

Article

Realized Volatility Spillover Connectedness among the Leading European Currencies after the End of the Sovereign-Debt Crisis: A QVAR Approach

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Abstract: This paper examines the time-varying spillover effects and connectedness between the euro and other EU and non-EU currencies after the end of the sovereign-debt crisis. We employ the Quantile Vector Autoregression connectedness approach using intraday data for seven currencies (the euro, the British pound, the Swiss franc, the Polish zloty, the Hungarian forint, the Czech koruna, and the Norwegian krone) spanning from 1 January 2016 to 30 November 2022. The results indicate that, almost in all quantiles, the currencies of Eastern European Group countries (i.e., Czech Republic, Hungary, and Poland) are net contributors of information spillovers to other currencies, while currencies of non-EU countries (Switzerland, UK, and Norway) are net takers. Further, we find that the euro is the highest transmitter of net information spillovers to all other currencies until 2021. Interestingly, after 2021, the euro changes to net information spillover taker from all other currencies; highlighting that external shocks (e.g., COVID-19, the energy crisis) have significant risk spillover effects on the European currency market. Policymakers and market participants could benefit from knowing which currency drives developments to avoid unexpected consequences.

Keywords: forex markets; QVAR; economic integration; European economies; realized volatility; spillovers connectedness

JEL Classification: C58; F15; F31; G15



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1. Introduction

The euro's volatility, distinguished by variations in its value against other global currencies, has wide-ranging implications beyond the frontiers of the Euro Area. This effect plays an instrumental role on the nominal exchange volatility of other non-euro European countries. The interconnectedness of European economies through financial and foreign direct investments, trade, and capital flows indicates that fluctuations in the euro could create undulating impacts throughout Europe (Nikkinen et al. 2006). Factors such as central bank monetary policies and interventions, trade relationships, and financial markets dynamics entwine, intensifying the effects of euro volatility on adjacent European currencies (Arabitel et al. 2008; Pastorek 2023). The euro significantly affects the realized volatility of other European currencies due to the aforementioned economic and financial factors. In particular, many European countries have already established long-term and extensive trade and economic relationships with the Eurozone, indicating fluctuations in the euro could influence their balance of trade, export competitiveness, and import costs, thereby exerting influence on their economic stability and causing volatility on their currency (European Central Bank 2015). Furthermore, the euro's role in international financial markets elicits investors to rebalance portfolios that relied on its fluctuations,

leading to capital flows that affect non-euro currency prices and also volatility ([Albertazzi et al. 2021](#)). Plenty of non-euro European economies often adjust and harmonize their monetary policies in response to the European Central Bank's decision-making to preserve financial stability, synchronize their economic cycles, and hold their competitiveness. This one could effectuate volatility in their currencies as markets respond to changing interest rate differentials and to the prospects of an economy in the future ([Bank of International Settlements 2019](#)). Therefore, these parameters, linked with the interconnected nature of European economies and financial markets, highlight the euro's significant effect on the realized volatility of other European currencies. Acknowledging these labyrinthine and puzzling interrelationships will be highly interesting for individuals, policymakers, investors, official bodies, and businesses operating in the European continent, as they explore the complexities of a continuously integrated and yet diverse economic area.

The theoretical background of this research is based on the Corden's theory ([Corden 1972](#)) regarding the economic integration of an area. According to [Corden \(1972\)](#), there are two fundamental components on the economic integration. The first part is what is known as an exchange rate union, or monetary integration, which is a region in which exchange rates have a stable connection to one another notwithstanding possible fluctuations in reference to nonunion currencies. The second element is convertibility, which is the complete elimination of all exchange restrictions within the region for both current and capital transactions. A customs union cannot function effectively without the ability to convert for transactions that are directly related to commerce. The main component of what may be referred to as capital market integration (financial integration) is convertibility for capital transactions, including interest and dividend payments. By "capital market integration," we imply the creation of a single capital market with no constraints of any type on intraregional capital flows. Therefore, economic integration may be viewed as essentially being composed of a capital market integration in addition to an exchange rate union.

During the first years of the Eurozone, EU officials mainly focused monetary integration on the creation of the European Central Bank and the control of monetary policy. The stabilization of inflation across the euro area (EA), through the monetary policy channel, the Stability and Growth Pact (monitoring member states' fiscal policy), and the EU economic governance bodies (European Council and Eurogroup) were considered adequate tools for the proper functioning of the monetary union. Therefore, we could say that the first component of the monetary integration was met in the EA. According to the convertibility criterion, the EU managed to lift any capital movement barriers among the member states. Capital transaction costs were eliminated for EU countries that use the euro as their currency, but capital market integration in the union is far from complete. If markets are fully linked, assets with the same risk characteristics will trade at the same price regardless of whatever market they are transacted on. Investors must deal with both common and country-specific or idiosyncratic risk in fully integrated capital markets, but prices only reflect common risk components since country-specific risk is fully diversifiable across all markets. Investors must account for and price both common and unique risks when markets are only partly integrated. Investors only deal with and price sources of risk that are peculiar to a certain nation if markets are totally divided. Since the sources of risk and their pricing may vary between markets, the identical projects in two nations may have different projected returns facing the relevant risk of each country. Therefore, we observe that the second component of the monetary union was only partially achieved, in spite of the establishment of the banking union, the European Stability Mechanism, the European Banking Union, and the upcoming Capital Markets Union. Moreover, a recent report of the [European Central Bank \(2022\)](#) concedes that, although the degree of financial integration in the EA is increasing, the capital markets integration has not yet reached a satisfactory level.

Exchange rates are highly connected with both monetary and financial integration ([Cacciatore et al. 2016](#)). The interest rates and the money supply are monitored by the central banks. The monetary policy affects the depreciation/appreciation of the currency, which influence the discounted cash flows and the real returns of current and potential

investments. Through the monetary integration channel, the exchange rates of two currencies should remain stable if a similar monetary policy is adopted (Fornaro 2022). Therefore, the exchange rate risk will be minimized, and this fact facilitates trade and financial transactions between two countries. Additionally, through the financial integration channel, the elimination of restrictions pertaining to cross-border financial operations allows (a) financial institutions to operate freely, (b) businesses to directly raise funds or borrow money, and (c) equity and bond investors to invest across the state line with fewer or limited restrictions (Kaltenbrunner 2015; Fornaro 2022). The presence of a steady exchange rate boosts the transactions among neighboring countries, where investors face similar exposure to risk and receive approximately the same real returns.

