, given the increased political unpredictability, close proximity, and implications of the new sanctions placed on Russia. They discovered that European stocks saw a large negative anomalous return after Russia designated two Ukrainian territories as independent areas. Additionally, the unfavorable stock price reactions persisted in the days following the occurrence. The severity of the stock market responses to this crisis differs significantly between industries, nations, and firm sizes.

According to Adekoya *et al.* (2023), Various crises that could happen at the national, regional, or worldwide levels regularly have a negative impact on the stock markets. They are examining the cross-correlation and multifractality between oil prices and top financial markets in world, before and during the most recent Russia-Ukraine conflict. In the oil and

stock markets, their empirical study identifies a strong multifractal behavior. Nevertheless, endurance is typically greater at the lower scales, which correspond to the start of the sampled eras. Additionally, the conflict has a strong explicit impact on how long do stock markets of Europe and oil prices last. On the other hand, it has a bigger implicit effect on the survival of the non-European financial markets over the price of oil. The world's three greatest economies are those of the US, China and Japan. However, during the conflict, all the countries were more affected by oil prices since their stock markets were less effective.

In times of increasing geopolitical risk, the study's main objective is to investigate the spillover effects of the dirty and green energy markets vs the global stock indices. They analyzed structural breaks, volatility interconnectedness indices based on the unique method suggested by Diebold and Yilmaz (2012), and volatility connectedness indices to indicate significant changes in shock transmission during in the period from Aug-2014 to May-2022. They also look into the benefits and drawbacks of using heterogeneous diversity in green energy hedging techniques. Estimated for risk diversification and mitigation are ideal weights and hedge ratios. They discover that while global equity markets generally exhibit more risk than clean energy indices, the expense of hedging in sustainable energy assets is higher. (Karkowska and Urjasz, 2023)

The crisis in Ukraine could have long-term effects with broad-reaching effects on availability and commodity pricing. Manufacturing, demand, and distribution of commodities will change as countries work to become more self-sufficient, creating opportunities for new providers. The likelihood of how long the conflict lasts and exactly how it affects supply chains will have a significant impact on commodity markets. Due to the conflict, trading is becoming increasingly expensive, and the fossil fuels trade has substantially diverged (Josephs, 2022a).

If Russia and Ukraine start a conflict, the problems with the supply chain will get worse, increasing the price of commodities. The industries with the largest worldwide manufacturing networks and the most reliance on energy and metal resources will face the biggest obstacles (S&P Global, 2022).

The fuel industries, particularly those engaged in power production and oil refinery, mining, transport services, and chemicals, will collapse first because Russia is a resource supplier to Europe (S&P Global, 2022). Russian fuel supply restrictions could cause energy shortages and price spikes (Bundesbank, 2022a).

The best gas and oil analytics company across the globe, Rystad Energy, estimates that 410 Mn. tons of LNG will be produced in 2022, compared to 436 Mn. tons of demand (GWN, 2022). According to this, demand will increase by 6.3% more than supply, signaling an LNG shortfall. Consider the effects of supply shocks on prices as an illustration.

Approximately 80% of natural gas Austria receives from Russia, has started releasing tenders to replace its reservoirs after announcing that a stoppage from its main supplier would cause a recession across the entire country. Austria built a tactical gas resource before the winter season by first procuring gas at a 45% premium over European base pricing (Bloomberg, 2022b).

Since the economy started to recover from COVID-19 pandemic, one of the primary causes of inflation Elbahnasawy and Ellis (2022). A shift in the market equilibrium will result in a decrease in GDP and an increase in inflation when the pressure of inflation is too great Roubini (2022). Oil and food prices will rise, further worsening the already unsustainable rate of inflation (Krugman, 2022).

According to one of the largest financial institutions in the world, BlackRock, the EU countries will invest more on energy in 2022, about 9% of their GDP (Bloomberg, 2022a). Commodity price increases accelerate the already high global inflation rate (Josephs, 2022a). Rising energy prices are responsible for most of the current inflation increase (ECB, 2022a).

Due to a strong increase in the price of commodities, Germany's industrial production price growth index jumped from 30.9% in March to 33.5% in April 2022 (DeStatis, 2022). The inflation rate has risen for two consecutive months at the end of March 2022, reaching 15.6% in Lithuania, 11.5% in Latvia, 14.8% in Estonia, 7.6% in Germany and 7.8% in the EU (Statista, 2022). The price of commodities in Germany increased 2.5% in March 2022 relative to February after being seasonally adjusted. One of the highest inflation in Germany since 1981 (Bundesbank, 2022b).

