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Unconventional Monetary Policy and Bond Market Connectedness in the New Normal*

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Abstract: Since the global financial crisis, major central banks gradually switched to unconventional monetary policies (UMPs) as part of their efforts to directly influence the long-term interest rates. This study analyzes the impact of conventional/unconventional monetary policies on sovereign bond return spillovers across countries and maturities since February 2007. Following the Taper Tantrum of mid-2013 and the ECB's policy convergence to other major central banks in 2015, the long-term return connectedness acrosss countries increased, overtaking the short-term connectedness and lowering the dispersion of connectedness measures across maturities. Over the same period, net connectedness from short- to long-term maturities weakens, while net connectedness from medium- to long-term maturities stays strong. Finally, panel regression results show that UMPs in the form of higher central bank asset ratios led to higher pairwise long-term return connectedness even when the control variables such as trade and portfolio investment flows and the distance between pairs of countries are included in regression analysis.

JEL classification: F34, G15, C32, G23.
Keywords: Unconventional monetary policy, quantitative easing, yield curve, vector autoregression, variance decomposition, elastic net.

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1 Introduction

The practice of monetary policymaking has changed drastically in the last decade. In the conventional monetary policy setting, central banks set the short-term interest rates according to a reaction function to achieve their policy objectives. The rest have simply been left to the transmission mechanism. The yield curve lies at the center of the transmission mechanism as the monetary policy changes do not affect only the short-end of the curve but also moves the whole term structure. A policy-induced change in short-term interest rates is expected to change the longer-term interest rates, which in turn affects financial markets as well as the investment and consumption decisions, and hence the real side of the economy.

The traditional transmission mechanism has weakened since the global financial crisis. The long-term interest rates responded much less to the monetary policy once the policy interest rates hit the zero lower bound (ZLB). In response, major central banks have begun to experiment with unconventional monetary policies (UMPs) to influence longer-term yields through the purchases of long-term government bonds. Those policies sometimes intended to flatten or invert the yield curve and sometimes went beyond and aimed to take full control of the bond yields (e.g., yield curve controls). So far, the UMPs have had substantial financial and real economic effects worldwide (see Gagnon et al. (2016)).

The extensive use of UMP measures (such as quantitative easing (QE), Large Scale Asset Purchases (LSAPs), and yield curve control (YCC)) led to an unforeseen expansion of the central bank balance sheets and created a liquidity glut. While the Federal Reserve (Fed) and the Bank of England (BoE) started the implementation of UMP measures immediately after the outbreak of the global financial crisis, the Bank of Japan (BoJ) and the ECB went ahead with their UMPs in 2011 and late-2014, respectively. As a consequence, the four major central banks' (Fed, ECB, BoJ, and BoE) combined assets had increased from \$3.5 trillion in January 2007 to \$15.3 trillion in February 2020 and reached \$24 trillion in January 2021, almost one year after the Covid-19 outbreak.[1]

In the age of unconventional monetary policies, there has been increased interest in the study of sovereign bond market spillovers. Perhaps because of data availability, many studies (e.g., Claeys and Vasicek (2014), Antonakakis and Vergos (2013), Conefrey and Cronin (2015), Fernández-Rodríguez et al. (2015), Karkowska and Urjasz (2021) and others) evaluated the sovereign bond yield spillovers at a single maturity, especially using the long-term bonds. They would then generalize the within-maturity analysis results to the entire term structure by addressing them as "bond market" spillovers or connectedness.

The tendency towards the use of long-term bonds may be seen as plausible since the longer-term bonds reflect valuable information on agents' short- and long-term expectations about the future behavior of the financial and macroeconomic variables. However, today it is common knowledge that bond yields at different maturities do not necessarily respond to economic, monetary, and financial shocks similarly (see Rudebusch and Wu (2008), Haldane and Read

[1] The total assets of Fed, ECB, BOJ, and BOE are respectively 7.4, 8.6, 6.8, and 1.1 trillion USD as of January 2021. Source: Thompson Reuters Datastream.

(1999)). The most common example is the central banks aiming at altering the shape of the yield curve. In particular, major central banks have been implementing UMPs since the global financial crisis lowering the long-term bond yields to flatten the yield curves while the short-term rates are stuck near ZLB. Therefore, non-parallel shifts in yield curves may generate asymmetry in short- and long-term bond market spillovers, and the generalization of long-term return connectedness to shorter-term bonds may not be valid in many circumstances.

This study analyzes the return spillovers in international bond markets, taking into account the potential asymmetry in the impact of UMPs on sovereign bond market spillovers over the full maturity spectrum. Having observed the possible implications of political, economic, and financial shocks and monetary policy actions on bond yields at different maturities, we undertake an analysis of the bond market connectedness for 12 different maturities across ten developed and developing countries from February 2007 through September 2020. Doing so, we relax the "parallel shift" assumption and allow for international sovereign bond return connectedness to differ across maturities. To be more specific, we separately estimate the within-maturity connectedness measures for bonds with maturities ranging from 3-months to 10-years. This analysis helps us track the behavior of sovereign bond return connectedness at particular maturities since 2007, assessing the impact of political, economic, and financial shocks along with monetary policy interventions.

Analysis results indicate that unconventional monetary policies have had a substantial impact on bond return connectedness. Thanks to the synchronized (but not necessarily coordinated) implementation of the unconventional monetary policies by major central banks, the connectedness of long-term bond returns across countries outpaced the connectedness of shorter-term bonds. In a similar vein, the dispersion of within-maturity return connectedness across 12 different maturities decreased permanently, as the ECB's policy stance converged towards that of the Fed in 2015. We also find evidence that the Fed's Operation Twist program had a significant impact on within-maturity return connectedness, lowering the connectedness of long-term returns while increasing the connectedness of short-term returns. The monetary policy response to the Covid-19 pandemic shock, which took the form of expanded liquidity lines to banks and the real sector, led to a surge in short-term connectedness.

We also focus on the connectedness across maturities using yield curve factors and obtain two valuable insights about the monetary policy effectiveness. First, in the pre-UMP era, the short- and medium-term bonds generate connectedness to the long-end of the yield curve, a finding consistent with the proper functioning of the monetary policy transmission mechanism. Second, once all major central banks started implementing UMPs, net connectedness from short- to long-term bonds declined and moved into negative territory, revealing the increased importance of long-term bonds as the return shock originators.

Finally, we use panel regressions to analyze the impact of monetary policy interventions on pairwise bond return connectedness along with other factors, such as distance, trade flows, and portfolio investment flows between pairs of countries. The secondary regression results support the results we obtained from the analysis of total directional connectedness measures.

In particular, they show that unconventional monetary policy measures led to higher pairwise long-term bond return connectedness over time.

Section 2 reviews the related literature. Section 3 discusses the impact of unconventional monetary policies on the bond market spillovers. Section 4 provides the details of the methodology, including data and estimation. Section 5 analyzes the results for joint, within-maturity, within-yield curve connectedness, and across-maturity connectedness in a time-series perspective. Section 7 focuses on the secondary regression analysis of bond market connectedness determinants. Section 8 concludes the paper.

2 Literature

Our paper cuts across several strands of the bond market literature. First, it is directly related to the international bond market literature. Codogno et al. (2003), Bernoth et al. (2004) and Lemmen and Goodhart (1999) analyze the yields and yield spreads in the international bond markets, Nowak et al. (2011) and Hilscher and Nosbusch (2010) search for the relationship between macroeconomic fundamentals and idiosyncratic characteristics of bond markets using international sovereign bond market data. In other respects, Attinasi et al. (2009), Schuknecht et al. (2009), Beber et al. (2009), and Ammer and Cai (2011) analyze the country-specific risks, defaults, credit default spreads, and other aggregate risk factors that affect the bond pricing, yield spreads, and trading activities in bond markets. Following the global financial crisis and European debt crisis, academic interest has shifted towards the contagion and spillovers in financial markets, including the bond markets. Studies such as De Bruyckere et al. (2013), Alter and Schuler (2012), Calice et al. (2011), Gomez-Puig and Sosvilla-Rivero (2014), Arghyrou and Kontonikas (2012) study the shock transmissions in international bond markets using contagion and spillover models.

There is also a growing literature on *empirical networks* that have focused explicitly on sovereign bond market spillovers using publicly available bond market data. Using structural vector autoregressions, De Santis and Zimic (2018) analyze the bond market connectedness among the US and European sovereign yields. They show that connectedness among sovereign bond yields declined in the 2008-2012 period due to financial fragmentation. Applying the factor-augmented Diebold-Yilmaz connectedness framework, Claeys and Vasicek (2014) explore European sovereign bond market spillovers. They find that peripheral countries were more vulnerable than the core during the European debt crisis. Fernández-Rodríguez et al. (2015) investigate the volatility spillovers in eleven Eurozone countries using the Diebold-Yilmaz framework over the 1999-2014 period and show that systemic shocks can explain more than half of the change in volatilities. Antonakakis and Vergos (2013) show that shocks from peripheral Europe had a higher destabilizing impact in financial markets during the Eurozone crisis. The "peripheral to peripheral" connectedness tended to be larger than the "core to core" connectedness. Buse and Schienle (2019) explore the default risk connectedness of Eurozone sovereign bonds using credit default swap and bond market data. They discover that financial aid to troubled countries and ECB's unconventional policy tools helped decrease the connectedness following the Eurozone crisis.

The literature on bond market spillovers generally utilizes different proxies such as long-term bond yields, yield spreads, term premiums, CDS premiums, and returns or volatilities of these measures to examine the various aspects of bond market connectedness. However, little attention is paid to identifying the link between connectedness and maturity characteristics of different financial assets. Nyholm (2016) conducts connectedness analysis for US and EU bond market spillovers using short- and long-term yields. Results show that while policy interest rate spillovers across the Atlantic increased only slightly, total bond return connectedness risen significantly in the aftermath of the global financial crisis. Xu et al. (2016) analyze the connectedness of the dynamic Nelson-Siegel factors estimated from the CDS series for systematically important banks. Empirical results suggest that the level (long-term) factor connectedness tends to be higher than the connectedness of the slope and curvature factors. In a very recent paper, Umar et al. (2021) analyzes the connectedness of yield curve components of Eurozone bonds. Their findings reveal that the dynamic within-yield curve factor connectedness of all components has dropped significantly during the Eurozone crisis and increasing afterward.

This study exploits a large dataset on sovereign bond yields with a maturity spectrum from short to long-term bonds. The data set allows us to produce standard measures of bond market connectedness for different maturities; moreover, it enables us to examine the across maturity bond connectedness. Analyzing the connectedness across maturities and countries is especially important in the "new normal" when monetary policy aims to control the yield curve with large scale asset purchases or forward guidance rather than adjusting short-term policy rates. The implementation of UMPs led to a plethora of papers evaluating the effectiveness of these policies on macroeconomic and financial aggregates in general. There is also a whole literature studying the effects of UMPs on bond markets that most of these studies provide evidence on the impact of UMPs on different proxies of bond markets. A popular approach has been the *event study analysis*, which focuses on the market indicators immediately before and after the announcement or kick-off of the policy UMP implementation to uncover evidence about the direction of change. D'Amico and King (2013) argue that the Federal Reserve's large-scale purchases of U.S. Treasury securities were a natural experiment. Using security-level price and quantity data, they show the local supply effect in the yield curve. Bauer and Neely (2014) study the international spillovers of FED's UMP action after the global financial crisis. Trebesch and Zettelmeyer (2018) focus on the impact of ECB interventions on the Greek debt market and find a significant twist in the Greek yield curve. De Santis (2020) uses the Bloomberg discussions to construct a "news" index to identify the impact of ECB's asset purchase program (APP). Their findings indicate that APP has a substantially larger impact on the euro-area yields than discussed in the literature. Neely (2015b) uses a portfolio balance model to identify the effect of large-scale asset purchases on the global bond yields and exchange rates and found announcements of LSAPs achieved a reduction in international long-term bond yield. Gagnon et al. (2016) argues that the earlier studies focused on the effect of the first round QE announcement on bond yields. It further argues that the estimated effects of QE announcements diminished as the Federal Reserve moved to the second and third rounds of QE policy in 2010 and 2012. Similar results are obtained for QEs of the ECB and the Bank of Japan; the announcement effect died out in the subsequent QEs.

