The Impact of Russo-Ukrainian War on the EMU Convergence: Did National Energy Subsidies and Fiscal Transfers Help?[1]

Kuo-chun YEH – Ya-chi LIN** – Shiang-yuan CHU****

Abstract

The Russo-Ukrainian War caused energy prices to soar, without decreasing European reliance on liquid natural gas from Russia. Furthermore, the higher energy prices compared to the prewar period compelled richer countries to increase energy subsidies without EU permission. This, in turn, could lead to divergence in inflation, economic performance, and government bond yields within the EMU. IMF warned that the stability of EMU was under threat, which implies the monetary union would be exposed to the same dangers as before the onset of the sovereign bond crisis in 2010 – 2015. This study analyzes whether the EMU is facing such dangers, utilizing the sigma convergence approach proposed by Phillip and Sul (2007) and panel estimation. This method provides more precise indications of economic symmetry than traditional unit root tests, allowing for clearer policy implications. Empirical analysis suggests that, so far, the EMU has not faced the danger of divergence. However, unilateral energy subsidies without coordination could be a key determinant affecting government bond yield spreads.

Keywords: *energy prices and subsidy, σ-convergence test, government bond yield, EMU convergence*

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Introduction

The Russo-Ukrainian War has led to a significant increase in energy prices, and International Monetary Fund (2005) warned that it has threat the stability of European Monetary Union (EMU). In the case of natural gas in Europe, the prices are still higher than pre-war times despite efforts in diversification, storage, and energy subsidy. However, from January to July 2023, Belgium and Spain still ranked second and third in importing Russian LNG, indicating the failure of energy diversification and the ongoing threat of energy shortages. Essentially, the uninterrupted war elevated energy prices, increasing pressure on EMU inflation and causing economic recession due to monetary policy contraction.

Fossil energy sources often act as substitutes, the global prices of oil, coal, and natural gas surged simultaneously following Russia's invasion of Ukraine in early 2022. Despite variations in natural gas consumption intensity across Eurozone member countries, the broad-based spike in fossil fuel prices exerted a profound impact on total energy consumption costs across the entire region. Natural gas prices have remained structurally higher than pre-war levels, suggesting that price volatility remains a persistent threat to the EU in the context of a protracted conflict.

These energy price shocks have led to substantial and highly divergent inflationary pressures. In 2022, Harmonized Index of Consumer Prices (HICP) inflation rates ranged from 5.9% in France to 18.9% in Lithuania. In Lithuania, energy costs directly accounted for approximately half of the annual inflation rate. In contrast, energy contributed roughly 3% to inflation in France, while exceeding 5% in countries such as Belgium, Estonia, Greece, Latvia, and the Netherlands.[2] As noted by Ari et al. (2022), these cross-country variations are driven by differences in wholesale market structures, regulatory frameworks, national policy interventions, energy contracting practices and the reliance on Russian natural gas. Such inflation divergences pose a significant challenge to the stability of the European Monetary Union (EMU) (Riegert, 2023), which our study aims to analyze.

Certain wealthier member states, such as Germany and France, might unilaterally increase energy subsidies to prevent businesses from moving to China and the U.S. due to their lower energy costs and more feasible subsidies (e.g., Inflation Reduction Act, IRA). While these unilateral activities without EU permission are beneficial for price controls and improving national economic conditions, making their government bonds more attractive and causing lower bond yields, other relatively poorer member states may struggle to afford energy subsidies without

[2] Although Gazprom began restricting supplies in late 2021, the inflationary impact during that period remained relatively muted and localized. We argue that the February 2022 invasion represents a more definitive structural turning point, as it triggered a sustained surge in global energy markets that fundamentally altered the Eurozone's macroeconomic trajectory.

the EU's collective decisions, leading to higher government bond yields and fiscal burdens. Mario Draghi emphasized that Europe was "going nowhere" if it failed to address the question of high energy costs, and industrialists called for a single Energy Union with a common market (Hollinger and White, 2023). Due to the surging energy prices, the average debt as a percentage of GDP reached 92.9% in 2022Q3 for the EMU countries, violating the convergence criteria of 60% (Stability and Growth Pact). The dangerous situation before the onset of the European sovereign debt crisis could reoccur (Riegert, 2023). Note that there are still some differences between the possible outcome above and the 2010 – 2015 sovereign debt crisis: in the latter, the EU experienced an economic recession, which makes quantitative easing (QE) and the Pandemic Emergency Purchasing Program (PEPP) reasonable. At this moment, more expenditure would be less feasible, and the so-called "anti-fragmentation tool" proposed by the ECB is still unclear.

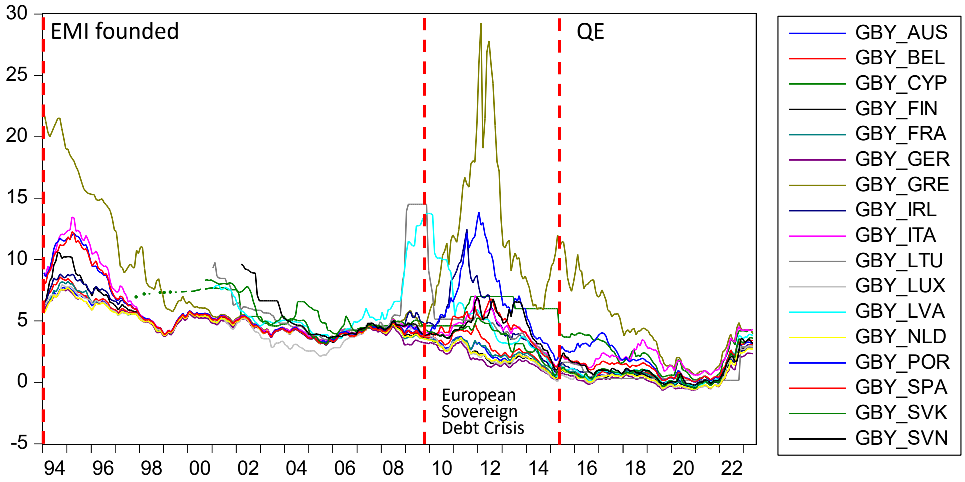
The purpose and contribution of this paper are to explore the following questions: Is the EMU facing a similar risk before the sovereign debt crisis now? Have energy issues, including unilateral subsidy, been determinants of the EMU's divergence if we use government bond yields as an indicator of convergence? These are not easy to answer using the so-called eyeball-economics. For instance, looking at Figure 1, it is obvious that yields gradually converged after the launch of the European Monetary Institute (EMI). This suggests that investors had sufficient confidence in the upcoming EMU, believing that the quality of bonds from member states was closely aligned. Investors held onto these beliefs until the sovereign debt crisis, and it's unlikely that such confidence will return to the 2009 levels permanently without substantial and powerful institutional reform within the EU. Despite this challenge, the impact of European QE and the subsequent PEPP is evident, effectively fostering convergence within the EMU.

In contrast, the message from Figure 2 is not clear. We can observe that the PEPP prevented the danger of potential divergence, but it appears to have relapsed since the war starting in February and QE's conclusion since May 2022. Will the divergent trend, stemming from unstable energy prices, potential unilateral energy subsidies, unclear anti-fragmentation strategies, and an incomplete fiscal union, pose a threat to the EMU's survival? We require a more precise method to assess the above issues.

The structure of this paper is as follows. Sections 1 and 2 are devoted to a literature review and the mechanism of how surging energy prices impact EMU divergence, respectively. Section 3 explains how we define convergence and introduces the method applied in this paper. To achieve this, we adopt an effective method developed by Phillips and Sul (2007) to test the convergence of the idiosyncratic components in the panel data. Section 4 describes the empirical results, including the current degrees of EMU convergence since the Russo-Ukrainian war, and the impact of richer member states' energy subsidy on EMU convergence. The last section concludes and provides policy implications.