After reviewing a few research that examined into how the value of various international currencies compared to the USD and likewise. The conflict between Russia and Ukraine had an influence on stock market indices. Given the small number of research that have looked at the effectiveness of the currency exchange market, researchers used the event study approach with market model estimates to analyze the performance of the USD against the other exchange rate during the Russo-Ukrainian war (Dewenter *et al.*, 2005; Hayward, 2018).

The impact of exchange rates on international trade is another justification for studying exchange rates, according to several hypotheses. One of these ideas, the flow-oriented strategy, asserts that exchange rates with weaker signal have less expensive exports, enhancing the ability of companies with an export focus to compete (Bahmani-Oskooee and Saha, 2016).

In the short term, Nusair and Olson (2022) supported the flow-oriented strategy. Furthermore, Lyócsa and Plíhal (2022) explained that how the conflict influenced unstable exchange rates, especially the value of the Russian ruble. They also think that other currencies would eventually be impacted by the war's shock.

Chortane and Pandey (2022) investigates how the Russo-Ukrainian conflict impacts the value of several world currencies in comparison to the USD by using market model projections and event analysis techniques. But a region-by-region analysis reveals that the Middle East and African (ME&A) currencies are modest while the Pacific currencies significantly increased, European currencies – mainly the Russian ruble, Polish zloty and Czech koruna depreciated against the US dollar. They illustrate how the Russo-Ukrainian conflict impacted the global currency values. They also demonstrate the steep decline in the value of the Polish zloty and Czech koruna in relation to the US dollar as a consequence of the monetary and financial sanctions placed on Russia.

Notably, swings in energy prices have a significant impact on all parts of the economy, particularly financial markets, through exchange rates (Qiang *et al.*, 2019). In certain research, the important oil or -exporting economies are examined in relation to the oil price and FX rate nexus. One of them, , demonstrates a strong impact of oil rates on real FX rates in Venezuela using the vector error correction model (VECM). In Japan, Uddin *et al.* (2013) find a similar link. According to some analyses, During the 2008 financial crisis, the correlation among oil prices and FX rates grew more interdependent (e.g., Ding and Vo, 2012; Ji *et al.*, 2020). The correlation of currency fluctuations with commodity prices is examined by Salisu *et al.* (2019). Their approach demonstrates that the accuracy of forecasting decreases with lower data frequency and also is enhanced by adding structural breaks and asymmetry. They obtained five important trading currency pairs and disaggregated commodity price indices. Kassouri and Altıntaş (2020) look into how trade shocks affect currency rates in several

African nations. According to their analysis, the impact is particularly noticeable in the nations that export energy.

One of the main sources of energy in the world, oil and natural gas, are being affected by Russia's invasion of Ukraine. In addition, it appears that the war's effects on the oil sector are distinct from those of other crises. Oil prices increased significantly during the Russo-Ukrainian war while falling amid the financial crisis of 2007–2008 and the COVID-19 outbreak. Geopolitical concerns, according to Gong and Xu (2022), have a considerable impact on the interconnection of commodity markets as a whole, but they significantly affect the net spillover of different commodity markets.

Fahmy (2022) emphasizes how concerned investors are about green investments and how their understanding of climate hazards is expanding, particularly in the wake of the Paris Agreement. The author makes the argument that growing public knowledge becomes a factor on how prices of clean energy relate to those of oil and technology companies. The impact of high oil price on green power equities differs across equity investments and quantiles and is asymmetry in the long term, according to Zhang *et al.* (2020), who used quantile-on-quantile wavelet methodology to make their discoveries. Similar to this, Yahya *et al.* (2021) examined the link among the renewable energy equities and price of oil, and discovered non-linear, long-term relationships between the two categories of assets. They specifically acknowledged that renewable energy assets have been the main driver of the oil prices in the recent aftermath of the financial crisis. Last but not least, it is yet unknown how well the Russian invasion affects the worldwide movement toward renewable energy.

Using a sizable panel of 73 nations, Lo *et al.* (2022) determines the effects of the Russian invasion on financial system, which are influenced by the nation's reliance on Russian commodities. The authors noted that as a result of the war, financial markets witnessed an increase in price fluctuations and a fall in asset returns. Their findings demonstrate that, regardless of the degree to which the country is dependent on Russian commodities, the continuous war has a negative influence on stock markets which raises volatility.

According to early evidence of conflict, the government's support for the progressive phase-out of energy resources and the adoption of renewable energy alternatives is provided by Steffen and Patt (2022). The authors found that the Swiss people strongly supported sustainable energy policy; nevertheless, public funding must be converted into political action. The link between the financial market and energy during turbulence has been brought to light by the findings of earlier investigations. Tension between the Russia and Ukraine's effects and the COVID19 epidemic on the framework connecting dirty and clean energy with the financial market, however, has not been the subject of any study. Finding the connections is crucial for governments and regulators to manage potential market volatility in the energy and stock markets, as well as for investors developing an investment strategy.