3 UMPs & Bond Market Spillovers

In a financially integrated world, unconventional monetary policy actions have further implications and repercussions for the international bond markets than the conventional ones. MacCauley (2017) similarly argues that even when the unconventional and conventional policies have similar effects on market interest rates, unconventional policies were more likely to enhance the strategic interactions among countries. For instance, as the Large-Scale Asset Purchase Programs (LSAPs) reduce bond yields in the home country, they encourage debt issuance by foreign corporations in the home currency, which helps push the yields in other countries down. He shows that non-US non-financial firms issued more dollar-denominated debt than US non-financials following the Fed's LSAPs. Taylor (2013) emphasizes the spillover amplification mechanism, which goes into effect when a central bank deviates from the rule-based monetary policy. He argues that this mechanism can create even larger deviations from policy rules when other central banks respond. The discretionary deviations from such policies create pressure on other central banks to respond.

In particular, Coeure (2017) analyzes the market response to the UMPs that UMP shocks create substantial spillovers through different channels. A vast number of studies on the bond market spillovers systematically identify the effects/channels potentially responsible for the shock transmission to other sovereign bond market indicators and proxies. Fratzscher et al. (2013) argue that *signalling*, *confidence*, and *liquidity* channels may also be relevant for analyzing the international repercussions of LSAPs. Neely (2015a) promote the idea that UMP actions may reinforce comovement in the global markets based on the *portfolio rebalancing channel*. Krishnamurthy and Vissing-Jorgensen (2011) argue that QEs can also have a substantial impact through additional channels such as the *inflation* channel and the *long-term safety* channel. Gagnon and Collins (2019) emphasize the primary effect of QEs as "market-calming". Bernhard and Ebner (2016) defines *economic outlook*, *confidence* channels and *monetary policy reaction* channel.

The variety of channels captures many common and specific aspects of the bond market spillovers generated by UMP actions. Nevertheless, there is no clear evidence that those channels are mutually exclusive or complementary, so that a UMP action by a central bank may activate multiple channels simultaneously or successively. There is also no widespread agreement in the literature on the "signs" and magnitudes of the impact of UMPs on bond market spillovers. Thus, there are no readily available precise measures of the aggregate spillover effect in response to an UMP action. The effects may complement one another, or they may cancel out each other in the short run. It is also possible that the combination of these channels may yield the UMP action to be more or less effective in the long run. Therefore, analyzing the aggregate spillover effects in the international bond markets requires additional tools to measure the overall connectedness.

To capture the aggregate bond market spillover effects, we carefully analyze the time-series behavior of the sovereign bond market connectedness measure for a set of countries, taking into account the wide-ranging maturity spectrum of sovereign bonds. The connectedness may be seen as a "global" latent variable that summarizes the directional spillovers across a set of financial assets. In our case, those assets are the sovereign bonds of countries. The identification of the spillover effects generated by UMP actions is not straightforward under the connectedness methodology. Nevertheless, the connectedness methodology helps us keep track of the changes in bond market spillovers in response to global and country-specific shocks and obtain the medium and long-term trends in the bond market spillovers.

4 Methodology

Given the difficulties in obtaining propriety data on the network linkages among financial institutions and investors, it is considerably hard to measure and analyze financial networks. Recent studies have shown that it is possible to uncover the statistical information on the underlying financial networks using only the publicly available market data. Granger-Causality networks of Bilio et al. (2010), long-run partial correlation networks of Barigozzi and Brownlees (2017) are related studies. To estimate the connectedness of sovereign bond yields, we utilize the Diebold-Yilmaz connectedness index (DYCI) framework. DYCI is based on the decomposition of the forecast error variance obtained from an N-dimensional vector autoregression (VAR). It was introduced in Diebold and Yilmaz (2009) and developed further in Diebold and Yilmaz (2012), and Diebold and Yilmaz (2014).[2]

There are certain advantages to using the DYCI framework. It allows one to measure the future expected variation in i-th variable accounted for by a standard deviation shock to j-th variable, based on variance decompositions and using publicly available market data. Thanks to variance decompositions, the estimated network structure is complete, links are weighted and directed. Derived for all pairs of variables in the multivariate system, bilateral linkages with different weights make it possible to assess variables' comparative importance for others in the network. Furthermore, the linkages are not bilaterally equal; it captures the asymmetry in connectedness among financial assets. Fourth, it allows using high-frequency market data when it is essential to observe the immediate market responses to shocks hitting the financial system. Furthermore, as Arsov et al. (2013) pointed out, DYCI is highly adaptive to data changes, and its predictive power is one of the highest among other indicators.

4.1 Data and Estimation

The impairments stemming from shocks can be quickly amplified through the cascading effects. Hence, it becomes crucial to address direct and indirect links across assets. One can achieve this by introducing a large number of financial assets in the connectedness analysis; therefore, the

[2] The technical details of the DYCI framework and further discussions provided in Appendix A.

analysis of the sovereign bond connectedness requires sizeable bond market data. The number of sovereign bond yield curves is critically important to achieving appealing empirical results. It allows for a more considerable variation in information about the international bond market developments. On the other hand, the connectedness analysis of sovereign bonds with different maturities depends not only on the number of countries covered but also on the maturity coverage. In this study, we exploit bond yield data from the Thomson Reuters (TR) financial database which maximize both country and maturity coverage.

The differences in coupon structures are observably significant among developed and developing countries; that problem also requires particular attention. Instead of using *dirty* yields of traded bonds, we choose to utilize zero-coupon yields to avoid bias in estimation results due to distinctive coupon structures among sovereign bonds. On the other hand, using zero-coupon yields to estimate the yield curve allows us to complete the missing data systematically. It provides further opportunities to increase the number of countries in the analysis. As pointed out by Andreasen et al. (2017), using synthetic yields can remove relevant pricing information and even create pricing errors. However, considering the trade-off between the data coverage (the number of countries and maturities) and detailed pricing information, we put more weight on the data coverage.

The zero-coupon yield data are available in the Thomson-Reuters financial database for many countries with a wide range of maturities. In the analysis, we use a balanced panel of 9 countries, plus the Eurozone yield curve data[3], which includes 3-month to 10-years maturity bonds.[4] Instead of employing country yield curves from the Euro area, we prefer to use the Eurozone yield curve. Being subject to a single monetary authority constitutes a gravitational force that pushes the pairwise directional sovereign bond market connectedness among the Eurozone countries much higher relative to others in the sample. Other alternatives, such as selecting a small subset of Euro area countries or using only large Euro area countries' yield curve data at the cost of ignoring valuable information from other Eurozone bond markets, do not materially contribute to the connectedness analysis. Considering that each of these choices is arbitrary and does not add much to the connectedness analysis results, we decided to conduct our analysis using the "aggregate" yield curve data for the Euro area.

The valuation of debt securities requires discounting the expected future cash flows and the bond's value at the maturity date. To apply the connectedness analysis on bond returns, we convert the synthetic bond yields to bond prices using the well-known equation that relates the price ($P_{i,t}$) and the yield ($r_{i,t}$) as $P_{i,t} = \frac{100}{(1+r_{i,t})^N}$. Then, we convert the zero-coupon bond prices to dollars to eliminate the impact of exchange rate fluctuations and calculate the daily logarithmic returns for sovereign bonds. In the empirical analysis, we include zero-coupon bonds with a maturity spectrum from 3-months to 10 years.[5] Due to data availability, we kept

[3]We obtain the Eurozone yield curve data from the ECB Statistical Data Warehouse.

[4] The ten countries included in the analysis are Australia (AUS), Denmark (DNK), Eurozone (EUR), Japan (JPN), Norway (NOR), Russia (RUS), Switzerland (CHE), Thailand (THA), United Kingdom (GBR), United States (USA).

[5] The balanced panel data for 3- and 6-month bonds are not available throughout the full sample period. Therefore, we do not include these maturities in the connectedness analysis until July 2011.

shorter-term bonds (i.e., 1-month) or longer-term bonds out of connectedness analysis. The sample period includes October 2006 through September 2020, which covers the global financial crisis, European sovereign debt, and banking crisis, and the era of quantitative easing policies.

5 Measures of Sovereign Bond Market Connectedness

Our sample (February 2007 – September 2020) covers one of the most eventful periods in finance history. Extensive monetary policy interventions following financial crises in the U.S. and Europe had effectively altered the dynamics of global financial markets. The Covid-19 shock of March 2020, which has proven to be a game-changer for the global economy as a whole, also profoundly affected bond markets.

Many studies in the literature focused on different aspects of the two crises and the post-crisis monetary policy implementation. This section provides four measures of connectedness and analyze how the monetary policy interventions and external shocks affected bond market return connectedness across countries and maturities over time.

5.1 Within- and Across-Maturity Connectedness

Figure 1 reports the dynamic system-wide bond return connectedness across countries and maturities. The sub-periods during which each of the four major central banks (Fed, ECB, BoE, BoJ) implemented unconventional (QE) policies are highlighted by green (Fed), blue (ECB), yellow (BoJ), and red (BoE) colored shades in Figure 1. Figure 1 also highlights political, economic, and market-related developments that had a significant impact on global sovereign bond markets.

The connectedness index (black line) is estimated using a dataset that includes sovereign bonds from ten countries with ten different maturities (1-to-10 year). Even though the estimation employs an elastic net sparse estimation method, 100 variables in the system leads to a relatively high (95.3) system-wide connectedness index for the first sub-sample rolling window. As the index's initial value is already high and the maximum possible value it can reach is 100, over a period longer than 13 years, the index fluctuates in a narrow corridor between 93.8 and 97.2. We also include the 3- and 6-month treasury bill returns in the connectedness analysis (red line) when return data for shorter-maturity bonds are available starting in July 2011.[6] As expected, the index with the daily returns for 3- and 6-month treasury bills lies above the index without them; still, the two system-wide connectedness indices move in tandem over the 2012-2020 period.

From 2007 to 2020, the system-wide connectedness index goes through at least five significant upswings, each of which pointing out a major financial market episode: Global financial crisis of 2008-2009; Eurozone crisis and signing of the Eurozone fiscal compact in March 2012; the taper tantrum period of the second half of 2013; the Brexit decision of June 2016 followed by

[6] A balanced dataset for 3- and 6-month returns were available beginning in July 2011. However, the VAR model estimation consumes the initial (size of window size + lag structure) observations, and we provide connectedness results, including 3- and 6-month treasury bills by late February 2012.

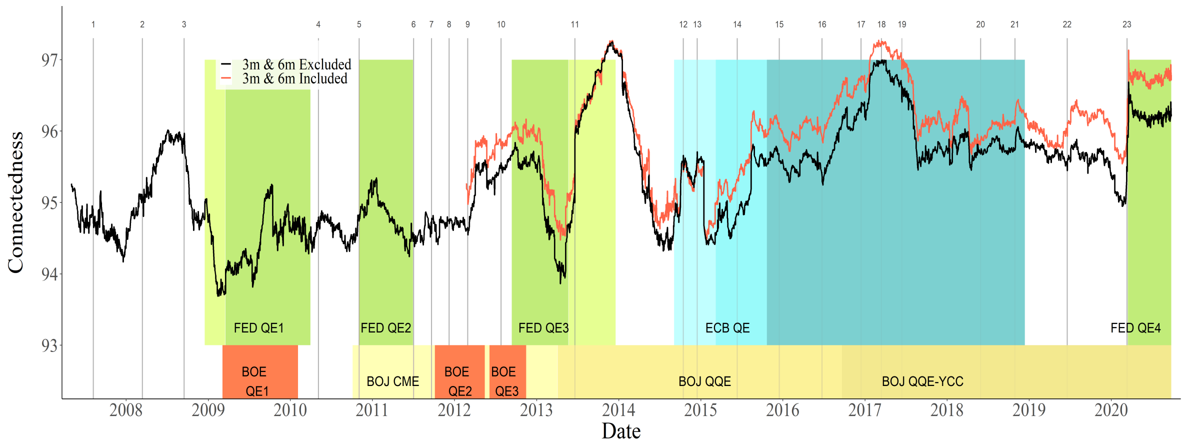

Figure 1: System-wide Connectedness – Across Countries and Maturities

Timetable of important events: **1.** BNP freezes $2.2 Billion assets in investment funds (08/08/07) **2.** JP Morgan acquires troubled investment bank Bear Stearns (03/16/08) **3.** Bankruptcy of Lehman Brothers (09/15/08) **4.** U.S. stock market flash crash and first Greek austerity plan (05/06/10) **5.** Fed QE2 announced (11/03/10) **6.** Second Greek austerity bill approved by Parliament, violent protests followed (06/29/11). Fed QE2 terminated(06/30/11). EU bailout plan decision postponed. Borrowing costs for Italy and Spain jumped. (07/03/11). **7.** Fed launches $400 bn. Operation Twist program (09/21/11) **8.** ECB's LTRO I (12/08/11) **9.** ECB's LTRO II (02/29/12) and Eurozone fiscal compact agreement (03/02/12) **10.** Draghi's "Whatever It Takes" pledge (07/26/12), followed by the announcement of OMT (08/02/12) **11.** Bernanke announces Fed's "tapering" decision (06/20/13). **12.** Bond market flash crash (10/15/14) **13.** U.S. and EU sanctions on Russian-occupied Crimea (12/19/14) **14.** Renminbi crisis (06/12/15) **15.** ECB stimulus less than the market expectation & Fed hikes policy rate seven years after GFC. (12/16/15) **16.** Brexit: UK votes to leave EU. (06/23/16) **17-18-19.** Fed's three rate hikes (12/14/16; 03/15/17; 06/14/17) **20.** Italy fear spreads in international markets (05/29/18) **21.** Market correction after ugly October (10/30/18) **22.** Fed opens door to potential rate cut (06/19/19) **23.** Covid-19 and the March meltdown in the US Treasury market (03/11/20) Shadings indicate the episodes of QEs which are already in plot area. Lighter and darker shadings addresses the details about the implementations of QE policies. FED QE1 - Lighter Shading: Announcement of QE and start buying program for mortgage-backed securities and agency debts. FED QE1 - Darker Shading: Fed starts to buy treasury securities. Fed QE3 - Darker Shading: Announcement and implementation of Fed QE3. Fed QE3 - Lighter Shading: Taper Tantrum. ECB QE - Light Shading: Announcement of QE. ECB QE - Medium Shading: Announcing the roadmap of QE program. ECB QE - Dark Shading: ECB initiates the bond purchases. BOJ - CME: Comprehensive Monetary Easing. BOJ - QQE: Quantitative and Qualitative Monetary Easing. BOJ QQE-YCC: QQE and Yield-Curve Controls.

the Fed's rate hike decisions in late 2016 and the first half of 2017; and finally, the Covid-19 shock of March 2020.