Taking these political and economic aspects into consideration, a research lacuna is observed that concerns the evolution of the economic integration of EU non-euro economies and other European countries that do not participate in the EU, after the end of the 2010 sovereign debt crisis in the Euro Area¹. The research aim of this paper is to explore the role and the economic influence of the euro's volatility on the volatility of non-euro European currencies² during the COVID-19 and ongoing inflation era. In particular, this paper set the stage for exploring how and why euro volatility influences the realized volatility of other European currencies, highlighting the intricate web of economic and financial interdependencies within Europe. Therefore, this research under study attempts to answer the following questions: Does the euro play a highly influential and leading role on the European currencies? Is the euro a net volatility contributor³/receiver to the volatility of non-euro European currencies?

In order to address these questions, we relied on the Quantile Vector Autoregression Model (QVAR) connectedness developed by Ando et al. (2022), utilizing realized volatility and directional volatility spillover connectedness between the nominal exchange rates of the non-euro European countries and the EA. Particularly, the spillover connectedness measures how the euro's realized volatility shocks other currencies realized volatility, or vice versa. This concept is crucial in understanding the interconnectedness among the exchange rates under study, where a disturbance in one currency could propagate to others, potentially causing widespread instability.

Furthermore, QVAR connectedness has many advantages, such as the following: (i) It is well-suited to handle extreme events, outliers, and heavy-tailed distributions. Hence, it focuses on the tails of the distribution where most of the systemic risk lies. (ii) It is a flexible model since it can be implemented on a wide range of asset classes and markets, encompassing equities, bonds, commodities, and currencies. It is also flexible enough to capture different categories of dependencies, inter alia linear, nonlinear, or time-varying. (iii) It is easy to interpret and communicate, even to non-experts. It gives a clear view of how different assets or markets are interconnected and how they contribute to systemic risk. (iv) It can capture dynamic changes in systemic risk over time, which is particularly relevant in fast-moving markets, financial crises, or external shocks such as the COVID19 pandemic. All in all, quantile connectedness is a powerful model for measuring and monitoring systemic risk, which is critical for financial regulators, investors, and policymakers (Chatziantoniou et al. 2021; Ando et al. 2022). To the best of our knowledge, no other research has explored this subject under study utilizing high-frequency data for the currencies of these European economies in order to explore the degree of net volatility transmissions between the euro and other European currencies after the end of the sovereign debt crisis in the Eurozone. Only Huynh et al. (2023) and Hung (2021) attempted to test spillovers and connectedness in international and Eastern European foreign exchange markets. However, their study was based on the generalized VAR or a multivariate EGARCH model using daily frequency data.

Our empirical findings reveal that in almost all quantiles the currencies of Central and Eastern European countries (CEE) (i.e., Czech Republic, Hungary, and Poland) are net contributors of information spillovers to other currencies, while currencies of non-EU countries (Switzerland, UK, and Norway) are net takers, which supports the view that

non-EU countries are the followers and not the leaders of EU policy developments. Further, it is observed that the euro is a net information spillover contributor to all other currencies until 2021, while after 2021 the euro changes to net information spillover taker from all other currencies. This is quite interesting since it illustrates that external shocks (e.g., COVID-19, the energy crisis) have significant risk spillover effects on the European currency market.

Finally, our results may produce significant implications for market participants and policymakers. In particular, investors can benefit from knowing which currency drives developments to build their own strategies for maximizing their wealth. Policymakers can use this information to avoid unexpected consequences of exogenous shocks, such as COVID-19.

The remainder of the paper is organized as follows. Section 2 briefly outlines the Literature review. Section 3 includes the dataset analysis, Section 4 describes the methodology, and Section 5 presents empirical evidence/discussion. Lastly, Section 6 concludes the paper and mentions implications for policymakers and market participants.

2. Literature Review

Since the creation of the European monetary union, academia has mainly been concerned with the sustainability of the union and the degree of its monetary integration (Vlaar 2004; Feldstein 2005; Kruse 2011; Hajek and Horvath 2016). During the last decade, plenty of different voices were heard regarding the level of monetary and financial integration not only among the euro member-states, but also between the Eurozone and other European countries (Dabrowski et al. 2014; El-Shagi and Tochkov 2022; Stoupos and Kiohos 2022).

Existing literature is based on various methods used to examine the dynamic connectivity and the volatility effects among the nominal exchange rates in Europe. Nikkinen et al. (2006) applied a VAR model to ascertain the dynamics of implied volatilities across currencies. Their results indicate that potential exchange rate volatilities among major European currencies are closely linked. Other researchers attempt to explore the degree of exchange rate integration in the European currencies by applying dynamic co-integrated models. Their results provide evidence that the major European currencies are not integrated in the long run (Gil-Alana and Carcel 2020; Stoupos and Kiohos 2017). Gadea and Gracia (2009) mainly focused on the level of monetary integration in the (EA) using real exchange rates. Their results reveal a high level of integration among the EA core member-states.

Other researchers focused on the examination of long-term volatility parameters (clustering, asymmetry, persistence) and directional volatility spillovers among the European currencies. For instance, Tamakoshi and Hamori (2014) found asymmetric responses in correlations among the euro, the sterling, and the Swiss franc applying a time-varying asymmetric DCC-GARCH. Their paper indicated higher dependency during periods of joint appreciation than during periods of joint depreciation. Dimitriou and Kenourgios (2013) demonstrated that a decrease of exchange rate correlations exists during periods of turmoil, suggesting different vulnerability of the major European currencies based on the results of the M-FIAPARCH(1,d,1)-DCC model. Malik (2005), implementing the FI-GARCH model, discovered that the euro is more volatile to the sterling. Similar findings were reached by Zumaquero and Rivero (2011) and Beer and Fink (2019). Das and Roy (2022), who explored the exchange rate return co-movements and volatility spillover and connectedness between BRICS and developed countries, relied on a DCC-MGARCH and a standard VAR model. Their results show the presence of significant return co-movements and volatility spillovers between the foreign exchange markets across different countries. Recently, Albrecht and Kocenda (2024) provided an assessment of volatility connectedness between the currencies of Central European countries from 2009 to 2022 using VAR connectedness. Their findings unveiled asymmetries in connectedness that are dominated by negative volatility, especially during periods of economic distress.