F i g u r e 1

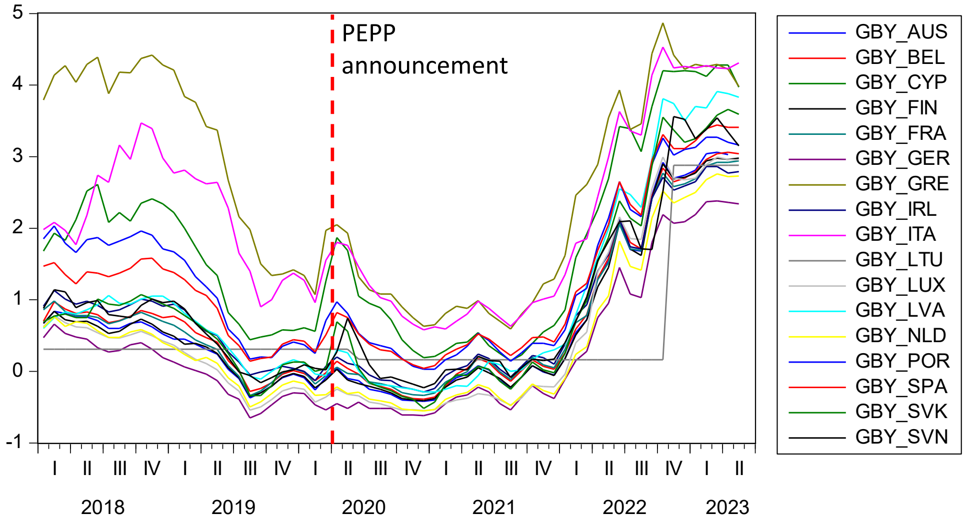
10 Year Government Bond Yield, 1994 – 2023 (%)



Source: IMF International Financial Statistics; Federal Reserve Bank of St. Louis, Economic data; Author's computation.

F i g u r e 2

10 Year Government Bond Yield, 2018 – 2023 (%)



Source: IMF International Financial Statistics; Federal Reserve Bank of St. Louis, Economic data; Author's computation.

1. Literature Review

A significant body of literature has discussed the importance of an effective fiscal transfer mechanism for the sustainability of the EMU at a micro-level, particularly in terms of regional development. However, few studies have paid attention to the macro-level, especially concerning the spillovers of the current war on the EMU. Cimadomo et al. (2020) explore the role of financial integration versus official financial assistance in consumption smoothing. In the early years of the euro, only about a third of country-specific output shocks were smoothed; however, in the aftermath of the crisis, almost 60% of these shocks were absorbed. The provision of official loans to distressed governments in the wake of the crisis considerably improved risk sharing since 2010.

Cimadomo (2022) highlights that risk-sharing mechanisms across euro area countries have been weaker than in the United States, primarily due to a lower degree of risk-sharing through European capital markets. Risk-sharing has improved since the start of the pandemic, i.e., between 2020 and 2022, mainly explained by a stronger credit channel. Havlik et al. (2022) detect larger effects for monetary than for fiscal announcements in the Covid-19 pandemic, suggesting that fiscal support can play a stabilizing role if it includes a significant transfer component. Garcia et al. (2023) analyze the impact of the Covid-19 pandemic shock, finding that a lower bound on nominal interest rates in the euro area amplifies the negative international spillovers affecting the euro area. The positive spillovers from fiscal measures, such as the new Next Generation EU implemented in the euro area, combat the pandemic. Analyzing existing fiscal-federal systems, Burriel et al. (2020) demonstrated that effective cross-regional stabilization of asymmetric shocks tends to work, financed out of cyclical central government budgets. Capella-Ramos et al. (2020) provide evidence that net fiscal transfers have contributed to income redistribution across the EMU. While the EU structural and investment funds are essential for real convergence in the medium term, fiscal transfers are no substitute when it comes to promoting sustainable economic growth and convergence in the long term.

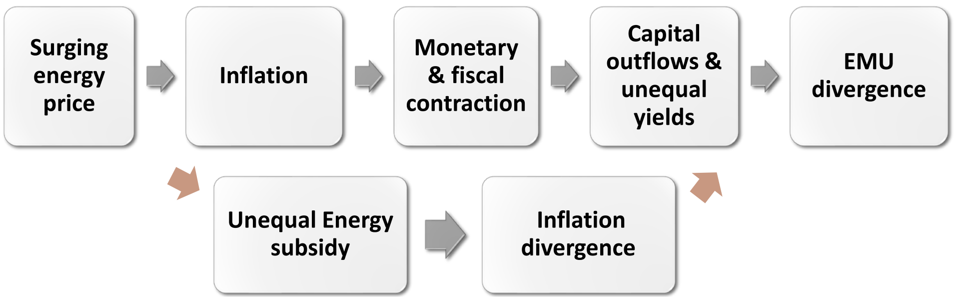
2. Mechanism

The surge in energy prices impacts EMU divergence through two channels, as illustrated in Figure 3. The first channel operates through the increase in households' cost of living (first-round effect), which raises the public's longer-term inflation expectations and exerts additional upward pressure on inflation (second-round effect). While the core inflation rate excludes energy prices, the second-round effects continue to push up the inflation rate. Despite the suppression of inflation causing a sharp slowdown in economic growth and an increase in unemployment, the rigorous monetary policy has led investors to anticipate the central bank's commitment to maintaining low inflation levels. This leaves businesses with little incentive to pass on heightened energy costs through higher prices (Bernanke, 2006). The uniform ECB interest rate may not be suitable for all EMU countries; hence, governments should adopt fiscal policies tailored to each country's economy. Without monetary sovereignty, government bond yields tend to diverge across EMU countries, contributing to EMU divergence.

Differences in wholesale markets, regulations, policy measures, and contracting practices result in unequal energy subsidies. The second channel involves the uneven energy subsidy across EMU countries, leading to cross-country variations in retail energy price inflation, which also contributes to instability within the EMU.

F i g u r e 3

Mechanism of Surging Energy Price Impacts on EMU Divergence



Source: Authors' computation.

3. Methodology and Data

3.1. Sigma-Convergence Test

As previously mentioned, we interpret the concept of EMU convergence (and divergence) from the perspective of member states' 10-year government bond yields, in line with the Maastricht convergence criteria and past sovereign debt experience. We assess EMU convergence before and after the Russo-Ukrainian war using the so-called "σ-convergence" test, with derivations detailed in the Appendix of this paper.

When describing time series data, traditional unit root tests and the co-integration approach are typically initial steps, but they have limitations in providing a precise indication of economic symmetry. Rejecting the conventional unit root test for time series across countries based on panel data tests does not imply convergence to the same long-term yield level or a decrease in the dispersion of member states' interest rates over time. Furthermore, rejecting the joint unit root hypothesis suggests that the series could be a mixture of I(1) and I(0). If the common components diverge faster than the convergence of the idiosyncratic components, the series may remain nonstationary.

In addition, the co-integration approach suggests that co-integrated series match each other in the sense that some of their linear relationships are stationary in the long run. However, co-integration does not explain the trends of the component variables but implicitly considers the system's unit root (Kong et al., 2019). This implies that the conventional co-integration test may have low power to detect the asymptotic co-movement of the idiosyncratic components.

Phillips and Sul (2007) proposed the σ-convergence test (or log *t* test) for the convergence of variances in cross-sectional data. They also introduced the concept of relative convergence, requiring the ratio of two time series to converge to unity in the long run when the series share common divergent stochastic or deterministic trend components. By decomposing panel data into a common factor and an idiosyncratic component, the σ-convergence test can detect the convergence of the idiosyncratic component without being influenced by the divergent nature of the common component. This approach is well-suited for examining macroeconomic data, which typically consist of both common factors and idiosyncratic parts.

Kong et al. (2019) expanded on Phillips and Sul's (2007) idea and introduced the concept of weak σ-convergence, referring to a decrease in cross-sectional variation over time in the panel. In contrast to Phillips and Sul's (2007) original log *t* test, the weak σ-convergence method utilizes linear trend regression to detect the decay of trend in cross-sectional variation after removing the common components. This method provides better control of size and greater discriminatory power when the series share common time decay patterns characterized by evaporating trends rather than divergent behavior. Since our research focuses on the bond yields of EMU member states since the Russo-Ukrainian war, exhibiting significant divergent trend behavior, we opt for Phillips and Sul's (2007) log *t* test approach. Examining the trend decay in cross-sectional variation over time allows us to analyze volatility trends and evaluate the synchronized bond yield situation in the EMU. Importantly, the σ-convergence approach enables us to investigate club-convergence among the cross-sections, indicating different groups of member states with similar yield paths.