In relatively calm periods, the system-wide connectedness index follows a smoother path around an average of 94.5% that lasts from 2007 to 2015. The index increases to around 95.5% once the ECB joins the Fed and other major central banks with its QE program, and stayed around that level throughout 2018 and 2019 before jumping by two percentage points once the Covid-19 shock hit the U.S. and European countries.

5.2 Within-Maturity Connectedness

The joint system-wide connectedness indices (Figure 1), as broad measures of sovereign bond market connectedness, reveal the aggregate fluctuations in bond market spillovers through time. However, we would also expect the financial crises and the UMPs to affect the connectedness of the short-, medium- and long-term bonds differently. The DYCI framework allows us to assess the monetary policy impact on bond return connectedness within each maturity of bonds separately. To obtain the *within-maturity* connectedness measures, we collect 1- to 10-year (3-month to 10-year following February 2012) in separate datasets and apply connectedness analysis for each maturity.[7]

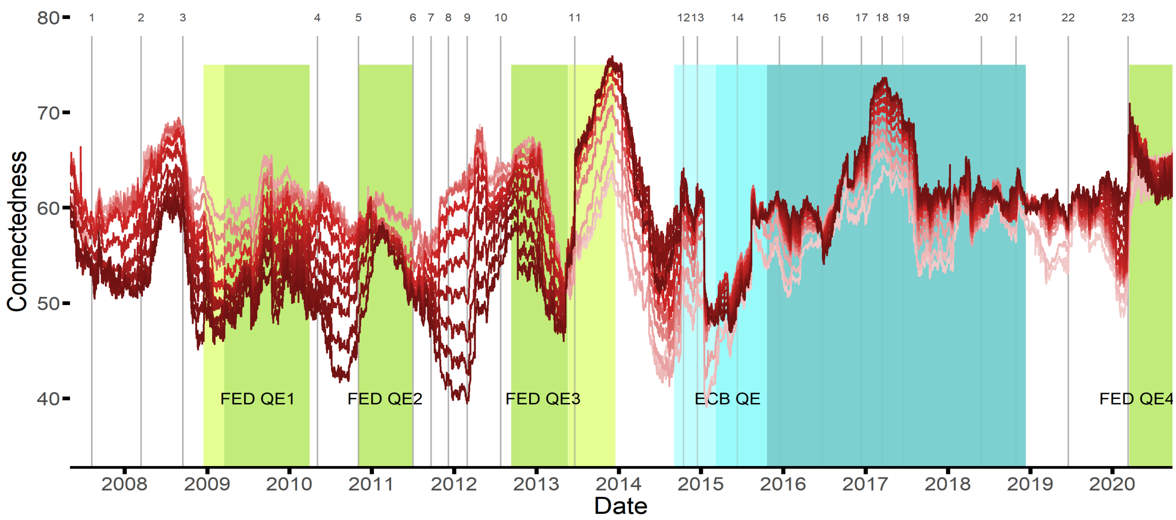

Figure 2: Within-maturity System-wide Return Connectedness Note: The timetable of important events is presented in Figure 1. Lighter colors indicate shorter maturities.

Figure 2 illustrates the within-maturity return connectedness indices. Not surprisingly, the time-series behavior of the within-connectedness measures shows a similar pattern with the joint system-wide connectedness in Figure 1. This result may seem to suggest that the within-maturity connectedness measure obtained for bond returns of a particular maturity can be used as a "bond market connectedness" measure. Yet still, the within-connectedness analysis offers much more.

Unlike the single-maturity or joint connectedness analysis, the within-maturity analysis introduces the *maturities* as a new dimension of the bond market connectedness analysis. The dispersion of the within-maturity connectedness measures provides crucial information on the bond market spillovers over different portions of the yield curve and the asymmetric impact of different shocks on the international financial system. The most striking example of dispersion is found in the Fed's Operation Twist (*OpTwist*), which aims to replace its maturing short-term bond portfolio with long-term bonds to flatten the U.S. yield curve. The impact of (*OpTwist* on the joint connectedness measure is barely visible (see Figure 1). In contrast, it increased the within-maturity connectedness dispersion of 1- and 10-year bonds from 7.2 points in September 2011 to 21.4 points in December 2011.

On a cursory look, the within-connectedness outcomes reveal two major episodes in bond market connectedness. First, the dispersion of within-connectedness measures along the maturities was much higher in the pre-tapering period but decreased significantly in the post-tapering period. Second, the within-connectedness measures are *hierarchically* ordered from short-to-long maturity bonds in the pre-tapering period. The hierarchical order of within-connectedness

[7] The maturity characteristics are self-explanatory. When we apply the connectedness analysis to 3-month maturity bonds, we can interpret the result as short-term bond connectedness with no hesitation. Similarly, when the within-connectedness of 10-year maturity bonds is measured higher than the 3-month maturity bonds, we consider that long-term bonds are more connected than short-term bonds.

measures is reversed; the long-term bonds become more connected than the shorter-term bonds.

5.3 Yield Curve Factors and Within-Maturity Connectedness

Since Nelson and Siegel (1987) and Litterman and Scheinkman (1991) there has been a consensus in the yield curve literature on describing the whole term structure of bond yields parsimoniously by several latent factors. In an overwhelming majority of contributions to the literature, both practitioners and academics rely on latent factors to summarize the information embedded in the yield curves using the level (long-term), slope (short-term), and curvature (medium-term) factors. In the next step, we utilize the principal component analysis to extract the latent factors from bond return data. In particular, we store the first three principal components of bond yields as yield curve factors and apply the within-yield curve factor connectedness analysis.[8]

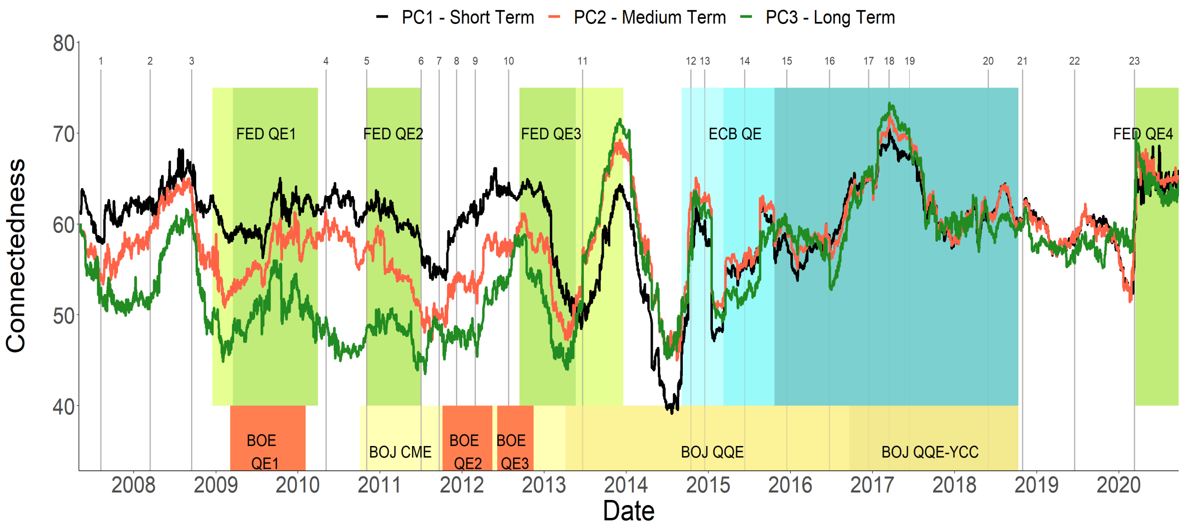

Figure 3: System-wide Principal Component Connectedness Note: See Figure 1 for the timetable of important events.

Figure A.1 shows the average variations explained by extracted factors for different maturity bond returns. First, as expected, the first principal component explains most of the variation in shortest-maturity bond returns. The second principal component, on the other hand, explains no variation in the short-term. Instead, it is expected to capture the variation as maturity grows, reaching a maximum in the middle of the curve around five years. The third principal component explains no variation in short-term bond returns and has limited explanatory power on medium-term bond returns on average; it explains variation at the long-end of the curve at most. For this reason, we identify the second principal component as the medium-term and the third component as the long-term factor.[9]

[8]The analysis relies on a standard factor model $X = F\Delta' + e$ where X and e are the $T \times N$ matrices of bond returns and error terms, F is the $T \times r$ matrix of r yield curve factors and Δ is the $N \times r$ matrix of factor loadings. To identify yield curve factors, we impose normalization restrictions on both factors and factor loadings following Bai and Ng (2013). First, we assume that $\frac{1}{T}F'F$ is an identity matrix. Second, the first square block of the factor loading matrix Δ' is assumed to be lower diagonal. The identification procedure requires the ordering of variables to be known; fortunately, we have a natural ordering of bond yields according to their maturities.

[9]We apply the principle component analysis (PCA) on exchange rate adjusted bond returns to complement

Providing a comparison between the connectedness of yield curve factors with bond return connectedness is not a straightforward task. For instance, all principal components, more or less, explain the long-term bond returns, e.g. 10-year maturity bond since $E(X_{l,t}) = \delta'_{l,s}F^s_t + \delta'_{l,m}F^m_t + \delta'_{l,l}F^l_t$. The within-connectedness of ten-year bond returns does not strongly comove with the long-term yield curve factor because the long-term bond return is a linear combination of all three principal components. Therefore, the within-yield curve factor connectedness does not provide a one-to-one correspondence to the within-maturity connectedness measures in Figure 2. It would be more appropriate to view the yield curve factor connectedness in Figure 3 as a more compact measure than the within-maturity measures in Figure 2.

Figure 3 presents the within-connectedness of yield curve factors over the full sample period as an alternative to the connectedness analysis for bonds with different maturities. First, the connectedness of all three yield curve factors fluctuates over time in response to economic and financial shocks as well as the changes in monetary policy. These fluctuations can be substantial at times, such as during the global financial crisis of 2008-09, or the taper tantrum of the second half of 2013, and the bond market flash crash of October 2014, U.S. rate hikes in 2017, and during the Covid-19 shock. A second and perhaps even more interesting conclusion relates to the behavior of the yield curve factors' connectedness before and after the Fed's tapering decision announcement and the ECB's QE program initiation.

From the beginning of the sample to the Fed's tapering decision in May-June 2013, the long-term yield curve factor connectedness always fluctuated below the short- and medium-term yield curve factor connectedness. While the gaps between the three connectedness measures were large before the tapering decision, they declined with the announcement. Once the ECB started its QE program in 2015, all three measures started moving much closer than before. This result is consistent with the within-maturity connectedness measures presented in Figure 2. In both cases, the long-term return connectedness dominated the short-term return connectedness as the two major central banks started relying more heavily on the unconventional monetary policy measures.