Investors that concentrate on hedging methods for investments in the stock market and global energy markets can benefit from the knowledge provided by empirical studies. Managi and Okimoto (2013) discover a favorable correlation between the cost of non-renewable energy and the clean energy cost. They also highlight the parallels between the market reactions to the stock prices of IT and clean energy company's stock.

In the next section of this paper, we discuss the methodology in which we go over the methods employed as well as the datasets and their sources. Next, we apply the techniques and discuss our own research findings and conclusions. Lastly, we discuss the study's limitations and how they can be overcome in future studies.

3. METHODOLOGY & DATA

Sampling of Data

In our research, we take the sample of daily frequency closing prices of S&P Europe 350 ESG index (SPEESEP) from Thomson Reuters Eikon and the data stream. To check the impact of Macro-economic variables on the mentioned index, we take 5 different variables data sets those are Inflation, exchange rate, interest rate, oil, and gas. All data frequency is daily, and sources are mainly ECB and Eurostat. The sample period contains April 20, 2021, to Nov 30, 2022. Relative returns are calculated for SPEESEP as $(Rt- Rt_{-1}/Rt_{-1})$.

Variables

For Inflation variable, we selected Harmonized Index of Consumer Prices (HICP) of EU27. The ECB uses the HICP as a gauge for inflation and price stability. It is a consumer price index that was developed using a technique that was standardized among EU member states. For Interest rate, we selected monthly EURIBOR and convert into daily rate. For exchange rate the variable we use in our research is EURO/USD. For oil variable we use Crude Oil Prices: Brent - Europe (MCOILBRENTEU) from www.fred.stlouisfed.org and lastly, for gas we choose EU natural gas TTF prices.

Analytical Techniques

We used the wavelet Coherence Transformation (WCT) method as Kuşkaya *et al.* (2021) to analyze the time and frequency dependencies for each pair of variables. The dependent variable in our research is SPEESEP relative return, and independent variables are Inflation, exchange rate, interest rate, oil, and gas.

Rationale for Methodological Choices

Fourier and wavelet transforms come first when discussing time series models for the economics and finance sectors. In spectral decomposition one of the techniques is the Fourier transform, it is a transformation technique that allows analysis. In the Fourier transform, the conversion of the frequency domain into the time domain is a function.

For each frequency, need to determine the Fourier functions' coefficients (Graps, 1995). The Fourier transforms a signal, when it shows the contain frequency, at which time what frequencies are available in the tranche that does not provide information about it. So, the information provides by Fourier transformation is about the whole time period not for just a specific time period. Hence the Fourier transform, analyzing signals whose frequency does not vary over time is a successful approach. Because of this property the scale-based analysis method in the study is the “wavelet analysis method" that we are going to use.

Theoretical Framework

The theoretical framework of this study is based on the application of spectral decomposition techniques to analyze economic and financial time series. Traditional Fourier

transform methods, which analyze signals with constant frequency over time, fall short when dealing with non-stationary data, where frequency content changes dynamically. To address this limitation, we employ the Wavelet Transform (WT), a sophisticated method that simultaneously analyzes data in both time and frequency domains. This allows for the decomposition of a time series into various frequency components and provides detailed insights into each component's behavior over time. The WT, particularly the Continuous Wavelet Transform (CWT), enables us to capture transient features and localize variations within the data, making it ideal for our study's focus on non-stationary economic indicators. Using wavelet analysis, we can discern both high-frequency, fast-changing patterns and low-frequency, slow-changing trends, thus offering a comprehensive understanding of the relationships between the S&P Europe 350 ESG Index and macroeconomic variables. This dual capability of wavelets to examine both the "tree and the forest" simultaneously is crucial for identifying intricate dependencies and temporal dynamics within the data (Graps, 1995; Zhao *et al*., 2004). A linear combination of the Fourier transform can also be used to define the wavelet function (also known as the mother wavelet function). However, $b \in \mathbb{R}\ n\ a\ d\ a \in \mathbb{R}+$, to be provided, each scaled wavelet function and the transformed $\beta\ (a,\ b)\ (t)$ may be written as follows according to the mother wavelet:

$$\beta(a,b)(t) = \frac{1}{\sqrt{|a|}}\beta\left(\frac{t-b}{a}\right) \tag{1}$$

where the term $1/\sqrt{|a|}$ is the factor representing the normalization that determines the wavelet's unit variance. The mother represents the wavelet β (.), which also includes the two control parameters a (scale) and b (position). Parameter ω is the conversion or position parameter. This variable affects the wavelet's position and orientation in the time domain. In equality, a is the parameter that controls the wavelet width. Additionally, it displays where the wavelet is in the frequency domain. Fast-changing features can be caught at lower scales, or high frequencies, when scale is analyzed in terms of frequency, whereas slower-changing patterns can be obtained at higher scales, or low frequencies. This instance demonstrates the adverse correlation between scale and frequency. Continuous Wavelet Transform (CWT), wavelet $\beta\ (a,\ b)\ (t)$ with respect to $\ddot{x}(t) \in L^2\ (\mathbb{R})$'s examined the time series of a particular wavelet, β (.), as can be described as follows:

$$W_{\ddot{x}}(a,b) = \int_{-\infty}^{\infty} ¥(t)\frac{1}{\sqrt{|a|}}\ \beta^*\left(\frac{t-b}{a}\right)dt \tag{2}$$

where $W\ddot{x}\ (a,\ \omega)$ represents WCT. The * in the equation shows the complex conjugation. On the other hand, small waves are referred to as wavelets, which differ from larger waves in many ways. In this sense, wavelets are categorized into various classes based on their traits. These wavelets can be classified into the following types: Mexican hat, Morlet, Meyer, Shannon, Biorthogonal, Daubechies, Symlets, Coiflets, and Haar. The Morlet wavelet transform can be used to assess both the amplitude and the phase because it has both real and imaginary portions. For time-frequency analysis, Morlet wavelet analysis has various benefits. The most important of these advantages is the Gaussian curve of the Morlet wavelet in the frequency domain. This characteristic reduces ripple effects that could be mistaken for oscillations by eliminating sharp edges (Cohen, 2019). The wavelet function, as described by Grossmann and Morlet (1984), is written as:

$$\lambda_{\varphi}(t) = \pi^{-1/4}(\exp^{i\varphi t} - \exp^{-\varphi^2/2})\exp^{-t^2/2} \quad (3)$$

Here the symbol φ indicates the central frequency parameter $\lambda\varphi(t)$ of the Morlet wavelet. In addition, φ determines how many oscillations there are in the Gaussian envelope. Thus, it is possible to provide better frequency location by increasing φ (Addison, 2017). The term $\exp^{-\varphi^2/2}$ is the complex sine wave's non-zero average is corrected by the correction parameter in the equation. However, when $\varphi > 5$, this situation can be neglected.

Cross-wavelet power, two time series, Wxy (a, b) time-series can be defined as the correlation among the local covariance and the scale (frequency band) at each instant. Hudgins *et al.* (1993) were the first to identify the cross-wavelet power of $x(t)$ and $y(t)$ of two time series, it is as follows:

$$W_{xy}(a,b) = W_x(a,b)\overline{W_y(a,b)} \quad (4)$$

where, Wx (a, b) and Wy (a, b), Wxy (a, b) as is the WCT of the time-series of $x(t)$ and $y(t)$. So, the cross is the wavelet power. Cross-wavelet transformations, both in time series, each time series that represents the covariance between the local areas with high joint strength scale shows (Vacha and Barunik, 2012).

Corresponding to Aguiar-Conraria *et al.* (2013), Wx (a, b) and Wy (a, b) are two of the time series of Harmony wavelet (wavelet coherency) is defined as follows:

$$R_{xy}(a,b) = \frac{|\mathcal{S}(Wxy(a,b))|}{\mathcal{S}(|Wxx(a,b)|)|^{1/2}\ \mathcal{S}(|Wyy(a,b)|)|^{1/2}} \quad (5)$$

In the equation Rxy represents the correlation. This value is a parameter that Decays between 0-1. If there is strong consistency among the frequency and time domain, the correlation will be equal to "1", if there is no consistency, the correlation will be equal to "0". Additionally, $\mathcal{S}$ denotes the smoothing parameter. If this correction does not happen, the consistency will always be strong, that is, "1". The analysis of the phase difference, for example, the correlation's direction (positive and negative correlation) also, the premise behind it (lead or lag) the remaining components such as the relationship between the phase gives the opportunity to identify relationships. The difference between the phase $x(t)$ and $y(t)$ time series is between (ξx, $y \in [-\pi, \pi]$ with) the relationship can be defined as in equation (6):

$$\xi_{xy}(a,b) = \arctan\left(\frac{\mathcal{I}(Wxy(a,b))}{\Re(Wxy(a,b))}\right) \quad (6)$$