The originality of the present study is that it attempts to examine the volatility spillover connectivity between the euro and other EU and non-EU currencies (major or minor), in order to explore the role of the European currency in volatility terms. Additionally, it uses the realized volatility with intraday data to shed new light on the volatility transmission

effects among the European currencies. Only [Warsaw \(2020\)](#) examined the realized asymmetric volatility spillovers in the European financial markets but focused on the volatility spillovers connectivity between the equity and the foreign exchange markets. He presented no empirical evidence for the volatility spillovers connectedness among the foreign exchange markets in the European continent.

3. Dataset

This research uses the nominal exchange rates of three EU non-euro CEE member-states⁴ and three non-EU countries⁵ against the US dollar and the nominal exchange rate of the euro against the US dollar. The exchange rates of each currency were expressed in US dollar terms, since the US dollar is the largest tradable currency across the globe and the US is the largest trade partner for the majority of European economies. The dataset intraday frequency is equal to 60 min from 00:00 GMT 01 January 2016 to 23:00 GMT 30 November 2022 (more recent data). The high frequency data promotes the investigation of the actual trading conditions among each currency. The specific dataset beginning point was chosen because, particularly following the signing of the third Memorandum of Understanding with Greece (mid-July 2015), economic and political stability gradually returned to the EU and the Eurozone ([Baldwin and Giavazzi 2015](#)). Additionally, this timespan includes the period of BREXIT negotiations, the COVID-19 pandemic, and the ongoing energy crisis. Therefore, the QVAR model will separately unveil the volatility spillover and connectedness among the aforementioned European currencies in each period (each quantile). The dataset of nominal exchange rates has been extracted from the Bloomberg Database[®] (Table 1).

Table 1. Data Presentation (Source: Bloomberg).

Variables	Acronym	Measure	Symbol	Frequency
Euro	EUR	USD/EUR	€/ \$	Intraday 60 min
Sterling	GBP	USD/GBP	£/ \$	Intraday 60 min
Swiss Franc	CHF	USD/CHF	F/ \$	Intraday 60 min
Polish Zloty	PLN	USD/PLN	zł/ \$	Intraday 60 min
Hungarian Forint	HUF	USD/HUF	Ft/ \$	Intraday 60 min
Czech Koruna	CZK	USD/CZK	Kč/ \$	Intraday 60 min
Norwegian Krone	NOK	USD/NOK	Kr/ \$	Intraday 60 min

Important milestones for the construction of the intraday time series are the following:

- Non-trading hours: We excluded any trading from the dataset that took place from Friday 21:00:01 GMT until Sunday 20:59:59 GMT.
- Holidays: We did not include any bank holidays in our dataset as the trading activity is extremely low. In particular, we erased the following bank holidays: Christmas, Boxing Day, New Years' Eve, Catholic Good Friday, Catholic Easter Monday, International Workers' Day, and Thanksgiving Day.
- Common sample: In order to have a common sample across each time series, the trading days were selected when the currencies are traded.
- Time zone: The Greenwich Mean Time (GMT) is used as the time zone in order to construct and weigh the dataset.
- Calendar sampling: the calendar sampling is chosen as it is the most used in the global literature and, hence, facilitates the comparability of the results.

4. Methodology

4.1. Realized Volatility

We assume the observed dependent variable (nominal exchange rates) log-price at trading day t and j intraday point as $\log(P_{tj})$. For $j = 1, \dots, \tau$ represents equidistant intervals at each trading 60 min-intervals. We follow [Andersen and Bollerselv's \(1998\)](#) process of

calculating the daily realized volatility (DRV), which is estimated as the sum of squared intraday returns:

$$DRV_t^{(\tau)} = \sqrt{\sum_{j=1}^{\tau} (\log P_{tj} - \log P_{tj-1})^2} \quad (1)$$

The realized volatility assembles in probability to the integrated volatility, $IV_t \equiv \int \sigma^2(t)dt$, as the number of subintervals tend to infinity, $\tau \rightarrow \infty$. Notwithstanding, the microstructure frictions add more noise to the estimated volatility, when the sampling frequency converges to zero. Hence, a trade-off emerges between the bias that is embedded in the realized volatility measure and its precision.

4.2. Quantile Vector Autoregression (QVAR)

Regarding the methodological procedure, the study employs the quantile connectedness tool developed by Ando et al. (2022). Firstly, a QVAR model can be derived from the function below:

$$k_t = e_t(\theta) + s_1(\theta)k_{t-1} + s_2(\theta)k_{t-2} + \dots + s_j(\theta)k_{t-j} + \omega_t(\theta) \quad (2)$$

$$v_t = o_t(z) + m_1(z)v_{t-1} + m_2(z)v_{t-2} + \dots + m_q(z)v_{t-q} + \omega_t(z) \quad (3)$$

where k_t shows a vector of endogenous covariates, θ indicates a quantile vector with values from zero to one, whilst j denotes the lag length of the QVAR fashion. Additionally, $s_j(\theta)$ is a QVAR coefficient matrix and lastly, e_t shows a mean vector.

By and large, the estimation of TDC (total directional connectedness) TO remainders, receiving a shock of a variable a TO all remainder variables e , is expressed as:

$$TO_a(P) = \sum_{a=1, a \neq e}^M \tilde{f}_{ea}(P) \quad (4)$$

where $\tilde{f}_{ea}(P)$ is the effect of a th covariates on the variance of the forecast error of the b th covariates at time P . Moreover, the TDC, FROM remainders, with a shock of a variable a FROM all remainder covariates e , is expressed as:

$$FROM_a(P) = \sum_{a=1, a \neq e}^M \tilde{f}_{ea}(P) \quad (5)$$

where $\tilde{f}_{ea}(P)$ shows the effect of the e th covariates on the variance of the forecast error of the a th covariates at time P . In addition, if we deduct expression five from expression four, the net TDC can be calculated as follows:

$$NET_a(P) = TO_a(P) - FROM_a(P) \quad (6)$$

In the aforementioned expression, if the value is higher than one, we can name the variable a net contributor. If the value of Equation (4) is lower than zero, we can name the variable a net receiver. Additionally, the TCI (total connectedness index) shows the strength of network association, and it can be computed by using the expression (7):

$$TCI(P) = K^{-1} \sum_{e=1}^K TO_e(P) = K^{-1} \sum_{e=1}^K FROM_e(P) \quad (7)$$

5. Empirical Findings

The findings are presented as follows: First, we present the descriptive statistics for our sample, then we exhibit our main results by performing a spillover connectedness for three quantiles (5th, 50th, and 95th), and lastly, we analyze results of dynamic connectedness.