3.2. Panel Regression Test

National energy subsidies or financial assistance from the European Union can have an impact on the economy. By adopting energy subsidies, inflation may not necessarily increase sharply, and energy prices may surge less severely. Financial aid from the EU can stimulate economies when member states are constrained by fiscal budget regulations. Through these two policy measures, country risks can be alleviated, and the disparity between government bond yields and those of other countries can also be diminished. In this subsection, we will assess the impact of national energy subsidies or financial assistance from the European Union on government bond spreads. The regression model is specified in equation (1).

$$mr_{i,t} = \beta_{0,i} + \beta_1 y_{i,t} + \beta_2 r_t^{EONIA} + \beta_3 \pi_{i,t}^{Gas} + \beta_4 Debt_{i,t} + \beta_5 G_{i,t} + \\ + \beta_6 ES_{i,t} + \beta_7 FA_{i,t} + \varepsilon_{i,t} \tag{1}$$

where $mr_{i,t}$ represents EMU convergence (Maastricht) criterion bond yield of country *i* in year *t*. The independent variables include: $y_{i,t}$ log of real GDP per capita, r_t^{EONIA} ECB monetary policy interest rate, which represented by Euro Overnight Index Average (EONIA), $\pi_{i,t}^{Gas}$ annual growth rate of gas price for non-household consumers, $Debt_{i,t}$ government consolidated gross debt in percentage of GDP, $G_{i,t}$ total government expenditure in percentage of GDP, $ES_{i,t}$ total energy subsidy in percentage of GDP, and $FA_{i,t}$ the ratio of financial assistance relative to GDP, respectively.

Alexopoulou et al. (2009) showed that an increase in real GDP per capita, serving as a measure of living standards, results in higher credit ratings, leading to lower government bond spreads. According to the expectations theory, long-term government bond yields are a function of short-term rates. The study also indicated that domestic money market liquidity may also be positively related with the liquidity conditions in the long term. Given that gas is one of the most widely used energy sources in Europe, the surge in gas prices is anticipated to induce cost-push inflation and subsequently impact interest spreads. Expanding government expenditure serves to mitigate economic downturns and has a negative effect on interest spreads. However, when the government experiences a large budget deficit and increases consolidated government debt, higher public indebtedness raises default risk, translating into higher government bond spreads. Energy subsidies may alleviate the transmission of surging gas prices to inflation and are expected to be negatively correlated with interest spreads. Financial assistance serves as a risk-sharing mechanism in the euro area, and thus, it is expected to be negatively correlated with spreads (Havlik et al., 2022).

Equation (2) decomposes the total energy subsidies into the explicit and implicit components, allowing us to discern the difference in the impact of the explicit and implicit energy subsidies. Our study emphasizes the effect of energy subsidy for surging gas prices, which is closely related to the explicit subsidy.

$$mr_{i,t} = \beta_{0,i} + \beta_1 y_{i,t} + \beta_2 r_t^{EONIA} + \beta_3 \pi_{i,t}^{Gas} + \beta_4 Debt_{i,t} + \beta_5 G_{i,t} + \\ + \beta_6 XES_{i,t} + \beta_7 MES_{i,t} + \beta_8 FA_{i,t} + \varepsilon_{i,t} \tag{2}$$

where $XES_{i,t}$ represents the explicit energy subsidies in percentage of GDP, which occur when the retail price is below a fuel's supply cost. $MES_{i,t}$ represents the implicit energy subsidies in percentage of GDP, which occur when the retail price fails to include external costs.

The impact of policies on interest rate spreads may evolve over time. We address potential temporal changes by incorporating interaction effects to examine the impact of subsidies across different periods. The dummy variables of year 2022 are inserted in equation (3) and (4). By multiplying the dummy variable with gas price change and energy subsidies in percentage of GDP, how Russo Ukrainian War changes the impact of gas price and energy subsidies on government bond spread could be detected. We also focus on the financial assistance after Covid-19, therefore the dummy variable of year 2020 – 2022 is also considered with the financial assistance variable.

$$mr_{i,t} = \beta_{0,i} + \beta_1 y_{i,t} + \beta_2 r_t^{EONIA} + \beta_3 \pi_{i,t}^{Gas} + \beta_3' \pi_{i,t}^{Gas} D_t(\tau_0) + \beta_4 Debt_{i,t} + \beta_5 G_{i,t} \\ + \beta_6 ES_{i,t} + \beta_6' ES_{i,t} D_t(\tau_0) + \beta_7 FA_{i,t} + \beta_7' FA_{i,t} D_t(\tau_1) + \varepsilon_{i,t} \tag{3}$$

$$mr_{i,t} = \beta_{0,i} + \beta_1 y_{i,t} + \beta_2 r_t^{EONIA} + \beta_3 \pi_{i,t}^{Gas} + \beta_3' \pi_{i,t}^{Gas} D_t(\tau_0) + \beta_4 Debt_{i,t} + \beta_5 G_{i,t} \\ + \beta_6 XES_{i,t} + \beta_6' XES_{i,t} D_t(\tau_0) + \beta_7 MES_{i,t} + \beta_7' MES_{i,t} D_t(\tau_0) \\ + \beta_8 FA_{i,t} + \beta_8' FA_{i,t} D_t(\tau_1) + \varepsilon_{i,t} \tag{4}$$

where $D_t(\tau)$ represents the dummy variable of the period τ,

$$\begin{cases} D_t(\tau) = 0, & if \quad t < \tau \\ D_t(\tau) = 1, & if \quad t \geq \tau \end{cases}$$

τ_0 is defined as the year of 2022, when the energy price fluctuated largely and some countries began increasing explicit energy subsidies. τ_1 is the year 2020 that financial assistance combating Covid-19 pandemic was applied.

In the final part of our empirical work, we will investigate whether the unilateral energy subsidy of Germany threatens EMU convergence. The greater unilateral energy subsidy lowers production cost, and makes Germany's exports more competitive relative to other EMU countries. We focus on the sample of the EMU countries except for Germany, and insert the variable of Germany's explicit energy subsidy in 2022 into equation (5).

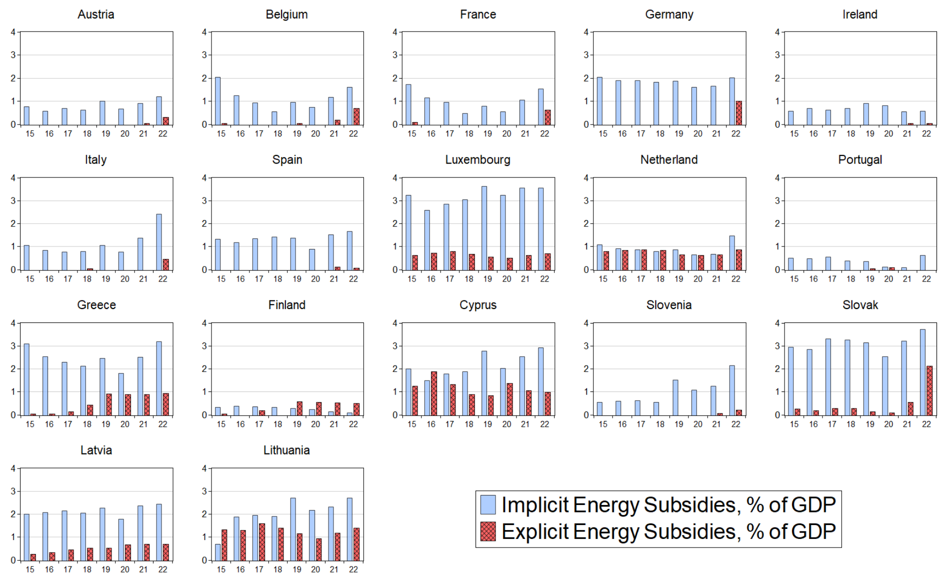
$$mr_{i,t} = \beta_{0,i} + \beta_1 y_{i,t} + \beta_2 r_t^{EONIA} + \beta_3 \pi_{i,t}^{Gas} + \beta_3' \pi_{i,t}^{Gas} D_t(\tau_0) + \beta_4 Debt_{i,t} + \\ + \beta_5 G_{i,t} + \beta_6 XES_{i,t} + \beta_6' XES_{i,t} D_t(\tau_0) + \beta_6'' XES_{GER,t} D_t(\tau_0) \qquad i \neq GER \qquad (5) \\ + \beta_7 MES_{i,t} + \beta_7' MES_{i,t} D_t(\tau_0) + \beta_8 FA_{i,t} + \beta_8' FA_{i,t} D_t(\tau_1) + \varepsilon_{i,t}$$

3.3. Data Source

The first part of our empirical work assesses the dynamics of government bond yields. We utilize data from 12 to 17 member states of the EMU, spanning from 1994M1 to 2023M4, obtained from the IMF International Financial Statistics. The second part evaluates the determinants of government bond yield spreads. We use the annual Maastricht criterion bond yields, Euro Interbank Offered Rate (EONIA), real GDP per capita, government consolidated gross debt as a percentage of GDP, and the government expenditure relative to GDP ratio for 17 EMU countries from 2015 to 2022. This data is sourced from Eurostat, the statistical office of the European Union.