In the equation, $\mathcal{I}$ (Wxy) and $\Re(Wxy)$ represent real and imaginary sections, correspondingly. If, $\xi xy \in (0, \pi/2)$ if it is, the series will move in phase and $x(t) \rightarrow y(t)$' ye will lead. If $\xi xy \in (0, -\pi/2)$ if, then the series will move in phase again, and in this case $y(t)$ is in the leading state. If $\xi x, y \in (\pi/2, \pi)$ then, the anti-phase decoupling between the variables is there, the series will move out of phase in this instance, and $y(t)$ is in the leading state. When the phase difference is π or $-\pi$, this shows that there is an anti-phase relationship. If $\xi x, y \in (-\pi, -\pi/2)$ on contrary, there is an anti-phase relationship and $x(t)$ is in the leading position. Finally, if the phase difference is at zero, in this case, $y(t)$ and $x(t)$ will move together.

4. RESULTS

The continuous wavelet spectrum is seen as having a vertical axis that represents frequencies and a horizontal axis that represents time (the higher the scale, the lower the frequency). The wavelet coherence determines the covariance between the two-time series in time-frequency space. Warmer colors (red) depict regions with robust connections, whereas cooler colors (blue) suggest lesser series reliance. Cold zones represent time and frequency without any series dependency outside of the noted areas.

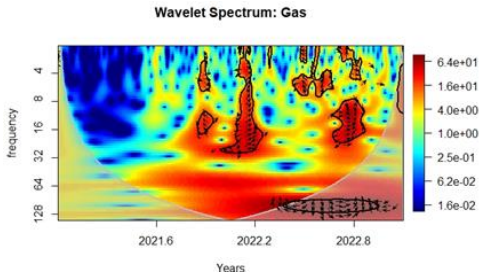

Figure no. 1 – Wavelet Spectrum (Gas) from 20, April 2021 to 30, Nov 2022

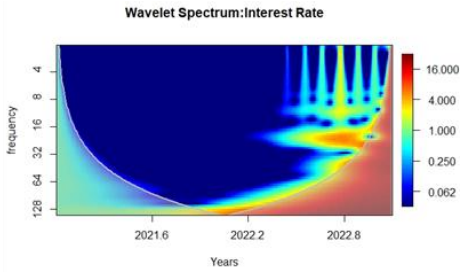

Figure no. 2 – Wavelet Spectrum (Interest Rate) from 20, April 2021 to 30, Nov 2022

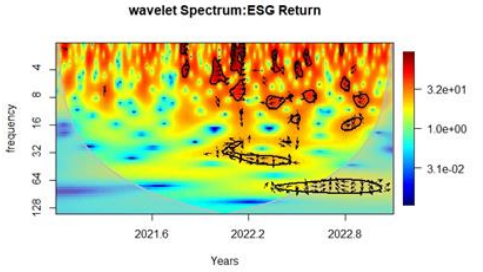

Figure no. 3 – Wavelet Spectrum (ESG Return) from 20, April 2021 to 30, Nov 2022

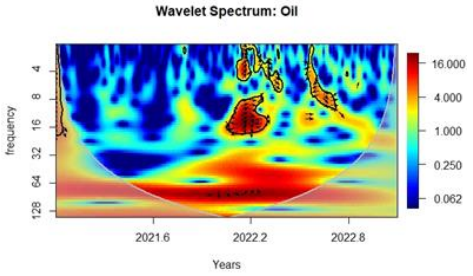

Figure no. 4 – Wavelet Spectrum (Oil) from 20, April 2021 to 30, Nov 2022

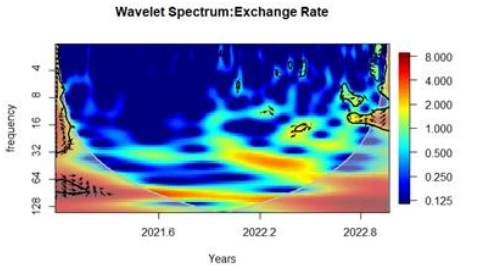

Figure no. 5 – Wavelet Spectrum (Exchange Rate) from 20, April 2021 to 30, Nov 2022

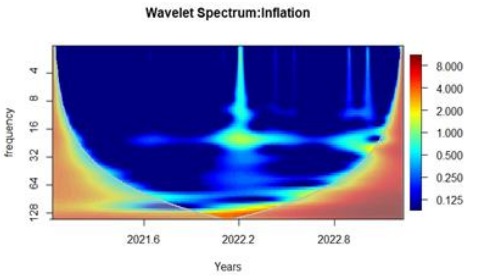

Figure no. 6 – Wavelet Spectrum (Inflation) from 20, April 2021 to 30, Nov 2022

The lag period relationships between the studied series are shown as an arrow in the wavelet coherence graphs. Two different time series move simultaneously on a specific scale when there is no phase difference between them. If the time series are in phase, arrows point

to the right (left) which we call (anti-phase). These series move in the same direction when they are in phase; when they are out of phase, they move in the other way. While the second indication is most important when an arrow points in a right-up or left-down direction, the first variable is leading when an arrow points in either a right-down or left-up direction.