The behavior of the factor connectedness measures over time is also consistent with the system-wide connectedness plot in Figure 1, both in terms of short-run fluctuations and the difference between the average levels of connectedness in the two subperiods. During Operation Twist, we obtain a similar dispersion among yield curve factor connectedness. A month after the launching of Operation Twist in September 2011, the short- and medium-term factor connectedness measures jump with no change in the long-term factor connectedness. The long-term factor connectedness increased after the EU fiscal compact in March 2012 along with the medium-term factor connectedness.

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the previous analyses. Therefore, we do not use the conventional Nelson and Siegel (1987) approach to extract the yield curve factors.

5.4 Yield Curve Factors and Connectedness Across Maturities

After analyzing the within-maturity connectedness, we can also use the yield curve factors to analyze connectedness across maturities. In particular, we focus on the 'net' connectedness between the level (long-term), slope (short-term), and curvature (medium-term) factors instead of using actual bond returns for different maturities to have a parsimonious interpretation.

Under the conventional monetary policy implementation, policy interest rate changes generate connectedness of short-, medium- and long-term interest rates through the transmission mechanism. Over the 14-year-long sample period, major central banks first experimented, later fully engaged with unconventional monetary policies in the form of quantitative easing programs. Directly targeting the long-term yields, the unconventional policies are expected to generate directional return connectedness from long- to medium and short-term bonds. Figure 4 provides the time-series of net connectedness from short- to medium- and long-term and from medium- to long-term bonds.

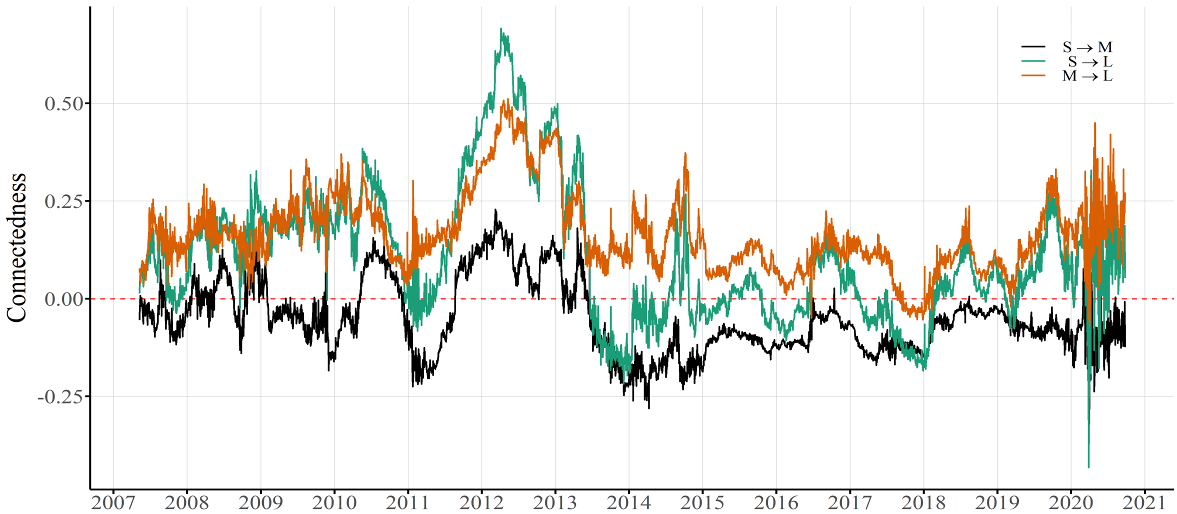

Figure 4: Net Connectedness Between Short, Medium and Long Maturity Bonds

As expected, the net connectedness from the short- to long-term ($S \rightarrow L$) bonds was relatively high from 2011 through mid-2013, reflecting the impact of the operation twist that started in the last quarter of 2011. The net connectedness from the short- to medium-term ($S \rightarrow M$) bonds was lower than $S \rightarrow L$ over this period, but it was positive until mid-2013. Furthermore, the net connectedness from the medium- to long-term ($M \rightarrow L$) bonds was also positive and close to $S \rightarrow L$ net connectedness over this period.

The three net connectedness measures show that the transmission mechanism was working quite effectively during the Operation Twist. The Fed's objective was to lower the long-term rates by changing the composition of its balance sheet in favor of the long-term bonds. Our analysis shows that the resulting changes in the short- and medium-term bond returns generated connectedness to the long-term rates.

With the Taper Tantrum that started in mid-2013, all three net connectedness measures drop close to zero. Afterward, $S \to L$ and $S \to M$ net connectedness measures fluctuated around the zero line until 2018. $M \to L$ net connectedness, on the other hand, stayed mostly above the zero line (except for 2017). All three net connectedness measures increased following the Brexit decision in June 2016. As the Fed started to increase its policy rate slowly, there was no increase in the $S \to L$ and $M \to L$ net connectedness in response to the first four 25 bp rate hikes (December 2015, December 2016, March, and June 2017), moving the policy rate to the 1.00-1.25 band. The bond market reaction started in earnest with the December 2017 rate hike, followed by four 25 bp rate hikes in 2018. Especially $M \to L$, and to some extend, $S \to L$ net connectedness increased in 2018 and 2019 and stayed positive until the Covid-19 pandemic in March 2020.

When the pandemic hit in mid-March, financial markets were adversely affected. Fed lowered its policy rate by 50bp on March 3 and then by 100 bp on March 16, hitting the zero lower bound. Other major central banks had undertaken similar rate cuts. After a drop in March, the $S \to L$ and $M \to L$ net connectedness mostly stayed in the positive territory, reflecting the central banks' liquidity provisions to stabilize the markets. However, due to unforeseen developments during the pandemic, all three net connectedness measures fluctuated substantially in 2020.

6 The New Normal of Bond Market Connectedness

In the previous section, we provided the joint, within-maturity, and within and across yield curve factor connectedness outcomes of our analysis and concisely described the major trends and changes in the behavior of sovereign bond market connectedness since 2007.

The one particular conclusion that we can draw from those four analyses is the tectonic shift in the bond market connectedness before and after 2013-2014. In the pre-2013 period, the joint connectedness indicates a lower level of system-wide connectedness relative to the post-2014 period. Meanwhile, the within-maturity connectedness presents two distinct features: i) within-connectedness dispersions are high before 2013 and but decline significantly afterward, and ii) the hierarchical order of short-to-long maturity connectedness is reversed following 2013. The within-yield curve factor connectedness analysis lends support to the conclusions from the joint and the within-maturity connectedness analyses. We argue that these pieces of empirical evidence suggest a substantial transition toward a "new normal" of bond market return connectedness. This transition, which is directly linked to the new normal in monetary policy-making, became apparent following the Fed's tapering decision and the ECB's initiation of its QE policies.

6.1 The Previous Normal

Before discussing the characteristics of the 'new normal,' we first discuss the major developments in the previous normal. Noticeably, we cannot provide long-term trends in bond market connectedness because of the data limitation. As our sample period starts a year before the global financial crisis, we are not in a position to extend the "old normal" to the pre-2007. The empirical evidence on the bond market connectedness before the global financial crisis displays a similar dispersion in short- and long-term within-maturity and within-yield curve factor connectedness. Moreover, there is no significant finding that the bond market connectedness was high during this period.

The bond market connectedness shows significant swings in turbulent times. Sovereign bond markets were highly responsive to market instability during the U.S. and global financial crisis of 2007-08. The system-wide connectedness index (Figure 1) got started at a relatively high point of 95.2% in the first half of 2007, but declined half a percentage point after the liquidity crisis of August 2007, towards the end of 2007. Yet, the index increased by 1.8 percentage points from late 2007 to July 2008. Following the collapse of Lehman Brothers in mid-September 2008, the U.S. Treasury injected more than $700 billion into the U.S. banking system, while the Fed and other central banks pulled the policy rates all the way down to the *zero lower bound* (ZLB). That prompted a rapid decline in short-term yields. As a result, the index drops down to 94.7 by the end of October 2008.

As this was not sufficient to calm the financial markets, the Federal Reserve announced the first round of its large-scale asset purchases (Fed QE1, highlighted by the yellow-green shaded area) at the end of November 2008. Thanks to the QE1 and accompanying measures, the calm was restored in the U.S. and global financial markets.[10] For instance, the VIX index dropped from 40 to 20, while S&P 500 index rose by almost 50%. Consistent with these developments, the connectedness dropped further to 93.7 by early 2009.

The first signs of the European debt crisis became visible in the second half of 2009. Reflecting the intensification of bad news emanating from several European countries (such as the U.K., Ireland, Portugal, and Greece), the index moved up by close to one and a half percentage points. In May 2010, there was a slight increase in the index due to the Greek sovereign debt crisis and the U.S. stock market flash crash. In the second half of 2010, it became apparent that Greece was not the only EU member country in trouble. News about the deterioration in the fiscal and financial balances of Ireland, Portugal, Spain, and Italy started to arrive throughout the summer of 2010. In late November 2010, the EU and IMF announced an €85 bn bailout package for Ireland. From the late summer to the end of 2010, the index went up by one percentage point.

Once it became apparent in the summer of 2010 that the U.S. federal government would not be implementing another fiscal stimulus package, the Federal Reserve started implementing its second round QE policy in the last quarter of 2010. Almost at the same time frame, the Bank of Japan initiated a QE policy of its own (called "Comprehensive Monetary Easing") policy to stimulate its weakening economy.

Unlike the other three major central banks, the ECB waited for some time to move into the unconventional monetary policy framework. While other major central banks were relying on quantitative easing policies to thwart the threat of deflation, ECB chose to increase its policy rate twice, in April and July 2011, to "keep inflation under control." As the ECB's monetary

[10] Bank of England also implemented a quantitative easing policy of its own from March 2009 to February 2010.

policy diverged from others, especially from that of the Federal Reserve, the index gradually declined, falling back one percentage point by mid-2011.

Over this period, the connectedness of the long-term (9- and 10-year) bond returns increased significantly while that of the short- and medium-term bonds did not change much (see Figure 2). In the meantime, as the EU's headaches with the Greek bailout plans continued in June 2011, the Euro debt crisis started to show its effects on Italy and Spain. Italian and Spanish government bond yields increased considerably in July. With increased worries in other bond markets, the system-wide index moved up gradually by less than half a percentage point in the late summer of 2011.

On September 21, 2011, the Fed announced the 'Operation Twist' program of replacing its maturing short-term bond portfolio with long-term bonds, which targeted flattening the yield curve. The program, which expired at the end of December 2012, entailed the Fed buying $667 billion (roughly $45 billion per month) in longer-term Treasuries above 6-year durations while selling the same amount in shorter-term securities under 3-year durations.

The Operation Twist had almost no effect on the joint system-wide connectedness index, which stayed unchanged around 94.5. However, the within-maturity connectedness of short- and long-term bonds moved in entirely opposing directions (see Figure 2). While the within-maturity (cross-country) connectedness of short-term (1- to 3-year bonds) bonds increased significantly (close to 10 percentage points), the within-maturity connectedness of longest-term bonds in our sample (8-, 9- and 10-year bonds) declined significantly. The connectedness indices for 4- to 6-year bonds also increased while the index for 7-year bonds stayed almost flat until the end of February 2012. As a result, the within-maturity connectedness dispersion increases from 2.5 in September 2011 to 7.5 at the end of February 2012.[11]

The behavior of the within-maturity connectedness measures over the period (see Figure 2) clearly shows that the Federal Reserve's Operation Twist was successful in lowering long-term yields. While Operation Twist lowered the within-maturity connectedness of long-term bond yields, the long-term yields in other countries stayed high over the period. As a result, the long-term yield connectedness declined, increasing the dispersion of bond market return connectedness (as measured by the standard deviation of the within-maturity return connectedness of 1-to-10-year bonds) tripled within a few months.

Mario Draghi took up his position as the new president of the ECB on November 1, 2011. Since then, the ECB no more considered policy rate increases again. Instead, it gradually moved in the direction of expansionary monetary policy interventions. Initially, it relied on conventional measures such as the policy interest rate cuts and the provision of liquidity and low-cost funds to the banking sector through the long-term refinancing operations (LTRO-I on December 8, 2011, LTRO-II on February 29, 2012). On top of these developments, on March 2, 2012, the EU member states signed the fiscal compact to strengthen the fiscal governance and coordination in the European Union.

Following the LTRO-II and the signing of the fiscal compact, the system-wide connectedness

[11] We measure the dispersion with the standard deviation of within-maturity connectedness measures for bond maturities from 3-month to 10 years.

index increased by close to one percentage point. More importantly, however, the dispersion of the within-maturity return connectedness of 1-to-10-year bonds started to decrease in response to these developments on the European front. While the within-maturity connectedness of long-term (from 4- to 10-year maturities) bonds began to increase, that of the short-term bonds (1- to 3 years) did not change much (see Figure 2.)