In the second empirical work, data on energy subsidies and financial assistance is also required. The data on energy subsidies is retrieved from the IMF Fossil Fuel Subsidies Data. Total energy subsidies are decomposed into explicit and implicit subsidies, as shown in Figure 4.

F i g u r e 4
Tendency of the Energy Subsidies from 2015 – 2022 (% of GDP)

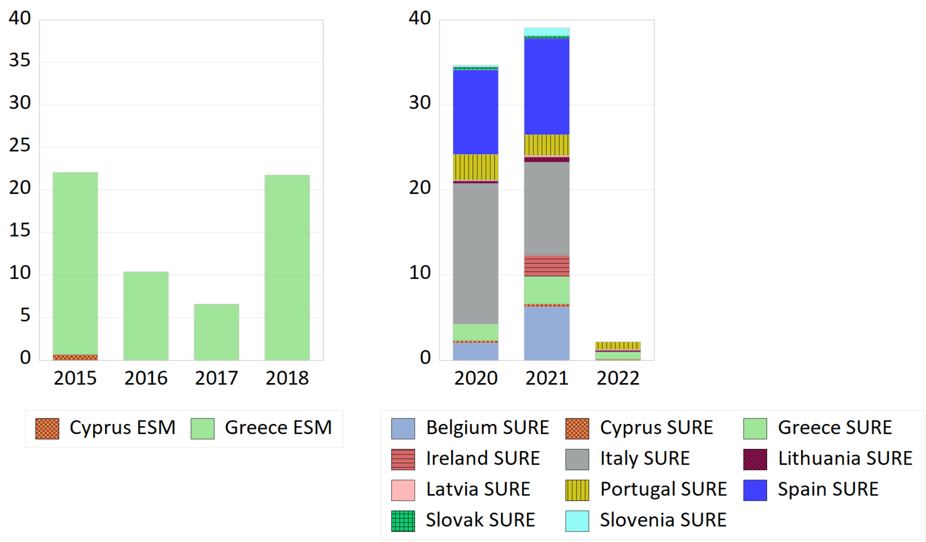


Source: IMF Fossil Fuel Subsidies data; Authors' computation.

Explicit subsidies occur when the retail price is below a fuel's supply cost, including direct support to producers. Implicit subsidies occur when the retail price fails to include external costs, such as contributions to climate change, local health damages, and traffic congestion and accident externalities associated with the use of road fuels, etc. Most EMU countries, including Austria, Belgium, France, Germany, Ireland, Italy, Spain, and Slovenia, display high implicit energy subsidies but low explicit ones before 2022. In 2022, the gas shortage triggered by the Russo-Ukrainian War boosted energy prices, leading all governments to increase explicit subsidies on the supply of natural gas.

Figure 5

Tendency of the Financial Assistance from 2015 – 2022 (billion EUR)



Source: European Stability Mechanism Programme Database; EU financial assistance, European Commission; Authors' computation.

A fully-fledged fiscal stabilization mechanism has not yet been introduced in the euro area. Several official facilities provided financial assistance to governments after European sovereign debt crisis.[3] The EMU countries began to recover from the crisis after 2015. Therefore, during our sample period 2015 – 2022, only the European Stability Mechanism (ESM) continued financial assistance during the

[3] EMU countries can request access to financial assistance mechanisms to preserve or restore financial stability, when experiencing or threatened by financial difficulties. The official financial facilities are the Greek Loan Facility, the European Financial Stability Facility (EFSF), the European Financial Stability Mechanism (EFSM), and the European Stability Mechanism (ESM), which were progressively activated from 2010 onwards in the EMU.

recovery from the European sovereign debt crisis. Beginning in 2020, the Temporary Support to mitigate Unemployment Risks in an Emergency (SURE) was designed to address the negative economic consequences of the coronavirus outbreak. The data in Figure 5 is retrieved from European Stability Mechanism Programme Database and EU financial assistance, European Commission.

The variables and the data source used in this study are summarized in Table 1.

T a b l e 1

Data Source

Variable	Definition	Source	Frequency	Sample period
$r_{i,t}$	Government bond yields	IMF International Financial Statistics	Month	1991M1~2023M4
$mr_{i,t}$	Maastricht criterion bond yields	Eurostat	Annual	2015~2022
r_t^{EONIA}	Euro Interbank Offered Rate (EONIA)	Eurostat	Annual	2015~2022
$y_{i,t}$	The real GDP per capita	Eurostat	Annual	2015~2022
$Debt_{i,t}$	The government consolidated gross debt in percentage of GDP	Eurostat	Annual	2015~2022
$G_{i,t}$	The government expenditure relative to GDP ratio	Eurostat	Annual	2015~2022
$\pi_{i,t}^{Gas}$	Annual growth rate of gas price for non-household consumers	Eurostat	Annual	2015~2022
$ES_{i,t}$	Total energy subsidy in percentage of GDP	IMF Fossil Fuel Subsidies Data	Annual	2015~2022
$XES_{i,t}$	The explicit energy subsidies in percentage of GDP	IMF Fossil Fuel Subsidies Data	Annual	2015~2022
$MES_{i,t}$	The implicit energy subsidies in percentage of GDP	IMF Fossil Fuel Subsidies Data	Annual	2015~2022
$FA_{i,t}$	The ratio of financial assistance relative to GDP, which is the sum of			
	European Stability Mechanism (ESM)	European Stability Mechanism Programme Database	Annual	2015~2022
	Temporary Support to mitigate Unemployment Risks in an Emergency (SURE)	EU financial assistance, European Commission	Annual	2015~2022

Source: Authors' elaboration.

4. Empirical Results

4.1. Panel Unit Root Test

We initially conduct conventional unit root tests on the interest rate differentials. The Euro InterBank Offered Rate (Euribor) is selected as the benchmark, and we investigate whether the government bond yields of EMU countries converge with Euribor. Euribor is the average interest rates at which Eurozone banks borrow unsecured funds from counterparties in the euro wholesale money market (or interbank market). The results are presented in Table 2.

T a b l e 2

Panel Unit Root Test of Interest Spread across EMU Country, $r_{i,t} - r_t^{Euribor}$

	1994M1 – 2023M4 12 countries			2015M3 – 2023M4 17 countries		
Test	*Statistic*		*p-value*	*Statistic*		*p-value*
Levin, Lin and Chu	–0.37		0.3543	–0.01		0.4941
Breitung	–1.69	**	0.0458	0.86		0.8043
Im, Pesaran and Shin	–6.58	***	0.0000	–3.09	***	0.0010
ADF-Fisher	98.16	***	0.0000	56.48	***	0.0091
PP-Fisher	103.26	***	0.0000	44.63		0.1050

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

Source: Authors' computation.