Figure 1 illustrates the realized volatility series, whilst some initial outcomes are displayed in Table 2. Regarding Table 2, all variables are significantly non-normally distributed, display leptokurtic distribution, are significantly autocorrelated, and do not have unit root and divulge ARCH/GARCH errors. Furthermore, the non-parametric Kendall rank correlation is implemented and shows that all covariates are positively correlated. Concerning Figure 1, all realized volatility series display a few high points and lows over the sample period.

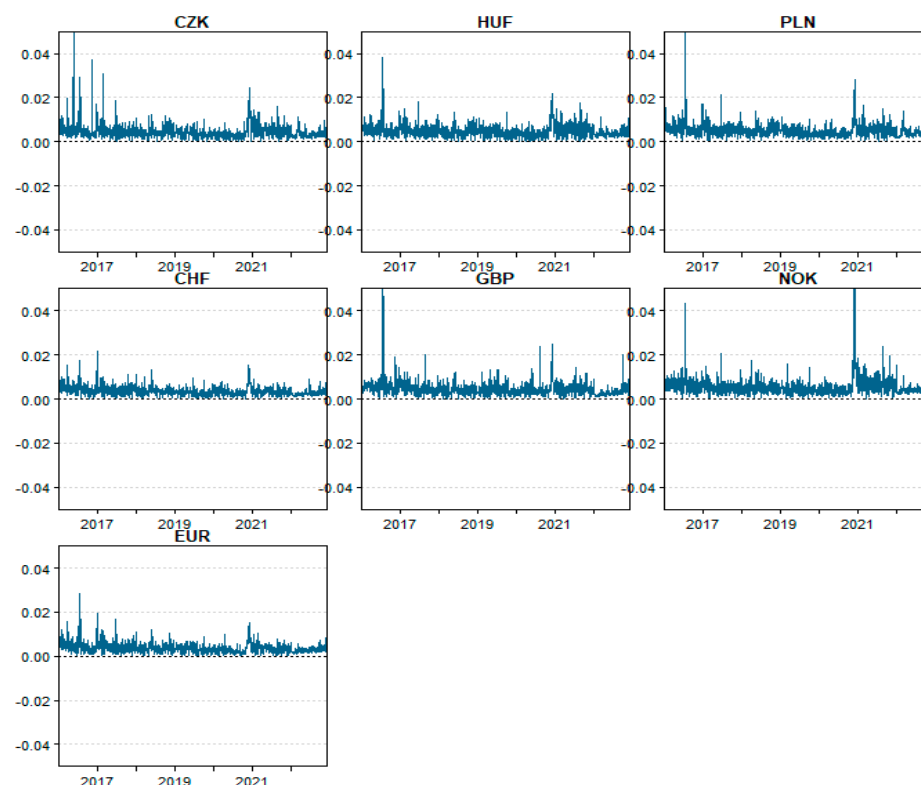


Figure 1. Realized volatility of variables.

Table 2. Descriptive Statistics and pre-tests.

	CZK	HUF	PLN	CHF	GBP	NOK	EUR
Mean	0.005	0.005	0.005	0.004	0.005	0.006	0.004
Skewness	5.466 ***	2.505 ***	4.242 ***	2.028 ***	8.343 ***	5.555 ***	2.752 ***
Kurtosis	57.529 ***	19.167 ***	49.935 ***	10.585 ***	160.099 ***	56.640 ***	19.871 ***
JB	21,462.717 ***	25,347.184 ***	65,689.663 ***	8298.505 ***	73,365.037 ***	15,162.675 ***	27,456.578 ***
ERS	−7.493 ***	−5.927 ***	−4.496 ***	−2.582 ***	−11.181 ***	−5.871 ***	−3.279 ***
Q(20)	711.443 ***	1104.203 ***	1145.597 ***	1015.812 ***	706.180 ***	2587.355 ***	915.660 ***
Q ² (20)	108.902 ***	570.757 ***	222.371 ***	629.048 ***	39.513 ***	1669.998 ***	268.683 ***
Non-parametric Kendall rank correlation							
	CZK	HUF	PLN	CHF	GBP	NOK	EUR
CZK	1.000						
HUF	0.578 ***	1.000					
PLN	0.599 ***	0.589 ***	1.000				
CHF	0.450 ***	0.430 ***	0.482 ***	1.000			
GBP	0.386 ***	0.383 ***	0.413 ***	0.404 ***	1.000		
NOK	0.520 ***	0.481 ***	0.530 ***	0.434 ***	0.419 ***	1.000	
EUR	0.632 ***	0.570 ***	0.629 ***	0.611 ***	0.450 ***	0.530 ***	1.000

Notes: The significance of 1% is displayed by the symbols ***. For skewness we used D'Agostino (1970) test, for kurtosis we used Anscombe and Glynn (1983) test, for normality we used Jarque and Bera (1980) test, and for stationarity we used Stock et al. (1996) test, while Q(20) and Q²(20) are Fisher and Gallagher (2012) weighted portmanteau test.

To begin with, we focus on connectedness analysis results. These are reported in Tables 3–5, where the findings are divided into extreme lower (5th), intermediate (50th), and extreme upper (95th) quantiles for the joint distributions. The main results that we observe are the following: (i) At first sight, the information spillovers from (to) others seem very high at three distinct quantiles. In the extreme lower (5th) quantile, the contributions from others vary between 79.34% and 82.83%, while the contributions to others vary between 73.41% and 88.73%. In the intermediate quantile (50th quantile), the contributions from others vary between 63.00% and 77.69%, while the contributions to others vary between 46.54% and 90.27%. In the extreme-upper quantile (95th quantile), the contributions from others range between 82.51% and 85.22%, while the contributions to others range between 76.94% and 91.76%. (ii) At the extreme lower and the extreme upper quantiles, contributions from (to) others are higher than at the intermediate quantile. (iii) The EUR is the highest transmitter of information spillovers to others at both the extreme lower and intermediate quantiles, giving 88.73% (over the 5th quantile) and 90.27% (over the 50th quantile), followed by PLN, with 85.98% and 81.23% in the 5th and 50th quantiles, respectively. (iv) The EUR and the PLN received the highest information spillovers from others at the extreme lower and intermediate quantiles. The EUR received 82.83% and 77.69% at 5th and 50th quantiles, respectively, while the PLN received 82.33% and 75.87% (at the 5th and 50th quantiles, respectively). This illustrates the presence of bidirectional information spillovers between EUR and other currencies as well as PLN and other currencies. It is worth mentioning that this phenomenon is also present in other currencies such as HUF and NOK. (v) At the extreme lower and intermediate quantiles, the smallest contributor to spillovers to other currencies is the GBP, with a value of 73.41% in the 5th quantile and 46.54% in the 50th quantile. (vi) At the extreme upper quantile, all currencies receive higher information spillovers, and most of them (more specifically, five out of seven) contribute to higher information spillovers. This may be explained by the fact that the COVID-19 pandemic constituted an exogenous shock that dramatically intensified the shock transmission (for more, see [Guhathakurta et al. 2020](#); [Khalfaoui et al. 2022](#)).