Unable to turn the tide with the implementation of LTROs, Mario Draghi appeared on stage on July 26, 2012, and made his famous speech: ECB was determined "to do whatever it takes to preserve the euro." Draghi's speech was followed by the early September announcement of Outright Monetary Transactions (OMT), an unlimited but sterilized bond-buying program. Draghi's speech and the OMT announcement had a significant impact, reducing bond yield spreads of Eurozone sovereign bonds. Finally, the dispersion of the within-maturity connectedness increased after the Fed's third QE program started in September 2012. The dispersion of the within-maturity return connectedness almost doubled from 2 points in September 2012 to 5 points as of the end of 2012.[12]

To summarize, the 'old normal' in our sample addresses a turbulent period that urges central bankers to experiment with new unconventional monetary policy tools. In this way, major central banks accumulate a considerable amount of assets in their balance sheets. Once the financial systems survived the disastrous effects of the global financial crisis, many of the major central banks experimented with UMPs to prevent potential negative spillovers to the real side of the economy. However, the big gap between the EU members' economic performances prevented the ECB's switch to unconventional monetary policies until 2012 and full-scale QE until 2015.

6.2 Reversal in Within-Maturity Connectedness: Fed's Tapering and ECB's Quantitative Easing

In his May 22, 2013 testimony before Congress, the Fed Chairman Ben Bernanke stated that the Fed might start slowing down its bond purchases in the second half of the year. His remarks had substantial repercussions in financial markets, leading to an increase in the long-term interest rates and generating a rise of 1.3 percentage points in the system-wide connectedness index within one month. Then, in his June 19, 2013 press conference, Ben Bernanke stated that the Fed would closely watch the economy's performance before deciding to taper its $85 billion asset-purchase programs. As the markets interpreted his speech as a serious sign of the end of the super-easy monetary policy era, long-term interest rates increased sharply not only in the U.S. but around the world, as well.

As a result of the market overreaction, which was later called the "taper tantrum," the system-wide connectedness index experienced another 0.7 percentage point increase at the end of June. The index kept up moving by another and a half percentage points throughout the rest of 2013, reaching 97.2 in early December 2013, while Federal Reserve remained silent about

[12] The Fed's QE3 program lowers the U.S. long-term bond returns further down, increasing the gap between other countries' and U.S. bond returns.

the tapering schedule. As the Federal Reserve announced the tapering schedule at the end of December 2013, the connectedness declined by more than one point. Once the data for June 2013 is dropped out of the rolling sample window and the tapering started in the U.S., the index dropped gradually close to three percentage points to slightly below 94.5%.

Moving forward, we trace the impact of the taper tantrum on the within-maturity connectedness in Figure 2. The big discrepancy between the within-maturity connectedness of short-term and long-term bonds (a phenomenon observed after the operation twist) declined as the ECB gradually moved towards the implementation of unconventional policies in 2012 even though the troubles of some EU-member states continued. The divergence between the within-maturity connectedness of different bond maturities further declined in the first four months of 2013. Over this period, the short-term bonds tended to have higher within-maturity connectedness than the medium- and long-term bonds. The taper tantrum's most critical impact was the drastic change in the within-maturity connectedness hierarchy in favor of long-term bonds. In May-June 2013, the within-maturity connectedness of the long-term bonds increased the most, followed by medium- and short-term bonds. The within maturity connectedness of the 4- to 10-year bonds was very much close to each other. From mid-2013 onwards, the long-term bond connectedness was higher than the short-term bond connectedness.

As the taper tantrum period came to an end in 2014, the return connectedness of the 10-, 9- and 8-year bonds declined faster than the 5- and 6-year bond return connectedness. In the second half of 2014, however, the LT return connectedness increased again, moving above the return connectedness for medium- and short-term bonds. This time around, the LT return connectedness increase resulted from the ECB's monetary policy framework becoming more synchronous with the UMPs of the Fed, BoJ, and BoE.

6.3 The 'New Normal' of Bond Market Connectedness

We use the term "synchronous" to underscore the monetary policy frameworks of major central banks getting in tune after the global financial and Eurozone crises. The term does not imply the simultaneous monetary policy moves by two or more central banks. Instead, we use it to characterize the new normal in which major central banks expand and maintain sizeable balance sheets to achieve their policy objectives.

In the last decade, we observe a rapid expansion of the central bank balance sheets through interventions in bond markets, especially in the market for medium- and long-term bonds. Therefore, in the new policy framework, policy actions are expected to affect domestic and foreign bond markets through several channels that we discussed in Section 3.

The ECB announced its QE policy in September 2014, followed by the details in February 2015. Eventually, the QE program implementation started in October 2015. From the second half of 2014 onwards, the impact of the increased monetary policy synchronization on the LT and ST bond return connectedness is quite visible.

Not only did the synchronization help the LT return connectedness move above the MT and ST return connectedness, but it also led to a substantial decline in the dispersion of the within-maturity connectedness in Figure 2. As a result, the two sub-periods (pre-2015 – post-2015) differ in terms of the dispersion of the within-maturity return connectedness. While the dispersion of within-maturity return connectedness is higher during the first period, once the ECB started following QE policy in 2015, the return connectedness dispersion declined substantially.

The ECB's expanding balance sheet, along with the Fed's already large balance sheet in the post-2014 period, had a substantial impact on the LT return connectedness through what has become known as the portfolio rebalancing effect in the literature. The ECB doubled its balance sheet by injecting 2.3 trillion euros in the market from the end of 2014 to the end of 2018. The Fed's balance sheet size was almost flat at the 4-4.5 trillion dollar range over this period. Fed continued the bond purchases only to replace the maturing bonds in its portfolio with no net additions. The European financial institutions and investors, who were provided excessive amounts of euro funds, converted euros into dollars and invested in the US treasury bonds, drawing the US LT bonds interest rates down along with the Eurozone LT bond returns. Therefore, the portfolio rebalancing effect is the mechanism through which the large balance sheets of major central banks led to higher LT connectedness over this period.

One might ask why we did not observe a similar portfolio rebalancing effect when the US Fed implemented its UMPs much earlier than the ECB. The answer is quite apparent. When the Fed was expanding its balance sheet from 2009 through 2014, the European banking and sovereign debt crisis of 2009-2012 rendered euro bond investments unattractive for American investors.

While the long-term bond yields went down, a similar decline in short-term yields did not occur because they were already close to the zero-lower bound. Besides, lower long-term bond yields in the U.S. and the EU forced investors in these countries to undertake portfolio rebalancing by moving funds to long-term bonds in other countries, lowering bond yields around the world over time as well. That is the underlying mechanism through which the long-term bond return connectedness has taken place across countries.

Until mid-2014, the ECB was the only major central bank that stayed out of large-scale asset purchases. After realizing that providing long-term financing to Eurozone banks did not generate the desired effect on the real side of the economy, the ECB governing council has finally decided to follow the other three major central banks. In September 2014, the ECB announced plans to implement its quantitative easing program to battle slow economic recovery and deflation threat. The program was implemented starting in March 2015, with a net asset purchase of €60bn per month. After the announcement, the system-wide index started to increase and reach above 91% by the end of 2014. Even though this increase lasted only several months, followed by a correction, the index started its upward trajectory in mid-2015 onwards, this time at a faster pace. The index reached close to 92% towards the end of 2015. In April 2016, ECB increased its monthly net asset purchases from €60 bn to €80 bn as of the mid-2016.

In the meantime, the Federal Reserve raised its policy interest rate in December 2015 by 25 basis points. This first policy rate hike since the global financial crisis was followed by another one in December 2016. Unlike other major central banks, the Federal Reserve continued to increase the policy rate three times in 2017 and four times in 2018, 25 basis points each time. However, as we discuss below, neither the system-wide nor the within-maturity bond return connectedness showed much of a reaction to the rate hike decisions of the Federal Reserve.

Bond markets in the UK and Europe were adversely affected by the Brexit decision on June 23, 2016. In response, the system-wide connectedness declined slightly. In one day, the within-maturity connectedness of the long-term bonds dropped more than the short-term bonds. However, both the UK and European bond markets rallied strongly in the weeks after the UK referendum, leading to a 0.60 percentage point increase in the system-wide connectedness index over the subsequent two months. Long-term bond connectedness recovered more (5.3 percentage points) than the short-term bonds (2.7 percentage points).

Donald Trump's victory in the 2016 U.S. presidential elections caught the global bond markets with a surprise. Interpreting Trump's promised infrastructure spending and tax cuts to result in higher U.S. government debt, bond markets reacted with a sell-off that had quickly driven U.S. interest rates to the highest levels in 2016. As a result, from November 8 to December 15 (one day before the Fed's rate decision), the system-wide connectedness index increased by 0.43 percentage points. The long-term bond return connectedness across countries increased more than the short-term bond connectedness across countries (2.5 percentage point increase for 3-month vs. 4.4 percentage point increased for 10-year bond return connectedness).

The third development that led to an increase in connectedness over the 2016-2017 period was the Fed chairperson Janet Yellen's January 19, 2017, Stanford University speech. In that speech, Yellen signaled a path of steady interest rate increases in the near future. In response to her speech, U.S. government bond yields soared to multi-week highs. That is evident in a 0.5% increase in the joint connectedness index from January 19 to the end of January 2017 (see Figure 1). The response of the within-maturity connectedness of bonds with different maturities differed significantly: while from January 18 to 31, the within-maturity connectedness of the 3- and 6-month treasury bills increased by 0.85 and 1.89 percentage points, respectively, the within-maturity connectedness of the 8-and 10-year bonds increased by 3.9 and 3.5 percentage points. (see Figure 2).

Fed increased the Fed funds rate target three times (March, June, and December) in 2017 and four times (March, June, September, and December) in 2018. As a result, the fed funds rate climbed to the 2.25-2.50% range as of the end of 2018. Faced with a possible slowdown in 2019, the Fed lowered the fed funds target rate three times in 2019. As of the beginning of 2020, the target range for the fed funds rate stood at 1.50-1.75%. None of these rate changes generated a significant increase in connectedness measures. As the data for earlier 2017 are dropped from the rolling window sample, the system-wide index fluctuated between 95.5 and 96% for a period longer than two years, from August 2017 to December 2019.

As a final point in this section, let us note that since the end of October 2019's Fed's balance sheet increased from \$3.8 to \$4.1 trillion. That is perhaps responsible for the more than doubling of the standard deviation of within-maturity connectedness measures for 12 bond maturities included in our analysis.

7 Monetary Policy and Connectedness: Secondary Regressions

In the previous sections, we have focused on analyzing the system-wide and total directional sovereign bond market connectedness measures over time. Our analysis of the behavior of the system-wide and cross-country/cross-maturity directional connectedness measures allowed us to graphically identify the impact of the monetary policy actions on connectedness. However, the graphical analysis is not conclusive because it does not rule out factors other than the monetary policy actions that could drive connectedness measures over time. To establish the relationship between the monetary policy actions and the bond market connectedness in a multivariate setting, we now undertake a multivariate regression analysis of the bond market connectedness across maturities and countries.

There are several ways to identify the determinants of the bond market connectedness through regression analysis. At an aggregate level, one can set up a regression model to estimate the impact of several macroeconomic and financial variables on aggregate connectedness measures, i.e., system-wide connectedness, to-connectedness, or others. Even though this approach is useful to assess the role of different factors on the overall connectedness dynamics, it is limited to deliver an elaborate answer to understand how individual bonds are connected. Instead, we take the pairwise connectedness measures from source to target country as the dependent variable in the following econometric analysis to study the impact of both conventional and unconventional monetary policy actions on the bond market connectedness across countries.

We first focus on the variables to measure monetary policy differences across countries, which we argued from the beginning are the critical determinants of pairwise bond return connectedness. Once we define the measures of monetary policy differences, we identify economic variables that can influence bond return connectedness across countries.

7.1 Measures of Monetary Policy Differences Across Countries

The directional connectedness measures are pairwise by construction. Fortunately, there are available pairwise data that quantify economic relations between countries, such as trade flows, portfolio flows, and holdings. In other cases, such as quantifying monetary policy differences across countries, it is usually not possible to find relevant pairwise economic data. Hence, we need to define monetary policy measures to capture the impact of conventional and unconventional monetary policy on bond market connectedness.