The PP-Fisher test (Choi, 2001) rejects the individual unit root hypothesis at the 5% significance level, while the null hypothesis of a unit root cannot be rejected by Levin et al. (2002) and Breitung (2001)'s test. Specifically, the Levin, Lin and Chu (2002) and Breitung (2001) tests assume cross-sectional homogeneity in the autoregressive processes and test the null hypothesis of a common unit root. Conversely, the Im, Pesaran and Shin (2003), Fisher-ADF, and PP tests allow for heterogeneous autoregressive processes across cross-sections. If a non-zero fraction of the individual processes is stationary, then the alternative hypothesis holds. As indicated in Table 2, the Im, Pesaran and Shin, Fisher-ADF, and PP tests reject the null hypothesis of non-stationarity, and the Levin, Lin and Chu test fails to reject the presence of a common unit root. These findings suggest that while stationary interest rate spreads exist within the panel, this stationarity is not universal across all series.

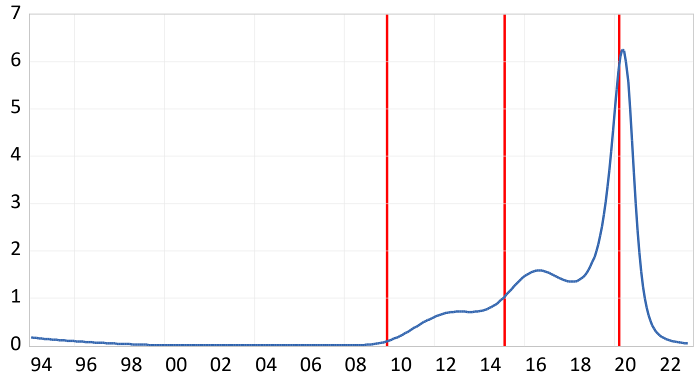
The outcomes of the traditional unit root tests are inconclusive, implying that interest rate convergence among EMU countries cannot be confirmed. Given the possibility of club convergence suggested by the σ-convergence approach, we can employ the σ-convergence test in this case.

4.2. Sigma-Convergence Test

Since the σ-convergence method is more effective in detecting trend decay in the cross-sectional variation after removing common factors, we can use this test to examine convergence among the member states, which indicates the synchronized government bond yield in EMU. To achieve this, we conduct the σ-convergence test for the full sample period from 1994M1 to 2023M4, as well as a subsample before the onset of the sovereign bond crisis (1994M1~2009M11, 12 EMU countries), the period of the sovereign bond crisis (2010M1~2015M2, 17 EMU countries), and the period during the COVID-19 pandemic and the Russo Ukrainian war (2020M3-2023M4, 17 EMU countries). Note that there are 20 member states in the EMU now, but we are unable include them all due to data insufficiency.

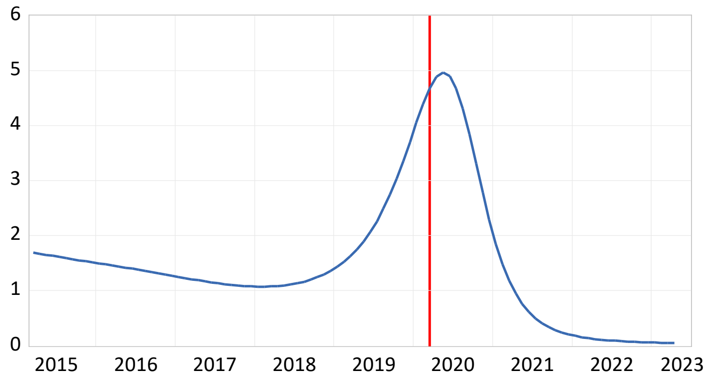
Figures 6 and 7 illustrate the cross-sectional variance of the relative transition coefficient H_t of 12 EMU countries in 1994 – 2023, and that of 17 EMU countries in 2015 – 2023, respectively. This variance reflects government bond yield volatility while accounting for trends. If H_t is negatively sloped, the volatility of the relative transition coefficient decreases over time, indicating the yield convergence. Figure 6 shows that the cross-sectional variance kept decreasing steadily until 2010, sharply increased from 2010 to 2020, and then converged again after 2020. Figure 7 narrows the time window and includes more member states to assess the effectiveness of the European QE in 2015 and the PEPP in 2020, though there was a brief period of slow convergence, possibly due to uncertainty about the pandemic rescue plan.

F i g u r e 6
Tendency of the Cross-Sectional Variance (H_t), 1994 – 2023M4, 12 Countries



Source: Authors' computation.

F i g u r e 7
Tendency of the Cross-Sectional Variance (H_t), 2015 – 2023M4, 17 Countries



Source: Authors' computation.

The results of the σ-convergence test in equation (A9) of Appendix, or the log *t* test, are presented in Table 3. In the sub-sample from 1994M1~2009M11 and 2020M3~2023M4, the test provides evidence of positive β_1 under $c \in [0.2, 0.3]$, the range where both power and size are satisfied. This indicates that the null hypothesis of yield convergence is accepted. β_1 turns significantly negative in the sub-sample in 2010M1~2015M2. Yield convergence is accepted after the formation of EMI (1994M1~2009M11), but the sovereign bond crisis brought about financial instability. The launch of QE and PEPP brought interest rates in EMU countries into synchronization, despite being impacted by the COVID-19 pandemic and the Russia-Ukraine war.

T a b l e 3
Results of the log *t* Test on Government Bond Yield of Euro Countries, $r_{j,t}$

	1994M1~2009M11 12 Countries		**2010M1~2015M2 17 Countries**		**2020M3-2023M4 17 Countries**	
c	β_1	(t-stat.)	β_1	(t-stat.)	β_1	(t-stat.)
0.20	0.83	(6.95)	–0.87	(–15.37)	4.58	(8.03)
0.21	0.74	(7.35)	–0.84	(–15.34)	4.58	(8.03)
0.22	0.63	(7.73)	–0.84	(–15.34)	4.64	(6.95)
0.23	0.57	(7.86)	–0.82	(–15.69)	4.64	(6.95)
0.24	0.45	(7.68)	–0.82	(–15.69)	3.54	(9.30)
0.25	0.31	(6.02)	–0.79	(–16.55)	3.54	(9.30)
0.26	0.17	(2.71)	–0.76	(–18.17)	3.54	(9.30)
0.27	0.01	(0.09)	–0.76	(–18.17)	3.19	(10.71)
0.28	–0.16	(–1.71)	–0.73	(–21.02)	3.19	(10.71)
0.29	–0.34	(–3.02)	–0.73	(–21.02)	2.97	(12.51)
0.30	–0.53	(–4.10)	–0.71	(–25.84)	2.97	(12.51)

Note:(1) Column 2: after EMI established and before European Sovereign Debt Crisis; Column 3: after European Sovereign Debt Crisis and before QE; Column 4: after PEPP.
(2) The log *t* regressions are based on equation (A9) in Appendix.
(3) Discarding some initial fraction of the time series data allows attention to be focused on the more recent changes, especially when the sample size is larger. Based on the simulation experience of Phillips and Sul (2007), c in the interval, 0.2 to 0.3, is a satisfactory choice, in terms of size and power.
Source: Authors' computation.

For the sub-sample 2010M1~2015M2, although yield convergence is rejected for the 17 Euro countries, there might be the existence of club convergence. The clustering algorithm of Phillips and Sul (2007) can detect the presence of 'club convergence' in the cross-sections. Table 4 and Figure 8 display the outcomes of club convergence on government bond yields spanning from 2010M1 to 2015M2, the period after the sovereign bond crisis and before the launch of QE. The 17 countries are classified into three clubs. In each club, yield convergence is proven based on the log t test. Italy, Portugal, Greece, Cyprus, and Slovenia, which have higher financial risks, exhibit the highest government bond yields among the three clubs. The Irish government is committed to maintaining a low fiscal deficit, and

Spain reaps huge profits from tourism, so the two countries are the fastest-recovering countries in the EMU. Lithuania switched its currency to the euro in 2015. Previously, Lithuania strictly abided by the Maastricht Treaty and controlled government bond yields. Therefore, Ireland, Spain, and Lithuania show club convergence. The rest of the sample converges toward the third convergence club.