Table 3. Spillover connectedness at the 5th quantile.

	CZK	HUF	PLN	CHF	GBP	NOK	EUR	FROM
CZK	20.66	13.92	14.13	12.51	11.53	12.82	14.43	79.34
HUF	13.06	18.00	14.84	13.39	12.25	13.65	14.81	82.00
PLN	13.13	14.64	17.67	13.17	12.19	14.12	15.07	82.33
CHF	12.16	13.84	13.85	18.60	12.44	13.51	15.61	81.40
GBP	12.05	13.43	13.77	13.12	19.83	13.70	14.09	80.17
NOK	12.36	13.87	14.61	13.32	12.67	18.46	14.71	81.54
EUR	13.08	14.33	14.77	14.46	12.32	13.88	17.17	82.83
TO	75.83	84.03	85.98	79.97	73.41	81.67	88.73	569.62
NET	−3.51	2.04	3.64	−1.43	−6.76	0.13	5.89	TCI = 81.37

Table 4. Spillover connectedness at the 50th quantile.

	CZK	HUF	PLN	CHF	GBP	NOK	EUR	FROM
CZK	33.90	12.95	13.28	8.35	6.58	10.46	14.49	66.10
HUF	12.60	28.01	15.23	9.41	7.61	11.93	15.21	71.99
PLN	13.00	15.56	24.13	9.82	7.96	13.29	16.25	75.87
CHF	10.26	12.34	11.95	28.97	7.79	10.83	17.86	71.03
GBP	9.19	10.18	11.06	9.14	37.00	11.61	11.84	63.00
NOK	10.96	12.56	14.41	10.03	8.66	28.77	14.61	71.23
EUR	13.44	14.96	15.29	13.48	7.95	12.59	22.31	77.69
TO	69.44	78.53	81.23	60.22	46.54	70.70	90.27	496.93
NET	3.34	6.53	5.35	−10.81	−16.46	−0.53	12.58	TCI = 70.99

Table 5. Spillover connectedness at the 95th quantile.

	CZK	HUF	PLN	CHF	GBP	NOK	EUR	FROM
CZK	17.49	13.90	14.20	13.30	13.06	12.67	15.38	82.51
HUF	14.98	16.03	14.36	13.29	12.97	12.91	15.46	83.97
PLN	15.42	14.47	15.65	13.26	12.87	13.09	15.23	84.35
CHF	14.99	14.36	13.92	15.39	13.09	12.59	15.66	84.61
GBP	14.75	13.44	13.65	13.13	17.47	12.89	14.67	82.53
NOK	14.57	14.16	14.09	13.63	13.43	14.78	15.35	85.22
EUR	15.43	14.32	14.38	13.65	12.96	12.80	16.48	83.52
TO	90.14	84.65	84.59	80.26	78.38	76.94	91.76	586.72
NET	7.63	0.68	0.25	−4.35	−4.16	−8.28	8.23	TCI = 83.82

Despite the fact that all currencies are contributors and recipients of information spillovers, it is important to illustrate the currencies that receive or transfer more information, as depicted in the “NET” rows of Tables 3–5. In particular, the highest net contributor in all quantiles is EUR, with values of 5.89%, 12.58%, and 8.23% at the extreme lower, intermediate, and extreme-upper quantiles, respectively. Similarly, the GBP is the highest net taker in the extreme lower and intermediate quantiles, with values of −6.76% and −16.46%, respectively. Interestingly, in almost all quantiles, the currencies of Eastern European Group countries (i.e., Czech Republic, Hungary, and Poland) are net contributors of information spillovers to other currencies, while currencies of non-EU countries (Switzerland, UK, and Norway) are net takers of information spillovers from other currencies. This may occur indirectly since the central banks of these countries follow the monetary policy of the ECB. Additionally, the Czech Republic, Hungary, and Poland maintain large amounts of money in bank accounts expressed in euros and the majority of the EU intercommunal transactions are conducted in euros (Grabowski and Grabowska 2021). Therefore, it may be reasonable that they are net contributors of information spillovers to other currencies (those of UK, Norway, and Switzerland), since the euro plays an important role in their economies.

The results of the dynamic net pairwise directional connectedness between currencies are presented in Figures 2–4. As can be seen, in the 5th and 50th quantiles, most of the currencies depict a net receiver behavior, except for the CZK-EUR, PLN-EUR, and NOK-EUR pairs, which reflect a net contributor action at the 50th quantile after 2021.

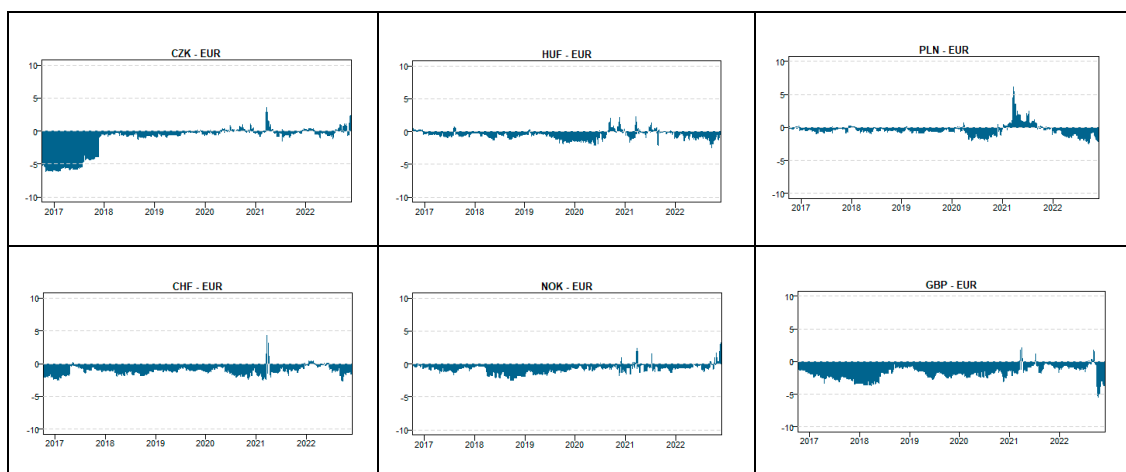


Figure 2. Dynamic net pairwise directional connectedness at the 5th quantile. Notes: Outcomes adapted from a 200-days rolling-window QVAR framework with lag length of order 1 (BIC) and a 20-step-ahead forecast.