First, we define the central bank policy rate spread between the source and target countries, $r_S - r_T$, as a measure of conventional monetary policy differences between the two countries. We would expect the coefficient of the policy rate spread between the source and the target country to be positive: An increase in the source country policy rate will lead to a rise in the source country's short-, medium- and long-term bond yields through the monetary policy transmission mechanism. As the investors act to exploit the resulting interest arbitrage opportunity, we would expect the connectedness to take place from the source country bond returns to target country bond returns.

Our sample spans a period of unprecedented expansion of central bank balance sheets in industrial countries. As the unconventional monetary policies have become a part of the monetary policy toolbox, using only the central bank policy rates would not be sufficient to capture the full effect of monetary policy on bond market connectedness. Towards that end, we use the difference of the central bank assets (normalized by the bond market size (BMS) of the two countries), $(CBAssets_S/BMS_S - CBAssets_T/BMS_T)$, as a right-hand side (RHS) variable. In a given period, when the central bank of the source country undertakes an unconventional monetary policy action to influence its medium-to-long-term interest rates, this action becomes apparent in its total assets.[13] A closer look at the major central banks' balance sheets reveals that the UMP actions boosted the size of central bank balance sheets in the previous decade.[14]

Assuming that the difference between the respective measures of the central balance sheets (source and target countries) is positive, we would expect it to generate bond market return connectedness from the source to the target country. We would expect the sign of the corresponding coefficient estimate to be positive. The purchase of local assets by the central bank is likely to lower the medium-to-long-term interest rates in the source country and lead to an increase in capital outflows from the source country, which in turn may lower medium-to-long-term interest rates in other countries, including the target country.

7.2 Economic Interdependence and Connectedness

A regression of pairwise dependent variables requires the use of pairwise independent variables. Fortunately, some macroeconomic and financial variables such as trade and investment flows are by construction pairwise. Similarly, the distance between two countries as a measure of geographical proximity is pairwise. The pairwise portfolio investment data presents the portfolio holdings of the source country in the target country, which can be used as a proxy for the financial dependence between the two countries. It is also possible to transform the portfolio holdings data to address the question of whether the source country is an essential source of capital flowing into the target country. To be more specific, we use the share of the portfolio capital investments from the source country to the target country in the total portfolio capital investments received by the target country $(K_{S\to T}/K_{World\to T})$.

While financial flows are likely to be the right measure of the financial dependence between two countries, we also include bilateral trade flows as an RHS variable to possibly the economic interdependence between pairs of countries. Here we focus on the relative importance of the

[13] We are fully aware that there are many items in the central bank balance sheet that are not affected by the UMP actions. Furthermore, some of the UMP actions, such as *forward guidance* and *Operation Twist*, do not necessarily create a change in the central bank's total assets.

[14] As of January 2021, the Fed's holdings of government bonds reached %64.3 of the total asset size. Including the federal agency debt and mortgage-backed securities, the share increases to %92.8. Similarly, ECB holdings of Euro Area countries' securities is %55.9 of its total assets size. It increases to %81.5 when we include the Long-term Refinancing Operation (LTRO), which is also "unconventional". Bank of Japan's holdings of Japanese Government bonds amounts to %76.1 of its total assets. It increases to %84.9 when we include the funds provided to commercial banks through the Loan Support Program to increase their lending power.

source country as a market destination for target country exporters. We, therefore, define the trade flow variable as the share of target country exports to the source country in the target country's total exports ($X_{T \to S}/X_{T \to World}$). The higher the share of the target country's exports to the source country in its total exports, the more susceptible the target country would be to aggregate demand shocks in the source country. An increase in the bond yields would result in higher pressure on aggregate demand in the source country, which would lower its import demand for target country goods. In such a case, bond yield return connectedness from the source to the target country is likely high.

Finally, in addition to the directional capital and trade flow variables, we include the distance between the source and target countries ($D_{S \leftrightarrow T}$) as the last RHS variable. The geographical distance between the two countries may explain pairwise bond market return connectedness, which may not be fully captured by the RHS trade and capital flow variables. We would expect the coefficient of the distance variable to be negative. The farther the two countries are located apart, the lower the pairwise bond market return connectedness between them.

The data on central bank key rates and balance sheets are collected from central bank reports. The cross-border investment positions of countries (pairwise portfolio holdings data) are downloaded from the Coordinated Portfolio Investment Survey (CPIS) of the International Monetary Fund (IMF) on an annual and semi-annual basis. Because the latest CPIS data is available for the second half of 2019, we restrict our sample for secondary regressions by 2019. The information on bilateral trade is available monthly in the Direction of Trade Statistics (DOTS) of IMF.

Since macroeconomic and financial variables are available monthly, we need to convert our daily pairwise connectedness measures to a monthly frequency. We tried different frequency conversion methods, such as taking the monthly mean, median, and maximum daily connectedness measures. Since all three conversion methods produced very similar regression results, we report only the results based on monthly mean connectedness measures. As already discussed above, the bond yield data on 3- and 6-months are not available throughout the full sample period. Therefore, we apply the secondary regressions for two different samples. The first covers the full sample period 2007-2019 (we drop the data for 2020 because of RHS data availability) and includes the within connectedness of 1- to 10-year maturity bonds. In the second sample, we also have the pairwise within-connectedness measures for 3- and 6-months; however, we restrict our sample to the 2012-2019 period.

We undertake the pooled regression analysis in two steps. First, we pool monthly observations of pairwise connectedness measures for all countries and maturities in one dataset and run panel regressions with five RHS variables as defined above. We add source and target country fixed effects and time fixed effects to see how coefficient estimates change as we introduce them in the pooled regressions. In the second step, we undertake regressions of pairwise connectedness measures over the full sample for each maturity separately and plot coefficient estimates over maturities from 3-months to 10-years.

7.3 Pooled Regressions

Pooled regression results for all countries and maturities over the two sample periods are presented in Table 1. The first (and fourth for the second sample) column shows coefficient estimates for all five variables without accounting for the source and target country and time fixed-effects. In the second and third (fifth and sixth for the second sample) columns, we repeat the pooled regressions with the source and target country fixed-effects, and the source and target country fixed-effects along with the time fixed-effects, respectively.

Table 1: Pooled Regressions

	(Short Sample)			(Long Sample)		
	(1)	(2)	(3)	(4)	(5)	(6)
CB Assets	0.051***	0.044***	0.044***	0.058***	0.040***	0.040***
	(0.003)	(0.008)	(0.008)	(0.003)	(0.005)	(0.005)
CB Policy Rate	-0.015***	-0.007	-0.007	-0.022***	0.024***	0.024***
	(0.003)	(0.009)	(0.009)	(0.003)	(0.007)	(0.007)
Trade	0.069***	0.035***	0.033***	0.042***	0.028***	0.027***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.002)	(0.002)
Investment	0.068***	0.017***	0.021***	0.082***	0.021***	0.022***
	(0.002)	(0.004)	(0.004)	(0.002)	(0.003)	(0.003)
Distance	-0.257***	-0.343***	-0.344***	-0.297***	-0.385***	-0.386***
	(0.003)	(0.004)	(0.004)	(0.003)	(0.003)	(0.003)
Adjusted R^2	0.156	0.418	0.425	0.165	0.527	0.533
Observations	102,600	102,600	102,600	134,100	134,100	134,100
Source Country FE	N	Y	Y	N	Y	Y
Target Country FE	N	Y	Y	N	Y	Y
Time FE	N	N	Y	N	N	Y

[1] Sample 1: May 2012 - Dec 2019, 3-months to 10-years; Sample 2: Aug 2007 - Dec 2019, 1-year to 10-years.
[2] Variable Definitions: 1) CB Policy Rate = $(i^p_S - i^p_T)$. 2) CB Assets $=(CBAsset_S/BMS_S - CBAsset_T/BMS_T)$. 3) Trade: SC's Share in TC Exports = $(X_{T\to S}/X_{T\to World})$. 4) Investment: SC's Share in Portfolio Holdings to TC $=(K_{S\to T}/K_{World\to T})$. 5) Distance between SC & TC = $D_{S\leftrightarrow T}$.
[3] *p<0.1; **p<0.05; ***p<0.01.

The regression results presented in Table 1 verify our expectation that the CB asset spread variable has statistically significant and positive coefficient estimates. However, contrary to our expectations, the CB policy rate spread's coefficient estimate is negative but only significant when none of the fixed-effects are accounted for (column 1) in the short sample.[15] When both country fixed-effects are included along with the time fixed-effects, coefficient estimates for the CB policy rate spread turn out to be statistically insignificant (see columns 2 and 3). In the longer sample, we have a similar result when we ignore fixed-effects (column 4). When we introduce country and time fixed-effects, the coefficient estimate becomes positive and statistically significant.[16]

[15] We consider the collinearity problem between CB assets and CB policy rate spreads. Our detailed inspection revealed that our estimation results do not suffer from the collinearity problem, perhaps because of the low variability of key policy rates.

[16] We think both the incorrect sign and weak statistical significance are due to the low variation of central bank policy rates throughout the shorter sample period. The number and frequency of changes in the key policy

As for other variables, the share of the target country exports to the source country in the target country's total exports has a statistically significant positive (0.033 (0.027) in column 3 (6) of Table 1) impact on bond return connectedness from the source to the target country. In other words, the larger the share of the source country in the target country's total exports, the more the target country becomes dependent on macroeconomic changes in the source country. As a result, the larger will be the bond return shock transmission from the source country to the target country.

We obtained a positive and significant coefficient estimate for the portfolio investments for all possible cases in the short and long samples. This shows that an increase in the source country's portfolio investment share in the target country increases connectedness from the source to the target country.

Finally, the coefficient estimate of the distance is of the expected negative sign: A 1000 km increase in the distance between two countries would reduce the bond return connectedness by 0.344 (0.386 for the full sample) points. Given that pairwise connectedness measures are likely to be in the several percentage points at a maximum, this is not a negligible amount. It is obtained along with the statistically significant estimates for the capital and trade variables.

7.4 Within-Maturity Pooling Regressions

Pooling variables for all countries and bond maturities, we obtained estimation results that establish the close link between the monetary policy actions and bond return connectedness across countries. However, it is quite possible that the resulting coefficient estimates could be due to some of the bond maturities while not to others. For that reason, we estimate pooled regressions of within-maturity pairwise connectedness for 3-month, 1-year, 5-year, and 10-year bonds separately. For the long sample, we drop the 3-months within-connectedness measures and focus only on the latter variables. The results are presented in Table 2. The coefficient estimates show that while the conventional monetary policy actions (as summarized by the CB policy rate spread) have a statistically insignificant effect on pairwise return connectedness for all maturities, even though the coefficients are negative in both samples. The only exception is the coefficient that we estimated for 5-years within-maturity bond connectedness in the long sample; it is positive and significant. In the short sample, the unconventional monetary policy actions have a statistically significant positive effect on pairwise bond return connectedness for 3-months, 5-year, and 10-year bond maturities as expected. In contrast, the coefficient for 1-year within-maturity bond return connectedness is positive but insignificant. In the long sample, we have found similar results for the impact of the unconventional monetary policy measures.

The coefficient estimates for trade flows presented in Table 2 are consistent with the ones presented in Table 1. All of the coefficient estimates are statistically significant and positive for all maturities except for the 1-year within-maturity bond return connectedness in the short sample. Coefficient estimates for portfolio investments do have a statistically significant and positive effect on pairwise connectedness only in the case of 1- and 5-years bonds, but not for

rates for the ten countries in our sample throughout 2007-2020 are presented in Appendix C.2.

Table 2: Secondary Regressions – Within-maturity Pairwise Connectedness

	(Short Sample)				(Long Sample)		
	3 Month	1 year	5 years	10 years	1 year	5 years	10 years
CB policy rate	-0.006	0.014	-0.009	-0.043	0.018	0.033***	-0.001
	(0.009)	(0.028)	(0.009)	(0.036)	(0.012)	(0.012)	(0.023)
CB assets	0.030**	0.019	0.044***	0.076***	-0.006	0.023**	0.080***
	(0.012)	(0.022)	(0.012)	(0.020)	(0.009)	(0.009)	(0.012)
Trade	0.011***	0.034***	0.047***	0.034***	-0.007	0.036***	0.043***
	(0.003)	(0.009)	(0.003)	(0.008)	(0.004)	(0.004)	(0.006)
Investment	0.005	0.096***	0.022***	-0.008	-0.007	0.040***	0.021***
	(0.004)	(0.014)	(0.004)	(0.010)	(0.005)	(0.005)	(0.008)
Distance	0.017***	-0.286***	-0.487***	-0.468***	-0.080***	-0.471***	-0.432***
	(0.005)	(0.011)	(0.005)	(0.013)	(0.006)	(0.006)	(0.010)
Adjusted R^2	0.119	0.444	0.672	0.718	0.230	0.675	0.705
Number of Observations	8,550	8,550	8,550	8,550	13,410	13,410	13,410

[1] Sample 1: May 2012 - Dec 2019; Sample 2: Aug 2007 - Dec 2019.
[2] Variable Definitions: 1) CB Policy Rate = $(i^p_S - i^p_T)$. 2) CB Assets = $(CBAsset_S/BMS_S - CBAsset_T/BMS_T)$. 3) Trade: SC's Share in TC Exports = $(X_{T\to S}/X_{T\to World})$. 4) Portfolio Capital Flows: SC's Share in Portfolio Flows to TC =$(K_{S\to T}/K_{World\to T})$. 5) Distance between SC & TC = $D_{S\leftrightarrow T}$.
[3] *p<0.1; **p<0.05; ***p<0.01

3-months and 10-years maturity bonds. In the long sample, it is significant and positive for 5- and 10-years maturity bonds. Coefficient estimates for the geographical distance measure are of expected sign except for the 3-month within-maturity bond return connectedness and statistically significant for all maturities.