Table 4

Results of Club Convergence on Government Bond Yield of Euro Countries, 2010M1~2015M2

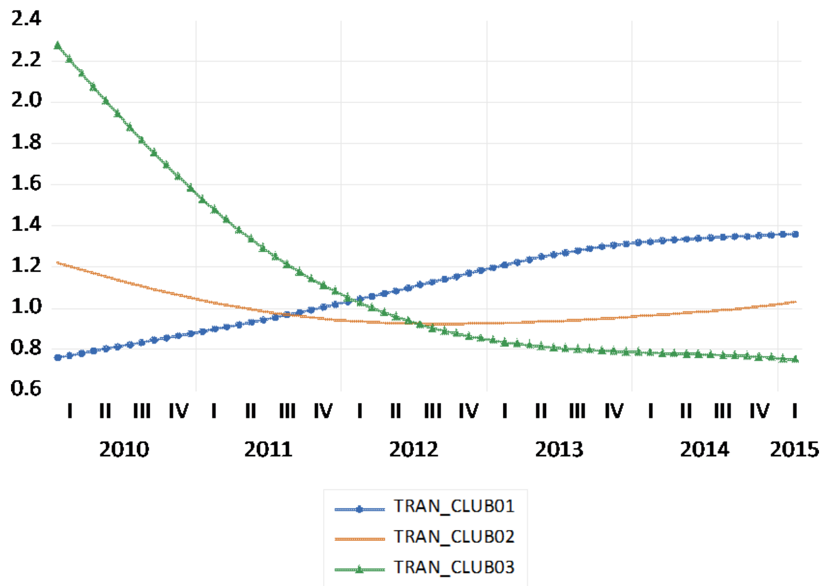
	log *t*	*t*-stat.	Countries
Club 1	0.03	(1.19)	Italy, Portugal, Greece, Cyprus, Slovenia
Club 2	0.25	(0.49)	Ireland, Spain, Lithuania
Club 3	0.39	(6.72)	Austria, Belgium, France, Germany, Luxembourg, Netherlands, Finland, Slovak, Latvia

Note: The result of club convergence from 2010M1 to 2015M2 is based on $c = 0.3$.

Source: Authors' computation.

Figure 8

Tendency of the Average Relative Transition Coefficient for the Three Clubs in Table 3



Source: Authors' computation.

4.3. Panel Regression Test

The convergence of government bond yield reflects that the economic stability of EMU remains intact, even when facing energy price surging. This subsection aims to discover how the policy measures impact the deflation of the government bond yield spreads. In addition to national government expenditure and energy subsidies, we also investigate the policy effect of financial assistance from the EU. The results are presented in Table 5 – 9.

We evaluate the effect of total energy subsidies, estimated by equation (1) and (3). The results estimated by ordinary least square are presented in Table 5. The coefficients of $y_{i,t}$, r_t^{EONIA}, $\pi_{i,t}^{Gas}$, $Debt_{i,t}$ and $G_{i,t}$ coincide with our expectations. Figure 5 shows that the largest financial assistance is applied by Greece, Italy, Spain and Portugal, etc. Therefore, financial assistance shows significantly positive relationship with interest spreads. In Column (2) we include the variable of retail gas price growth for the year 2022, but it doesn't show a significant impact on spreads. In Column (3), the variable of total energy subsidy in 2022 is inserted, and it shows a significantly positive effect, meaning the energy subsidy doesn't help to mitigate shocks. When focusing on financial assistance after 2020, it significantly lessens spreads, as shown in Column (4).

In the panel equation tests, the explanatory variables may be subject to reverse causality; for example, an increase in government bond yields may impair a government's ability to service its debt, leading to a rise in total government debt. In all specifications presented in Tables 6, the Durbin-Wu-Hausman test results significantly reject the null hypothesis that the government debt-to-GDP ratio ($Debt_{i,t}$) is exogenous. This implies that the Two-Stage Least Squares (TSLS) estimation is more appropriate. To ensure the validity of our instrumental variables, we employed the Hansen J-statistic (1982) to test for over-identification. The results confirm that the specified orthogonality conditions are satisfied. The results are the same as Table 5, except that the debt shows a significantly positive correlation with spreads, and the coefficient of total energy subsidy for the year 2022 turns insignificant.

Total energy subsidies can be decomposed into explicit and implicit ones, with the explicit ones used to subsidize the supply cost. Our study emphasizes the effect of energy subsidies for surging gas prices, which is more related to the explicit ones. We separate total energy subsidies into explicit and implicit subsidies, and the OLS and TSLS results are presented in Tables 7 and 8, respectively. Both results show that countries with higher explicit energy subsidies, such as Greece, Italy, Ireland, and Spain, display higher spreads. Focusing on the period in 2022, explicit energy subsidies did mitigate the shock and decrease spreads. On the contrary, countries with higher implicit energy subsidies, such as Germany and France, display lower spreads. However, the increase in implicit energy subsidies in 2022 instead raised interest spreads.

Table 9 presents the result of equation (5). There is some evidence supporting the enlargement of EMU divergence by Germany's explicit energy subsidy. However, when controlling the endogeneity, this effect become insignificant. Only slight evidence is found for the beggar-by-neighbor effect of Germany's energy subsidy policy.

T a b l e 5

OLS Results of Determinant of Government Bond Yield Spread, 2015~2022

	(1)	(2)	(3)	(4)	(5)
c	25.412*** (7.658)	26.690*** (7.007)	25.602*** (6.540)	16.301** (7.750)	17.326* (9.896)
$y_{i,t}$	−1.948*** (0.713)	−2.057*** (0.609)	−1.938*** (0.570)	−1.176* (0.665)	−1.237 (0.932)
r_t^{EONIA}	2.811*** (0.221)	2.535*** (0.478)	2.579*** (0.364)	2.535*** (0.392)	2.320*** (0.235)
$\pi_{i,t}^{Gas}$	0.004*** (0.001)	0.002 (0.002)	0.003*** (0.001)	0.004*** (0.001)	0.003** (0.001)
$\pi_{i,t}^{Gas} \times D_t(\tau_0)$		0.003 (0.003)			
$Debt_{i,t}$	0.004 (0.008)	0.004 (0.007)	0.006 (0.007)	0.008 (0.006)	0.008 (0.009)
$G_{i,t}$	−0.085*** (0.015)	−0.092*** (0.019)	−0.092*** (0.018)	−0.070*** (0.020)	−0.077*** (0.018)
$ES_{i,t}$	−0.072 (0.073)	−0.032 (0.049)	−0.192** (0.074)	−0.021 (0.053)	−0.131 (0.101)
$ES_{i,t} \times D_t(\tau_0)$			0.165*** (0.061)		0.146** (0.057)
$FA_{i,t}$	0.164* (0.083)	0.191** (0.093)	0.171* (0.087)	0.431*** (0.132)	0.440*** (0.113)
$FA_{i,t} \times D_t(\tau_1)$				−0.653*** (0.222)	−0.630*** (0.158)
N	136	136	136	136	136
R-squared	0.868	0.874	0.880	0.880	0.889
Adjusted R-squared	0.840	0.847	0.855	0.854	0.864
Redundant Fixed Effects Tests					
F statistics	7.068***	7.513***	8.400***	6.231***	7.239***

Note: 1. F-statistics significantly reject the null hypothesis of the redundant fixed effects in the unrestricted specification. The fixed effect specifications were adopted.
2. The constant term represents the average of the individual constants across the sample countries, while the sum of the fixed effect estimates is constrained to zero. For the sake of brevity, the individual fixed effect estimates are not listed in the tables.

Source: Authors' computation.