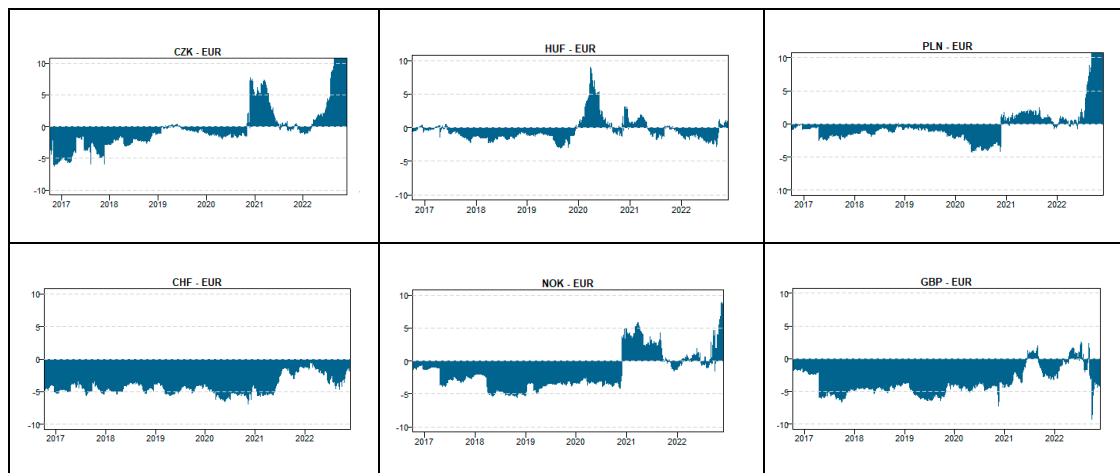


Figure 3. Dynamic net pairwise directional connectedness at the 50th quantile. Notes: Outcomes adapted from a 200-days rolling-window QVAR framework with lag length of order 1 (BIC) and a 20-step-ahead forecast.

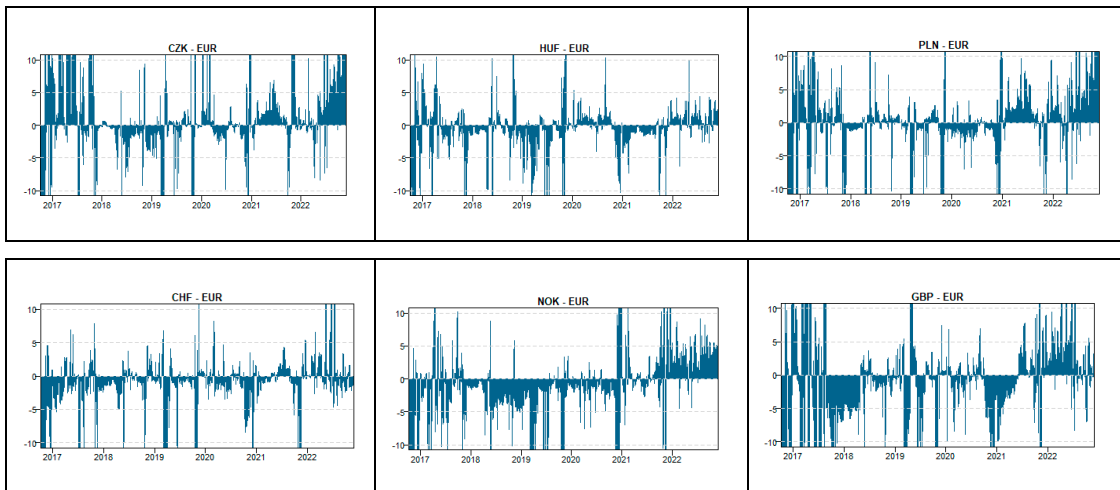


Figure 4. Dynamic net pairwise directional connectedness at the 95th quantile. Notes: Outcomes adapted from a 200-days rolling-window QVAR framework with lag length of order 1 (BIC) and a 20-step-ahead forecast.

To provide a comprehensive and thorough visualization of the total dynamic spillover connectedness among all currencies, we used a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast⁶. The results are displayed in Figure 5 as a heatmap visualization. The vertical axis of the figure represents the quantiles (i.e., $q = 0.05, 0.06, \dots, 0.94, 0.95$), while the color bar at the right side shows the degree of total spillover connectedness. The warmer the shade, the greater the degree of connectedness.

On that basis, in the illustration of dynamic total connectedness until 2021, the spillover connectedness is very low, between 40% and 60% quantiles. However, after 2021, it changes significantly, being high at all quantiles exceeding 75%. This suggests that COVID-19 constitutes significant exogenous factor that changes the pattern of spillover effect over currencies.

To shed light on this phenomenon, we consider the net total directional connectedness of each currency in the system. For this reason, we explore the sensitivity of the net directional spillover of currencies across the time-quantile space. The results are presented in Figures 6–12. In each figure, any currency with warm shade may be considered as net spillover contributing, and any currency with cold shade may be considered as net spillover taking. First, as can be observed from Figures 6–8, the CZK, HUF, and PLN are net information spillover contributors to all other currencies. This confirms our previous

analysis and indicates that the net spillover effect structure may be affected by the fact that these economies are highly bound to the EA, and also the euro plays an instrumental role in these countries. However, it is worth mentioning that until 2018 CZK was a net information spillover taker from all other currencies. This change is possibly related to the modification of the monetary policy of the Czech Central Bank. Especially, Czech Central Bank started gradually increasing the interest rate of the CZK in 2018.