Finally, we repeat the secondary regressions for bonds of all maturities separately and present the resulting coefficient estimates along with their corresponding 95% confidence intervals in Figure 5 and 6. The coefficient estimates are consistent with the ones presented in Table 2. Figure 5 shows that the central bank assets have a significant positive impact on bonds with 3-months and five years and longer maturities, while it has a statistically insignificant positive coefficient for bonds with 6-months to 4-year maturity. As the conventional monetary policy measure, the central bank policy rate difference has a positive and statistically insignificant coefficient for bonds with 6-months to 3-years maturities.

The coefficient estimates for the trade and distance variables are consistent with the results obtained in Table 2. We are likely to observe higher bond return connectedness from the source to the target country if it is an important market for the target country's exports. The effect of bilateral trade flows increases with maturity until 4-years; drops until eight years, and stabilizes afterward. The coefficient on the portfolio capital flows is positive and statistically significant from 6-months to 6-years. The impact of portfolio investment increases with maturity for shorter maturities, peaks around the 2-year maturity, and goes down afterward. We think this pattern is likely to be the result of the characteristics of the investment data. The CPIS data do not only include the holdings of the short and long-term debt instruments but also contain short and long-term equity investments and investment fund shares. Considering the equity

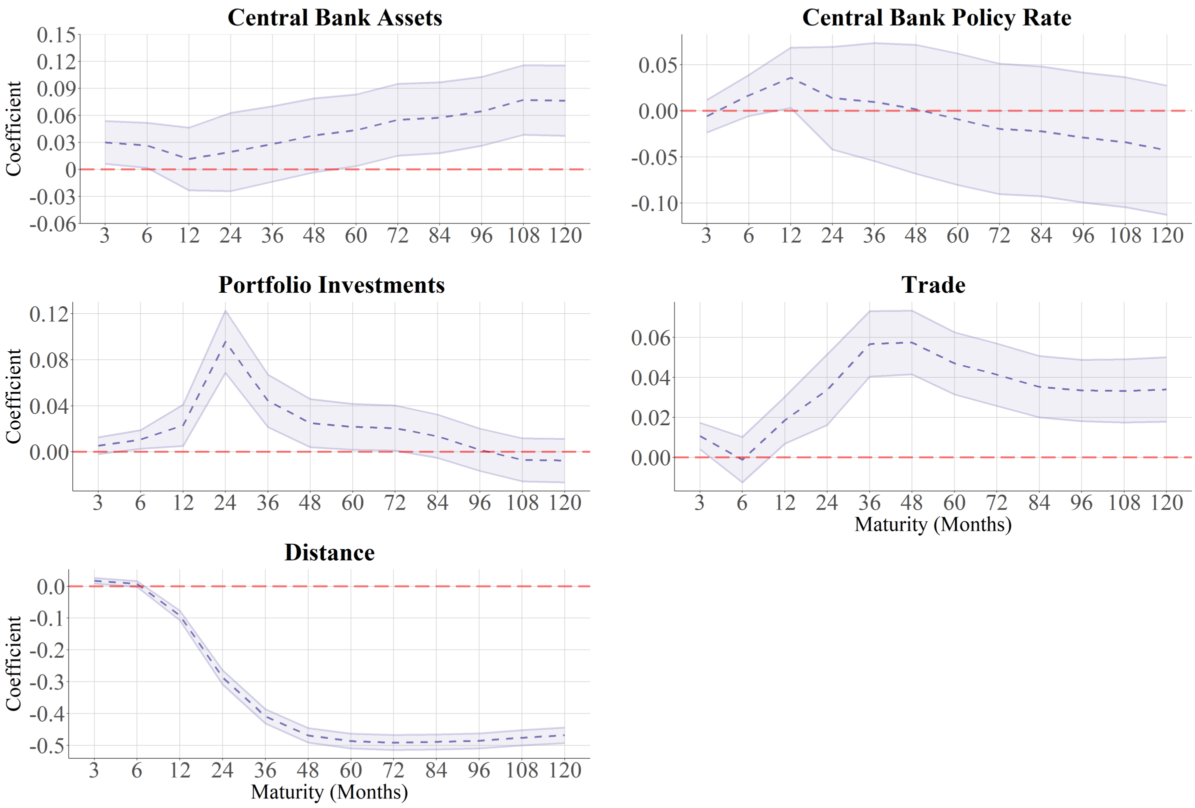

Figure 5: Secondary Regressions – Coefficients Estimates (3 Months-to-10 Years Maturity)

investments are short-term on average[17], it is not surprising that the statistically significant positive impact of investments is observed for the medium-term bonds. Finally, the farther apart the two countries are located, the lower will be the connectedness of bond returns from one to the other. Interestingly, the distance coefficient is positive and statistically significant in the case of 3- month bonds.

8 Conclusion

This paper utilized the Diebold-Yilmaz Connectedness Index (DYCI) methodology to analyze the transmission of daily sovereign bond return shocks across countries and maturities over the 2007-2020 period. The resulting bond return connectedness measures are used to study the possible impact of the conventional and unconventional monetary policies on the transmission of daily sovereign bond return shocks across maturities and countries over time.

We obtained important results that show the effects of UMPs on bond market connectedness over time. Thanks to all major central banks' persistent implementation of the unconventional policies after 2014, the long-term within-maturity connectedness across countries overtake the short-term connectedness and the dispersion of within-maturity connectedness measures de-

[17] The World Federation of Exchanges data shows average holding period of stocks in the stock markets of countries in our sample throughout 2012-2019 is 17.4 months (21 months for 2007-2019 period).

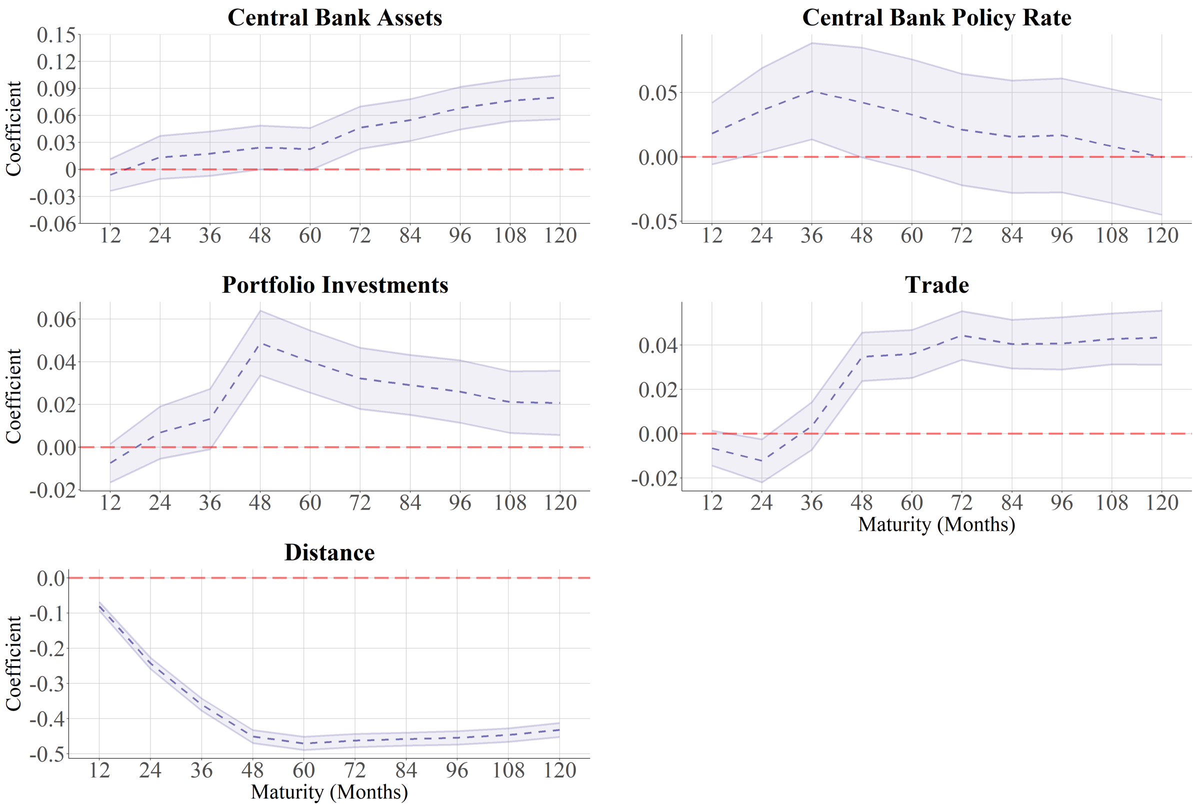

Figure 6: Secondary Regressions – Coefficients Estimates (1 Years-to-10 Years Maturity)

creased. Consistent with this finding, net across-maturity connectedness of short- to long-term maturity bonds drops down to zero over the same period.

We also show that the Fed's Operation Twist program lowered the within-maturity connectedness of long-term bonds while increasing short-term bonds. Similarly, the taper tantrum increased bond return connectedness significantly, but its impact on the within-maturity connectedness dispersion was not as large as Operation Twist's impact.

Finally, we use panel regressions to analyze the impact of monetary policy interventions on pairwise return connectedness along with other factors, such as the distance, trade, and portfolio investment flows between pairs of countries. In particular, consistent with earlier results, the panel regressions reveal that UMPs led to higher pairwise long-term bond return connectedness over time. In contrast, the conventional monetary policy tools affected the short-term bond connectedness with no effect on long-term connectedness.

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Appendices

A Diebold-Yilmaz Connectedness Framework

In this appendix, we introduce the Diebold-Yilmaz connectednes index framework, along with its system-wide and directional meaures. Diebold and Yilmaz (2014) provides a vector autoregression (VAR) based estimation methodology to measure connectedness among variables with the help of variance decompositions. From a broader perspective, the DYCI is not fundamentally different from the more familiar impulse response/variance decomposition analysis. Suppose we want to estimate connectedness for N assets. The first step of DYCI estimates an N variable VAR model with a specified lag structure. In the second step, using VAR parameters, we generate impulse-responses and variance decompositions for all N variables and normalize them to get comparable results.

In this case, traditional VAR estimation techniques have potential drawbacks. First, traditional methods are tightly fitting for large financial networks. A high number of variables compounded by lag structure requires a massive amount of parameters to be estimated. Most of the time, it is unlikely to enlarge the dataset to fit such a model. Even when it is possible, estimation results can become less responsive to variation in the markets observed through time. Second, in order to undertake the variance decomposition analysis, one needs to decompose the variance-covariance matrix. That, in return, requires the ordering of variables based on instantaneous causality among variables to obtain a well-known Cholesky decomposition structure. In a network setting, this procedure has a significant drawback, the ordering of a high number of assets is hardly achievable, and instantaneous causality among assets are not apparent in most of the cases. Diebold and Yilmaz (2014) attempts to overcome the "curse" of high-dimensionality with elastic net estimation and applies the ordering-invariant generalized variance decomposition (GVD).

Following in the footsteps of Diebold and Yilmaz (2014), we estimate an approximating VAR system of bond returns (conditional volatility or dynamic yield curve factors) with three lags and use GVD to acquire the connectedness measures from the estimated model. Details are provided in the following.

A.1 Generalized Forecast Error Variance Decomposition

The generalized approach to variance decomposition enables the resulting variance decompositions to be invariant to the ordering of variables in the VAR model. Although it allows for correlated shocks, GVD makes it possible to separate the effects of each shock, which is the main objective of the analysis.