In this spectrum the timelines we choose are actually divided into 2 scenarios which is before War and after War. From April 20, 2021, to Feb 20, 2022, is the time span before War and after onwards till Nov 30, 2022, the time span is after war. As you can see in Figure no. 3, SPEESEP ESG index return shows that before war the index is moving with normal fluctuations but after war you can see that the spectrum shows more red color and with arrow which shows that the index prices are volatile, and we can conclude that there are effects of war on SPEESEP index.

In Figures no. 2, no. 5 and no. 6 the variables exchange rate, EURIBOR and Inflation which shows almost similar pattern that in pre-war time period there is almost blue color which means there are not many fluctuations in the rates but after war you can clearly see the color changes into waves of yellow which shows that war have effects on these variables.

At last, Figures no. 1 and no. 4 the oil and gas variables are the independent variables which shows significance shift into wavelet that the color turns from blue to blood red and it's also logically appropriate according to GEP report that After conflict, the price of crude oil on the global market soared, rising from roughly $76 per barrel at the beginning of Jan 2022 to $110 per barrel by March 2022. Even the other larger markets, such as the stock exchanges in France, Germany and London (FTSE 100), as well as the S&P 500 and Dow Jones in the United States, all saw drops in the price of their stocks. The Russia-Ukraine conflict caused a global supply disruption that had an effect on hydrocarbon-dependent industries worldwide, including oil and gas prices.

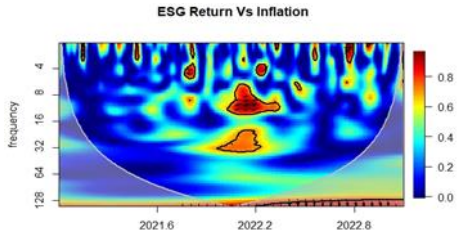

Figure no. 7 – Wavelet Spectrum between the SPEESEP Index with Inflation from 20, April 2021 to 30, Nov 2022

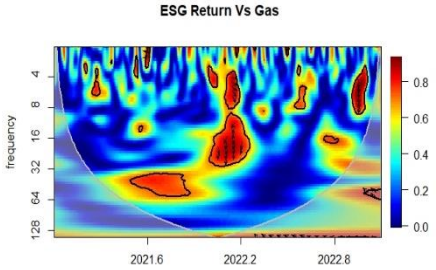

Figure no. 8 – Wavelet Spectrum between the SPEESEP Index with Gas from 20, April 2021 to 30, Nov 2022

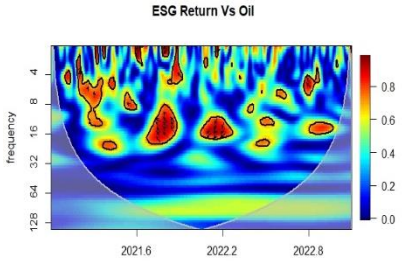

Figure no. 9 – Wavelet Spectrum between the SPEESEP Index with Oil from 20, April 2021 to 30, Nov 2022

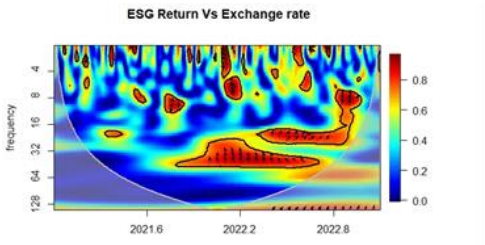

Figure no. 10 – Wavelet Spectrum between the SPEESEP Index with Exchange rate from 20, April 2021 to 30, Nov 2022

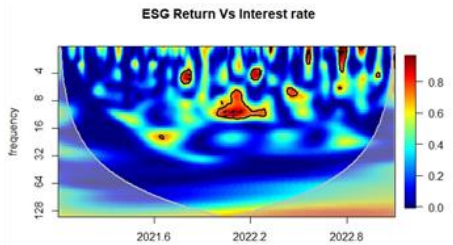

Figure no. 11 – Wavelet Spectrum between the SPEESEP Index with Interest rate from 20, April 2021 to 30, Nov 2022

We can see how the market was affected before and during the War and how macro-economic variables influenced markets from the plot. The intensity of cross-correlation is vigorous for exchange rate, oil, and gas, moderate for inflation and interest rate, according to the heat-map (color of the spectra).