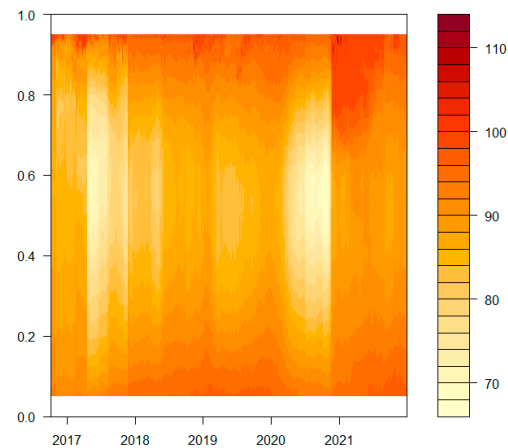


Figure 5. 1-year dynamic total connectedness. Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

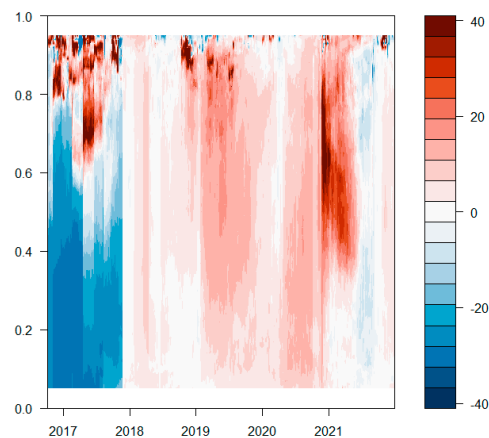


Figure 6. 1-year net TDC (CZK). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

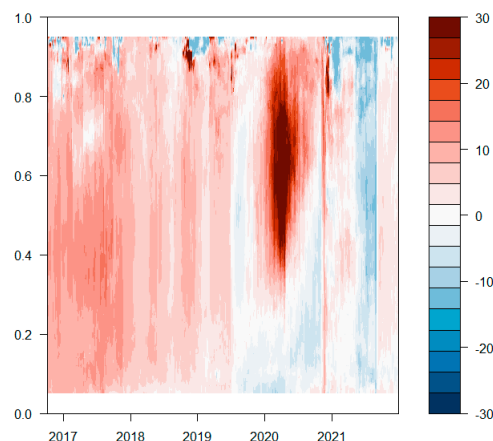


Figure 7. 1-year net TDC (HUF). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

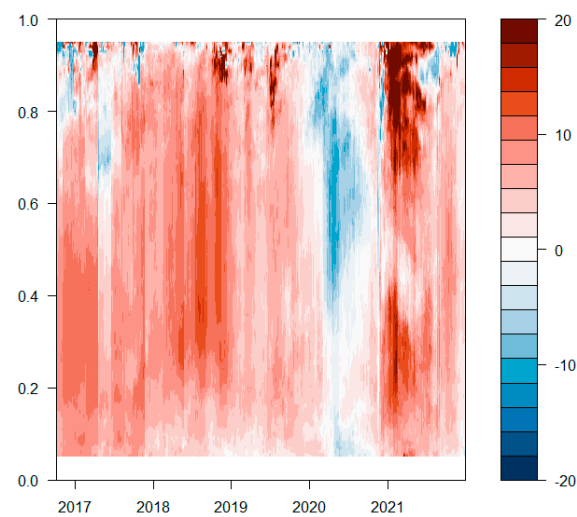


Figure 8. 1-year net TDC (PLN). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

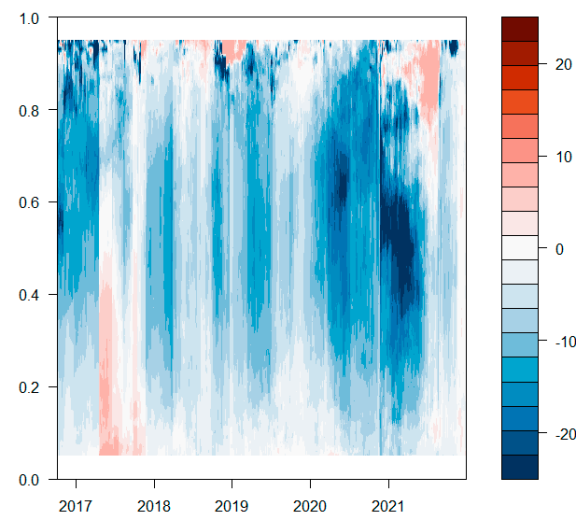


Figure 9. 1-year net TDC (CHF). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

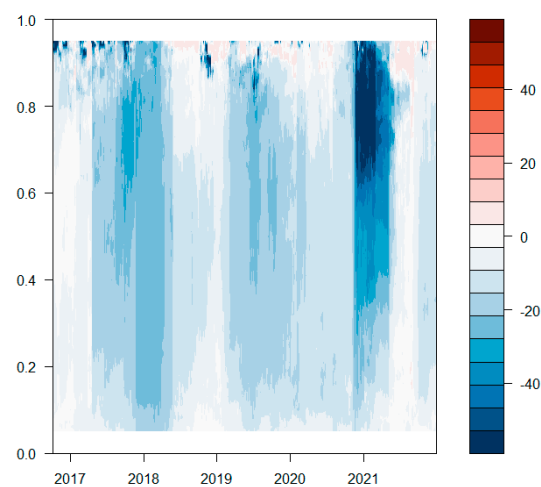


Figure 10. 1-year net TDC (GBP). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

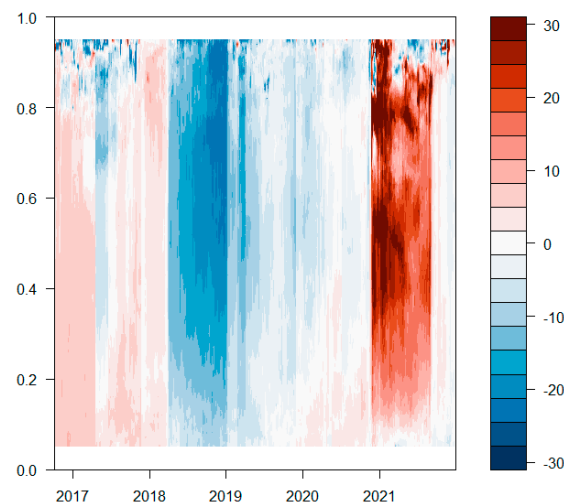


Figure 11. 1-year net TDC (NOK). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