Assume a covariance stationary N-variable p-th order VAR system with nonzero intercept such as

$$y_t = \nu + \sum_{i=1}^{p} A_i y_{t-i} + \varepsilon_t \qquad \varepsilon_t \sim (0, \Sigma) \tag{A.1}$$

where y_t is $N \times 1$ random vector, ν is a fixed $N \times 1$ vector of intercept terms, A_i are fixed $N \times N$ coefficient matrices where A_0 is an identity matrix and $A_i = \mathbf{0}$ for $i < 0$. ϵ_t is $N \times 1$ vector of residuals of the model and Σ is the $N \times N$ variance-covariance matrix. Under stability assumption, we can rewrite the vector moving average (VMA) representation of VAR process such as

$$y_t = \mu + \sum_{i=0}^{\infty} \Phi_i \varepsilon_{t-i} \tag{A.2}$$

where μ is mean vector, Φ_i are $N \times N$ coefficient matrices.

In the DYCI context, to get the relevant story about the linkages among variables (or sovereign bonds in our case), impulse-response and variance decomposition analysis is essential. However, traditional impulse-response and variance decomposition techniques require orthogonalization of error terms. In orthogonalization, the ordering of variables becomes essential to reach the lower-triangular Cholesky decomposition structure. As noted above, this procedure may not be feasible in network studies. Instead of using orthogonalized impulse responses, Koop et al. (1996) and Pesaran and Shin (1998) proposed an identification technique called as Generalized Forecast Error Variance Decomposition (GVD) under multivariate-normal distribution assumption. Unlike the well-known Cholesky decomposition, GVD is invariant to the ordering of variables.

H-step-ahead forecast error variance of variable i accounted for by a one-standard-deviation shock to variable j, $\theta_{ij}^{g}(H)$, is given by

$$\theta_{ij}^{g}(H) = \frac{\sigma_{jj}^{-1} \sum_{h=0}^{H-1} (e_i' A_h \Sigma e_j)^2}{\sum_{h=0}^{H-1} (e_i' A_h \Sigma A_h' e_i)} \tag{A.3}$$

where σ_{jj} is the variance of the j-th equation and e_i is the selection vector with one for the i-th element and zeros otherwise.

As shocks to variables are non-orthogonal, the row sums of the matrix obtained by generalized forecast error variance decomposition (FEVD) do not necessarily add up to unity. In order to get comparable results for each variable, we normalize each entry in the FEVD matrix by the sum of corresponding rows.

$$\tilde{\theta}_{ij}^{g}(H) = \frac{\theta_{ij}^{g}(H)}{\sum_{j=1}^{N} \theta_{ij}^{g}(H)} \tag{A.4}$$

A.2 Connectedness Measures

Once the entries of the variance decomposition matrix are normalized, the next step is to calculate various connectedness measures offered by DYCI. We start with aggregate measures of total system-wide connectedness; then, we move to granular and directional connectedness measures

- The sum of all non-diagonal elements of the normalized variance decomposition matrix make up the total connectedness, $C(H)$, in the system ("system-wide connectedness") is obtained as:

$$C(H) = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} = \frac{\sum_{\substack{i,j=1 \\ i \neq j}}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \tag{A.5}$$

- The sum of all non-diagonal elements of the i^{th} column of the normalized variance decomposition matrix make up the total directional connectedness transmitted by variable i to all other variables j, $C_{\bullet \leftarrow i}$ ("to connectedness"), is defined as

$$C_{\bullet \leftarrow i} = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{\theta}_{ji}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ji}^{g}(H)} \times 100 = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{\theta}_{ji}^{g}(H)}{N} \times 100 \tag{A.6}$$

- The sum of all non-diagonal entries of the i^{th} row of the normalized variance decomposition matrix make up the total directional connectedness received by variable i from all other variables j, $C_{i \leftarrow \bullet}$ ("from connectedness"), is given as:

$$C_{i \leftarrow \bullet} = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{\theta}_{ij}^{g}(H)}{\sum_{i,j=1}^{N} \tilde{\theta}_{ij}^{g}(H)} \times 100 = \frac{\sum_{\substack{j=1 \\ j \neq i}}^{N} \tilde{\theta}_{ij}^{g}(H)}{N} \times 100 \tag{A.7}$$

- The net total directional connectedness from variable i to all other variables $C_i(H)$ is called the "net connectedness", and is equal to the difference between the "to" and "from connectedness" of variable i

$$C_i(H) = C_{\bullet \leftarrow i}(H) - C_{i \leftarrow \bullet}(H) \tag{A.8}$$

- Finally, the net pairwise directional connectedness from variable i to variable j, $C_{i,j}(H)$ is equal to the difference between the pairwise connectedness from i to j and the pairwise connectedness from j to i:

$$C_{i \to j}(H) = \theta_{j,i}^{\tilde{g}}(H) - \theta_{i,j}^{\tilde{g}}(H) \tag{A.9}$$

B Elastic Net Estimator: Selecting and Shrinking the VAR Model

In this appendix, we explain the elastic net method that we use to estimate high dimensional vector autoregression without facing the low degrees of freedom problem. To deal with the high-dimensionality issue, we apply the *elastic net estimator*, a selection and shrinkage method to our data set of a large number of bonds and obtain return connectedness measures. Demirer et al. (2018) introduced the implementation of elastic net estimation in the connectedness framework. They argue that the sparsity of estimators does not necessarily impose sparsity in the implied networks because of the non-linear transformation of VAR coefficients in variance decompositions. This property ensures network structure to be complete even when the coefficient matrix is sparse.

The elastic net estimator (Zou and Hastie (1996)) solves

$$\hat{\beta}_{Enet} = \arg\min_{\beta} \left(\sum_{t=1}^{T} \left(y_t - \sum_{i} \beta_i x_{it} \right)^2 + \lambda \sum_{i=1}^{K} \left(\alpha |\beta_i| + (1-\alpha)\beta_i^2 \right) \right).$$

Elastic net is an estimator which combines a Lasso (least absolute shrinkage and selection operator) L_1 penalty and a ridge L_2 penalty. We have two tuning parameters, λ and $\alpha \in [0,1]$. An important point is that elastic net is lasso when $\alpha = 1$ and ridge when $\alpha = 0$. Unlike lasso, which may move only one of the strongly correlated predictors, elastic net makes sure that the these predictors are in or out of the model together with the aim of improving prediction accuracy relative to lasso.

The adaptive elastic net estimator (Zou and Zhang (2009)) solves

$$\hat{\beta}_{AEnet} = \arg\min_{\beta} \left(\sum_{t=1}^{T} \left(y_t - \sum_{i} \beta_i x_{it} \right)^2 + \lambda \sum_{i=1}^{K} \left(\alpha w_i |\beta_i| + (1-\alpha)\beta_i^2 \right) \right),$$

where $w_i = 1/\hat{\beta}_i^{\nu}$ with $\hat{\beta}_i$ the OLS estimate (or ridge if regularization is needed). Adaptive elastic net is also a mix of two estimators which are adaptive lasso and elastic net. It blends the good properties of two estimators. It has the oracle property like adaptive lasso and exhibits advanced predictor handling with highly correlated predictors like elastic net.

We will take $\alpha = 0.5$ without cross validation[18] and use 10-fold cross-validation to choose λ. We use OLS regression to obtain the weights w_i. Furman (2014) shows that the adaptive elastic net allows the efficient equation by equation estimation of VAR. Moreover, the estimated VAR model leads to accurate forecasts and valid impulse response functions.

[18] As Demirer et al. (2018) states the cross-validation of α requires time-consuming computations, while it adds little to the estimation precision. Moreover, as long as positive coefficients exist for both the ridge and lasso penalties, the estimator works consistently.

C Additional Plots

C.1 Variation Explained by Yield Curve Factors

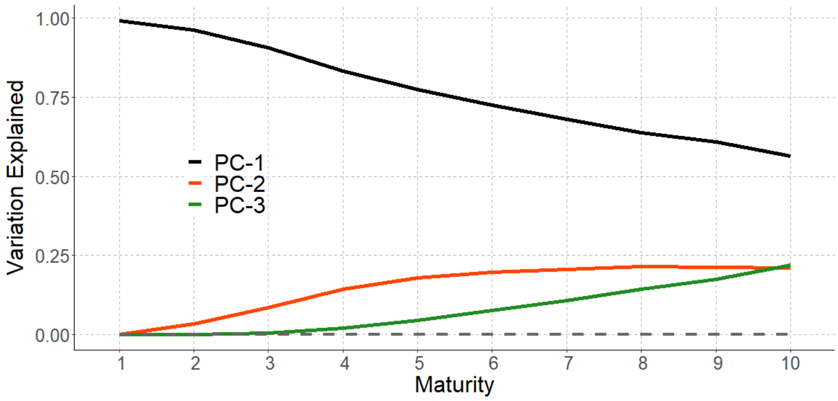

Figure A.1: Maturities and Yield Curve Factors

C.2 The Changes in Central Bank Policy Rate

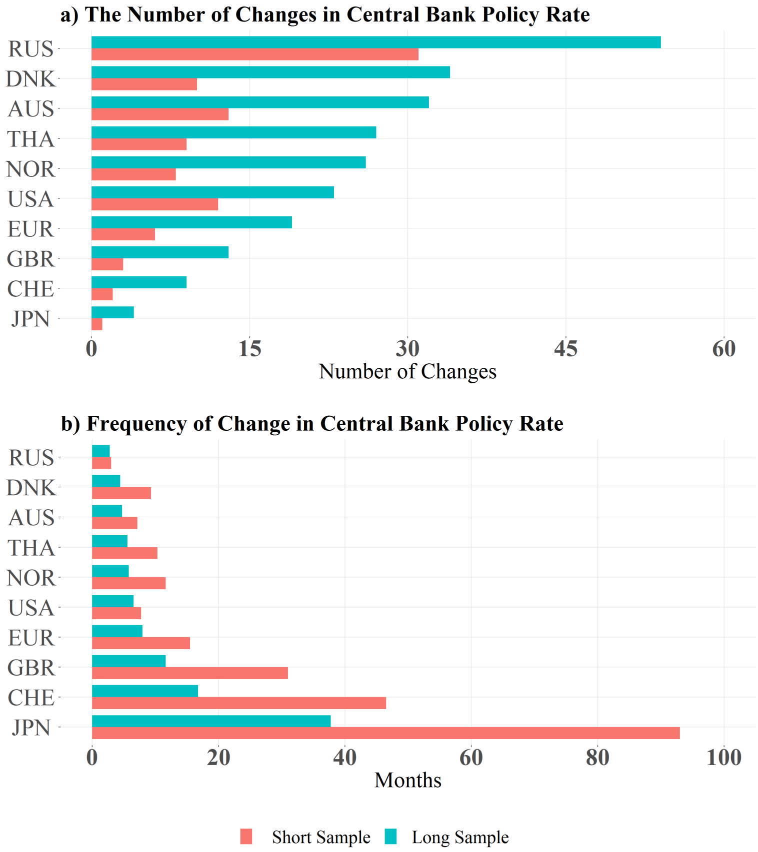

Figure A.2: Central Bank Policy Rate Changes

C.3 Total Assets of Central Banks

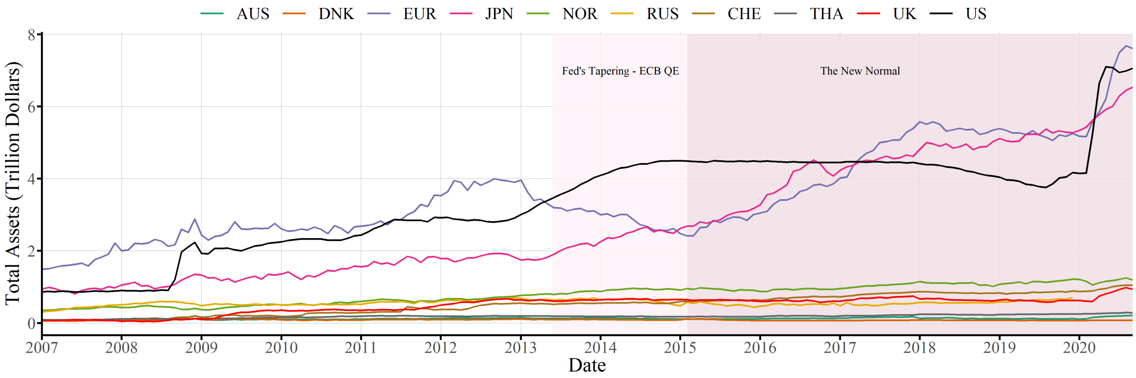

Figure A.3: Total Assets of Central Banks (Countries)