The heat map shows an increase in market connection from blue to red, according to Gencay *et al.* (2002). Blueish is weak, red is strong. Similar comparisons can be made between wavelet coherence plots and wavelet spectrum (WPS).

5. FINDINGS

The relationship between SPEESEP ESG return and inflation doesn't show much at the beginning of the study period till Jan 2022 but after when the insights of war confirmed and later on war started it exhibits high levels of volatility at the beginning of February 2022 till August 2022 we found same result as Lo *et al.* (2022) and from August it was getting normal use to high inflation. According to The Guardians (Partington, 2022) as food costs rise and oil prices rise because to Russia's invasion, the ECB aims to raise interest rates for the first time since 2011. The most recent survey revealed In June, energy prices jumped at an annual rate of roughly 42% as opposed to 39% in May.

The relationship between SPEESEP ESG return and interest rate doesn't show much at the beginning of the study period till Jan 2022 but after when the insights of war confirmed and later on war started it exhibits high levels of volatility at the beginning of February 2022 till September 2022 and after onwards it was expecting to be higher, according to Euronews (Liboreiro, 2022) ECB has announced a further significant increase in interest rates in an effort to reduce the record-high inflation in the eurozone. As it did in September all of the bank's three basic interest rates was increased by 0.3 percentage points. Interest rates offered by commercial banks to people and companies in the eurozone are directly impacted by the ECB's interest rate decisions.

The relationship between SPEESEP ESG return and exchange rate is the most volatile one as compared to inflation and interest rate. We find similar outcomes as Chortane and Pandey (2022) that in the beginning its doesn't show much but after when the insights of war confirmed and later on war started it exhibits high levels of volatility at the beginning of February 2022 till November 2022 but from December it is in recovery stage. According to the (DW news, 2022) the Euro has hit an all-time low against the US dollar as a consequence of surging inflation, the situation in Ukraine soared food and oil prices.

The relationship between SPEESEP ESG return and Oil is one of the most depending factor. Zhang *et al.* (2020); Yahya *et al.* (2021); Fahmy (2022); Adekoya *et al.* (2023) stated

the identical outcome as our findings that at beginning of April 2021 its show that there is volatility but after when the insights of war confirmed and later on war started it exhibits high levels of volatility at the end of February 2022 till April 2022 but later on it is stabilized. According to the Reuters (Lawler, 2022), the price of oil has stabilized around $110 per barrel in April, after rising to $139 per barrel in March which is the highest of 14-year price.

The relationship between SPEESEP ESG return and gas is one of the most depending on factor in Russo-Ukrainian War. According to a statistic from the BBC (Horton and Palumbo, 2023) Germany was the leading importer of natural gas last year, followed by Italy and the Netherlands. 40% of the natural gas used in EU countries came from Russia. Zhang *et al.* (2020); Yahya *et al.* (2021); Gong and Xu (2022) found same effects that from beginning its show that there is volatility but after when the insights of war confirmed and later on war started it exhibits high levels of volatility at the end of February 2022 till Nov 2022. According to Eurostat (2024), the cost of natural gas for residential consumers increased considerably from the previous year to €0.0861 per kWh in the 1st quarter of 2022, achieving the highest point since the data gathering began. Each of the 25 EU nations that reported non-household gas prices saw an increase in such costs during the first half of 2022. The increase ranged from 67% to 271%.

Discussion

Based on our results, independent variables (Inflation, Interest rate, exchange rate, Oil, and gas) show impact on SPEESEP ESG index as many researchers found same negative relationship like (Zhang *et al.*, 2020; Yahya *et al.*, 2021; Basdekis *et al.*, 2022; Chortane and Pandey, 2022; Fahmy, 2022; Gong and Xu, 2022; Lo *et al.*, 2022; Adekoya *et al.*, 2023). Exchange rate, oil and gas have the strong correlation with ESG index while Interest rate and inflation have moderate affects. we can conclude that Russo-Ukrainian war have a direct relation with macro-economic factors which we used in our research and accordingly these macro-economic factors are highly impacted ESG index.