T a b l e 6

TSLS Results of Determinant of Government Bond Yield Spread, 2015~2022

	(1)	(2)	(3)	(4)	(5)
c	14.658 (11.834)	8.836 (11.356)	15.715** (5.506)	−9.407 (20.128)	−8.065 (12.313)
$y_{i,t}$	−0.985 (1.108)	−0.529 (1.001)	−1.047* (0.474)	1.091 (1.863)	1.032 (1.122)
r_t^{EONIA}	2.945*** (0.385)	3.865*** (0.641)	2.767*** (0.554)	1.678** (0.929)	2.778*** (0.443)
$\pi_{i,t}^{Gas}$	0.002** (0.001)	0.007* (0.003)	0.002 (0.001)	0.004* (0.003)	0.003* (0.002)
$\pi_{i,t}^{Gas} \times D_t(\tau_0)$		−0.007 (0.004)			
$Debt_{i,t}$	0.033** (0.015)	0.039* (0.019)	0.030* (0.015)	0.072*** (0.022)	0.051*** (0.018)
$G_{i,t}$	−0.119*** (0.024)	−0.094** (0.025)	−0.122*** (0.021)	−0.134*** (0.037)	−0.105*** (0.021)
$ES_{i,t}$	0.014 (0.057)	−0.035 (0.067)	−0.067 (0.074)	−0.050 (0.121)	−0.024 (0.107)
$ES_{i,t} \times D_t(\tau_0)$			0.077 (0.042)		−0.036 (0.074)
$FA_{i,t}$	−0.128 (0.164)	−0.376 (0.274)	−0.061 (0.135)	0.126 (0.177)	0.272 (0.624)
$FA_{i,t} \times D_t(\tau_1)$				−1.189*** (0.358)	−0.970* (0.558)
N	118	118	118	118	118
R-squared	0.902	0.881	0.907	0.813	0.879
Adjusted R-squared	0.878	0.850	0.883	0.765	0.846
Durbin-Wu-Hausman-Stat.	8.836***	10.105***	11.316***	8.025***	7.198***
Hansen J-Stat.	21.714	13.458	21.689	9.281	11.036

Note: 1. We select the following as our instrumental variables: the GDP growth rate, the seasonal component of gas price inflation, the energy subsidy-to-GDP ratio and its first difference, the growth rate of the debt-to-GDP ratio, the current account-to-GDP ratio, the budget deficit-to GDP-ratio, a time trend, and the square terms of the aforementioned variables.

2. The constant term represents the average of the individual constants across the sample countries, while the sum of the fixed effect estimates is constrained to zero. For the sake of brevity, the individual fixed effect estimates are not listed in the tables.

Source: Authors' computation.

T a b l e 7

OLS Results of Determinant of Government Bond Yield Spread, 2015~2022

	(1)	(2)	(3)	(4)	(5)
c	27.145*** (7.853)	28.534*** (10.011)	26.312*** (6.441)	18.663*** (6.084)	18.375*** (6.799)
$y_{i,t}$	−2.091*** (0.713)	−2.206** (0.943)	−1.997*** (0.569)	−1.368** (0.552)	−1.325** (0.632)
r_t^{EONIA}	2.844*** (0.203)	2.627*** (0.263)	2.674*** (0.366)	2.562*** (0.176)	2.403*** (0.197)
$\pi_{i,t}^{Gas}$	0.003*** (0.001)	0.002 (0.002)	0.002** (0.001)	0.004*** (0.001)	0.003*** (0.001)
$\pi_{i,t}^{Gas} \times D_t(\tau_0)$		0.002 (0.001)			
$Debt_{i,t}$	−0.002 (0.007)	−0.002 (0.011)	0.001 (0.007)	0.003 (0.006)	0.005 (0.006)
$G_{i,t}$	−0.077*** (0.013)	−0.085*** (0.019)	−0.086*** (0.018)	−0.066*** (0.010)	−0.073*** (0.012)
$XES_{i,t}$	0.229** (0.099)	0.242* (0.139)	0.176 (0.124)	0.232** (0.090)	0.135 (0.156)
$XES_{i,t} \times D_t(\tau_0)$			−0.191** (0.084)		−0.045 (0.200)
$MES_{i,t}$	−0.214*** (0.074)	−0.188* (0.111)	−0.260*** (0.084)	−0.184*** (0.063)	−0.206** (0.084)
$MES_{i,t} \times D_t(\tau_0)$			0.225*** (0.085)		0.150* (0.090)
$FA_{i,t}$	0.188* (0.110)	0.212** (0.085)	0.198** (0.087)	0.437*** (0.131)	0.440*** (0.096)
$FA_{i,t} \times D_t(\tau_1)$				−0.630*** (0.157)	−0.611*** (0.130)
N	136	136	136	136	136
R-squared	0.872	0.879	0.880	0.886	0.890
Adjusted R-squared	0.845	0.851	0.851	0.860	0.863
Redundant Fixed Effects Tests					
F statistics	7.519***	7.944***	7.946***	6.514***	6.672***

Note: 1. F-statistics significantly reject the null hypothesis of the redundant fixed effects in the unrestricted specification. The fixed effect specifications were adopted.
2. The constant term represents the average of the individual constants across the sample countries, while the sum of the fixed effect estimates is constrained to zero. For the sake of brevity, the individual fixed effect estimates are not listed in the tables.

Source: Authors' computation.

T a b l e 8

TSLS Results of Determinant of Government Bond Yield Spread, 2015~2022

	(1)	(2)	(3)	(4)	(5)
c	13.743 (9.618)	6.189 (8.599)	15.839* (7.193)	−9.847 (18.555)	−2.142 (12.559)
$y_{i,t}$	−0.861 (0.891)	−0.242 (0.765)	−1.027 (0.665)	1.158 (1.742)	0.507 (1.145)
r_t^{EONIA}	2.937*** (0.388)	3.685*** (0.648)	3.280*** (0.612)	1.529* (0.892)	2.495*** (0.441)
$\pi_{i,t}^{Gas}$	0.002* (0.001)	0.006* (0.003)	0.002 (0.002)	0.005** (0.002)	0.005** (0.002)
$\pi_{i,t}^{Gas} \times D_t(\tau_0)$		−0.007 (0.004)			
$Debt_{i,t}$	0.031** (0.014)	0.043* (0.019)	0.027* (0.013)	0.071*** (0.024)	0.046** (0.018)
$G_{i,t}$	−0.122*** (0.020)	−0.107** (0.030)	−0.120*** (0.031)	−0.135*** (0.040)	−0.108*** (0.019)
$XES_{i,t}$	0.123 (0.091)	0.055 (0.086)	0.804*** (0.177)	0.149 (0.349)	0.774*** (0.293)
$XES_{i,t} \times D_t(\tau_0)$			−0.797* (0.334)		−0.865** (0.388)
$MES_{i,t}$	−0.096 (0.101)	−0.105 (0.074)	−0.226* (0.098)	−0.158 (0.222)	−0.299** (0.133)
$MES_{i,t} \times D_t(\tau_0)$			0.090* (0.230)		0.073 (0.220)
$FA_{i,t}$	−0.092 (0.163)	−0.361 (0.225)	−0.034 (0.245)	0.136 (0.121)	0.233 (0.946)
$FA_{i,t} \times D_t(\tau_1)$				−1.184*** (0.282)	−0.975 (0.877)
N	118	118	118	118	118
R-squared	0.909	0.888	0.909	0.808	0.891
Adjusted R-squared	0.886	0.858	0.883	0.756	0.858
Durbin-Wu-Hausman-Stat.	16.856***	13.687***	12.618***	16.542***	11.794***
Hansen J-Stat.	21.051	13.744	16.669	8.650	3.515

Note: 1. We select the following as our instrumental variables: the GDP growth rate, the seasonal component of gas price inflation, the energy subsidy-to-GDP ratio and its first difference, the growth rate of the debt-to-GDP ratio, the current account-to-GDP ratio, the budget deficit-to GDP-ratio, a time trend, and the square terms of the aforementioned variables.

2. The constant term represents the average of the individual constants across the sample countries, while the sum of the fixed effect estimates is constrained to zero. For the sake of brevity, the individual fixed effect estimates are not listed in the tables.

Source: Authors' computation.