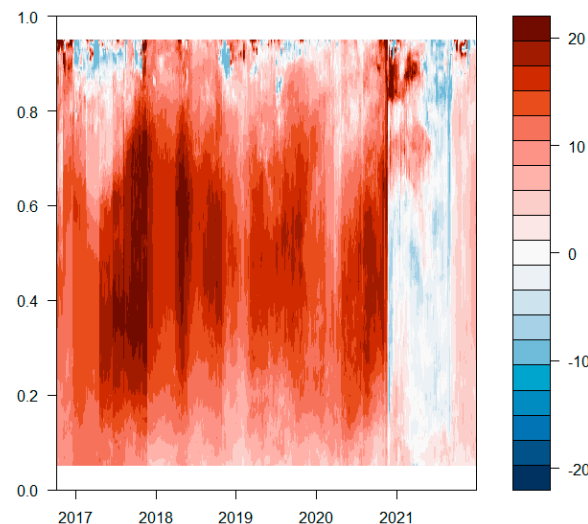


Figure 12. 1-year net TDC (EUR). Notes: Outcomes adapted from a 200-day rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

Second, as illustrated in Figures 9–11, the CHF, GBP, and NOK are net information spillover takers from all other currencies. This is also in line with our previous analysis and supports the theoretical argumentation that non-EU countries are the followers and not the leaders of EU policy developments. This is also related to the fact that the euro is the leading currency in Europe in trading terms (BIS 2022). During the sample period, the BREXIT negotiations were in force and the depreciation of the sterling was considerable. Moreover, it is important to indicate that the trading volume of the CHF and the NOK represents 5.2% and 1.7%, respectively, of the total daily transactions across the globe (BIS 2022). What should be noted is that the NOK is a net information spillover contributor to all other currencies after 2021. This may be explained due to the fact that the Norwegian Central Bank increased steadily but dynamically the interest rate of the NOK from 0% to 2.75% in 2022.

Third, the EUR is a net information spillover contributor to all other currencies until 2021. This is reasonable since the EU is the leader of currency policy development. Interestingly, after 2021 we observe that EUR changes to net information spillover taker from all other currencies, especially for the quantiles between 20% and 65%. This kind of change could happen due to various reasons such as monetary policy divergence, geopolitical

events, and alterations on investment flows. For instance, since this research uses the nominal exchange rate of USD/EUR, if the Federal Reserve's policies become more influential globally (e.g., due to FED's immediate response against rising inflation), the euro may react more strongly to US monetary policy (Chen et al. 2016). Also, global geopolitical developments, such as trade tensions (e.g., sanctions on Russia) or wars (Russian-Ukrainian War) could change the dynamics of currency movements, making the euro more reactive to external events (Bekaert et al. 2013). Additionally, macroeconomic instability and negative expectations for the European economy could affect directly the euro's fluctuations in the forex markets. For instance, the rising cost inflation, the increase of the government bond yields (due to rise of the ECB interest rates) in the Eurozone, and the aggressive response of ECB monetary policy in order to confront the increasing prices will lead the economy of the EA into a recession (Sabes and Sahuc 2023). The forex markets have already considered these parameters depreciating the value of the euro on average by 7% against the US dollar during 2022. Hence, the euro may experience higher volatility as it becomes more sensitive to external factors, necessitating robust risk management practices for investors and enterprises (Forbes and Rigobon 2002).

6. Conclusions

Understanding the role and the economic influence of the euro on the nominal exchange rates of non-euro European economies could contribute to economic integration. For this reason, we explore the time-varying spillover effects and connectedness between the euro and other EU and non-EU currencies after the end of the sovereign debt crisis. Accordingly, we employ the Quantile Vector Autoregression approach using intraday data for seven currencies (the euro, the British pound, the Swiss franc, the Polish zloty, the Hungarian forint, the Czech koruna, and the Norwegian krone) after the end of the European sovereign debt crisis.

First, the empirical results of almost all quantiles show that the currencies of the Central and Eastern EU Group countries (i.e., Czech Republic, Hungary, and Poland) are net contributors of information spillovers to other currencies, while currencies of non-EU countries (Switzerland, UK, and Norway) are net takers. This supports the theoretical argumentation that non-EU countries are the followers and not the leaders of EU policy developments.

Second, we find that the euro is a net information spillover contributor to all other currencies until 2021. Indeed, this is reasonable since the EU is the leader of currency policy development. However, after 2021, the euro changes to a net information spillover taker from all other currencies. This is quite interesting, since it illustrates that external (e.g., COVID-19, energy crisis) and internal shocks (contractionary monetary policy) have significant risk spillover effects on the European currency market.

It is worth mentioning that Sifat et al. (2022) find limited influence of US monetary policy on BRICS interbank markets, highlighting the importance of the US's overall financial health. In line with these contrasting effects of monetary channels, our findings emphasize the significant impact of external shocks on the euro. Research on emerging economies suggests a limited direct influence of developed economies' monetary policy on internal markets (Lubys and Panda 2021). These contrasting findings create an opportunity for comparative studies investigating the factors driving differences in volatility spillover patterns between developed and emerging economies or between regions with varying degrees of monetary policy independence.

The findings of the study have important implications for policymakers and market participants. The former could use our results to support regulatory policies to avoid unexpected consequences of exogenous shocks, such as COVID-19. The latter could benefit from knowing the currency that drives developments to build their own strategies for maximizing their wealth.

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Conflicts of Interest: The authors declare no conflict of interest.

Notes

- ¹ The EA debt crisis terminated in July 2015 after the 3rd rescue package to Greece (Baldwin and Giavazzi 2015).
- ² Sterling, Swiss franc, Norwegian krone, Czech koruna, Polish zloty, and Hungarian forint.
- ³ “Volatility contributor” refers to if the euro’s realized volatility primarily affects the realized volatility, or the degree of variation in the nominal exchange rate of other currencies under study. Volatility “receiver” refers to if the realized volatility of other currencies under study primarily influence the realized volatility or the degree of variation of the euro.
- ⁴ Czech Republic, Hungary, and Poland.
- ⁵ UK, Switzerland, and Norway.
- ⁶ We applied a 150-day rolling-window QVAR framework for robustness, and the findings are almost identical. They are available upon request.

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