6. CONCLUSION

The motive of this study is to examine how such macroeconomic variables influence the SPEESEP Index during the Russo-Ukrainian War. Interest rates, exchange rates, inflation, oil, and gas prices are among the macroeconomic data that were considered in this study. The interest rate is calculated using the EUIBOR rate, and inflation is calculated using the HICP. These factors were chosen in accordance with market views as observed in numerous research on the impact investing sector. The Wavelet Coherence transformation method has been used to process and evaluate the data for this investigation. The macroeconomic variables in this study serve as explanatory variables, with the return on the SPEESEP index serving as a dependent variable. In conclusion, the initiative intends to assess how macroeconomic variables affected the SPEESEP Index during the Russo-Ukrainian War.

Our findings indicate that while interest rates and inflation have limited impact on the ESG index, exchange rates, oil, and gas show a substantial association. The Russo-Ukrainian War directly correlates with these macroeconomic parameters, significantly impacting the SPEESEP index.

The purpose of this study is to give analysts and the general public more reliable and understandable information about the relationship between macroeconomic risk variables and

the sustainability of the ESG industry. It helps investors make better decisions by providing them with baseline knowledge on identifying and reducing the impact of these variables on their assets. Furthermore, reducing risk and maximizing profitability can be achieved by implementing rules inside the ESG business that are based on these findings. For investors who care about the environment, the outperformance of shares in the energy sector has presented a big problem since the advent of the environmental, social, and governance (ESG) investment phenomenon. The performance of ethical investors, who generally underweight oil and gas companies in their portfolios, has abruptly declined in contrast to traditional funds.

On 23, March 2022 in Financial Times, John Kerry, a US climate envoy, has cautioned states against switching to coal in order to wean themselves off Russian gas. But despite these calls, Europe is moving away from Russian gas and toward alternative fossil fuels. According to the European Commission, the bloc can replace its reliance on imported Russian energy over the next five to ten years by using 5% more coal than initially anticipated. According to a recent analysis from financial data provider MSCI, under the worst-case scenario, emissions might increase by up to 0.8 gigatons of CO2 equivalent in the first year if Europe substitutes all of its imports of Russian gas with coal.

On the way to achieving energy independence, renewables are a crucial element. The urgency of switching to sources of renewable energy, such as wind and solar power. Which are more difficult for climate laggards like Russia to disrupt and also ensure energy independence, is made more urgent by the ongoing war in Europe. The case for expanding green energy in the short term is strengthened by the fact that shares of renewable energy companies have been rising steadily since the start of the war, including those of European giants like Ørsted, vestas, and Siemens Gamesa.

Even though shares of renewable energy companies have recently increased in price, the European Union's changeover will take some time. Germany's updated plan increased solar power to 20 gigawatts by 2028 and onshore wind energy to 10 gigawatts by 2027, rather than 2035 as reported in (Goldman Sachs: ESG Implications of Russia-Ukraine Conflict).

The implications for investors and stakeholders in the ESG sector are profound and far-reaching. Firstly, understanding the correlation between macroeconomic variables and the sustainability of the ESG sector provides investors with valuable insights into risk management strategies. By recognizing how factors such as interest rates, exchange rates, and commodity prices impact the ESG index, investors can make more informed decisions regarding portfolio allocation and risk mitigation. This knowledge allows stakeholders to adjust their investment strategies to navigate market volatility effectively.

Additionally, this research gives investors the ability to adapt their financial objectives with their environmental, governance and social principles. Investors should prioritize sustainable investments that benefit society and the environment in addition to producing financial rewards by understanding how macroeconomic factors affect the ESG sector. Making ethical and financial decisions in harmony encourages more responsible and long-term investment decision-making.

The results of this study also have consequences for regulators and policymakers in the ESG industry. Through an awareness of the ways in which macroeconomic factors impact the sustainability of ESG investments, governments can enact focused measures to encourage and facilitate responsible investment practices. This might involve actions to advance accountability, openness, and disclosure in the ESG space, which would boost investor trust and maintain the integrity of the market.

The limitations of our study are that due to the lack of data and information, the S&P Europe 350 ESG Index may not represent the real situation. Also, in order to cover all possible aspects, we had to limit the scope and focus on just one factor that affects Europe's ESG index – political conflict between Russia and Ukraine. However, I would still recommend this research for those who are interested in how political conflict affects a country's ESG index. One of the limitation of our research on how the Russian-Ukrainian conflict affects the S&P Europe 350 ESG Index is that there is no negative news for the market when there are long periods of time with low yields. One of the important factors in establishing the link between ESG and Russia-Ukraine war is that most investors are concerned about long-term growth prospects in Russia due to their proximity to Europe.

For continuing the research line, we suggest that in future it is more appropriate to increase the time span of data because in our research the data is limited and we cannot rely on it for future outcome, one more thing they can add is the number of injuries and injuries as a proportion of total casualties.

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