T a b l e 9

Results of Determinant of Government Bond Yield Spread, 2015~2022

	(1) OLS	**(2) TSLS**
c	27.279*** (8.554)	−16.191 (19.214)
$y_{i,t}$	−2.158** (0.798)	1.813 (1.779)
r_t^{EONIA}	2.007*** (0.238)	3.814* (1.921)
$\pi_{i,t}^{Gas}$	0.001 (0.001)	0.004 (0.003)
$Debt_{i,t}$	0.005 (0.009)	0.054** (0.019)
$G_{i,t}$	−0.087*** (0.016)	−0.094** (0.037)
$XES_{i,t}$	0.041 (0.321)	0.562** (0.251)
$XES_{i,t} \times D_t(\tau_0)$	−0.084 (0.257)	−0.895*** (0.288)
$XES_{GER,t} \times D_t(\tau_0)$	0.516*** (0.172)	−0.672 (0.936)
$MES_{i,t}$	−0.146 (0.087)	−0.222** (0.094)
$MES_{i,t} \times D_t(\tau_0)$	0.116*** (0.032)	0.193 (0.220)
$FA_{i,t}$	0.438*** (0.042)	−0.091 (1.351)
$FA_{i,t} \times D_t(\tau_1)$	−0.540*** (0.134)	−0.706 (1.301)
N	128	111
R-squared	0.894	0.876
Adjusted R-squared	0.866	0.835

Note: 1. F-statistics (6.33) significantly reject the null hypothesis of the redundant fixed effects in the unrestricted specification. The fixed effect specifications were adopted. The constant term represents the average of the individual constants across the sample countries, while the sum of the fixed effect estimates is constrained to zero. For the sake of brevity, the individual fixed effect estimates are not listed in the tables.
2. Durbin-Wu-Hausman-Stat. (19.73) significantly rejects the null hypothesis of exogenous government debt-to-GDP. Hansen's J-statistic (5.95) confirms that the instrumental variables satisfy the required orthogonality conditions. These instruments include the GDP growth rate, the seasonal component of gas price inflation, energy subsidy to GDP ratio, the change of energy subsidy to GDP ratio, the growth rate of debt to GDP ratio, current account to GDP ratio, budget deficit to GDP ratio, trend and the square of the above variables.

Source: Authors' computation.

Conclusion

The Russo-Ukrainian War has caused energy prices to skyrocket. Under the Covid-19 recession and surging energy prices, the average debt as a percentage of GDP for the EMU countries reached the highest record, violating the convergence criteria of 60%. The dangerous situation prior to the onset of the European sovereign debt crisis could return. The purpose and contribution of this paper are to explore whether the EMU is facing a risk similar to the sovereign debt crisis now and whether unilateral energy subsidies are determinants of the EMU's divergence.

Based on our empirical results, we conclude that: First, the EMU kept converging from the EMI to the sovereign crisis. Although EMU divergence occurred after the sovereign debt crisis, it has become stable since the COVID-19 pandemic and the Russo-Ukrainian War. However, the ECB monitors the enlargement of financial instability and considers the so-called "anti-fragmentation tools." The application of these tools is still vague to investors. Second, the EMU overnight rate and government expenditure can effectively narrow yield spreads, indicating the power of QE and national fiscal policies. Third, higher debt ratios and energy prices still pose a threat to spread widening. The risk of a debt crisis still exists. Fourth, explicit energy subsidies and financial assistance decreased spreads during the crisis period. In contrast, implicit energy subsidies had no significant effect. Finally, some richer member states (e.g., Germany and France) intend to implement an industry-wide energy subsidy without EU permission. Only slight evidence is found for the beggar-by-neighbor effect of Germany's energy subsidy policy. Unilateral actions in the EMU could worsen the convergence, which needs further exploration.

Following Western sanctions, Russia's fossil fuel export revenues continued to decline, reaching a new low in 2025 as both pipeline gas and LNG exports faced significant headwinds. The EU remained a primary destination for Russian LNG, accounting for a substantial share of Russia's remaining shipments. Thanks to the REPowerEU Plan, the share of Russian gas in the EU's total import mix has plummeted from approximately 45% in 2021 to less than 20% by May 2025. The convergence trends within the European Monetary Union merit further investigation.

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Appendix: Derivations of Sigma-Convergence

Adopting the σ-convergence approach by Phillips and Sul (2007), the government bond yield, denoted as $r_{j,t}$, can be decomposed into the systematic risk $\lambda_{j,t}\mu_t$ and the idiosyncratic risk $a_{j,t}$ as follows

$$r_{j,t} = a_{j,t} + \lambda_{j,t}\mu_t . \tag{A1}$$

Here, *j* and *t* represent the country and time, respectively. μ_t represents the systematic risk factor for the government bond yield, while $\lambda_{j,t}$ captures the time-varying factor loading coefficients that reflect the individual effects on systematic risk. μ_t is assumed to have some deterministic or stochastically trending behavior that dominates the idiosyncratic component $a_{j,t}$ as $t \to \infty$. To separate the common components from the idiosyncratic components, we transform Equation (1) as

$$r_{j,t} = \left(\frac{a_{j,t}}{\mu_t} + \lambda_{j,t} \right) \mu_t . \tag{A2}$$

The systematic risk factor can be measured by the cross-sectional mean of the interest rate that is *I*(1). Then, μ_t also follows an *I*(1) process and $a_{j,t} / \mu_t$ converges to zero over time. Following this, the national government bond yield is decomposed into a common trend component and a time-varying idiosyncratic element. Denoting the idiosyncratic component $b_{j,t} \equiv \left(\frac{a_{j,t}}{\mu_t} + \lambda_{j,t} \right)$, the national government bond yield in (A2) can be rewritten as

$$r_{j,t} = b_{j,t}\mu_t . \tag{A3}$$

Thus, $b_{j,t}$ shows the individual relative coefficient between $r_{j,t}$ and the common trend component μ_t. The interest rate differential between EMU countries is defined as follows:

$$r_{j,t} - r_{k,t} = (b_{j,t} - b_{k,t})\mu_t , \tag{A4}$$

where $b_{j,t} - b_{k,t}$ indicates the relative yield gap of idiosyncratic risk between country *j* and *k*. If these idiosyncratic components converge asymptotically to some common *b* in the long run, the yield gap then diminishes. Since the common component μ_t is *I*(1), when the common factor diverges faster than the convergence of the idiosyncratic components, the interest rate differential may remain non-stationary. Therefore, we examine if convergence holds for the idiosyncratic components $b_{j,t}$ instead, applying Phillips and Sul's (2007) log *t* test method.

According to Phillips and Sul (2007), factoring out the common trend component μ_t in (A4) leads to the specification for $b_{j,t}$ in the semiparametric form

$$b_{j,t} = b_j + \sigma_j \xi_{j,t} L(t)^{-1} t^{-\alpha}, \tag{A5}$$

where b_j is fixed, $\xi_{j,t}$ is i.i.d. across *j* but weakly dependent over *t*, $L(t)$ is a slowly varying function and $L(t) \to \infty$ as $t \to \infty$, α is the decay rate. Utilizing this specification form, $b_{j,t}$ converges to b_j for all $\alpha \geq 0$. When $b_j = b$ for all *j*, the condition for convergence in the model can be given as

$$\operatorname*{plim}_{k\to\infty} b_{j,t+k} = b \text{ if and only if } b_j = b \text{, and } \alpha \geq 0, \tag{A6}$$

$$\operatorname*{plim}_{k\to\infty} b_{j,t+k} \neq b \text{ if and only if } b_j \neq b \text{, or } \alpha < 0. \tag{A7}$$

(A7) indicates divergence when $b_j \neq b$. However, if $\alpha \geq 0$ at the same time, there is a possibility of local convergence to b. We test the joint hypothesis of interest rate convergence

$H_0 : b_{j,t} \to b$ for all *j*,

$H_1 : b_{j,t} \nrightarrow b$ for some *j* (no interest rate convergence in at least one country).

The common factor μ_t could be removed by dividing the cross-section mean of income:

$$h_{j,t} = \frac{y_{j,t}}{N^{-1}\sum_{j=1}^{N} y_{j,t}} = \frac{b_{j,t}}{N^{-1}\sum_{j=1}^{N} b_{j,t}}, \tag{A8}$$

where $h_{j,t}$ is the relative transition coefficient and converges to unity under the null of convergence. Then, the cross-sectional variance $H_t = N^{-1}\sum_{j=1}^{N}(h_{j,t}-1)^2$ decreases over time. Following Phillips and Sul (2007), the log *t* regression model (or the σ-convergence test) is given as:

$$\log\frac{H_1}{H_t} - 2\log(\log t) = \beta_0 + \beta_1 \log t + u_t \quad \text{with} \quad t = T_0, \ldots, T. \tag{A9}$$

The long-run convergence of interest rate is rejected if β_1 is significantly negative. Phillips and Sul (2007) suggested the data processing with $T_0 = [cT]$ for some $c > 0$ and $c \in [0.2, 0.3]$ for the size and power of the test. We have $\widehat{\beta_1} = 2\hat{\alpha}$, where $\hat{\alpha}$ is the estimate of α under H_0.