



The impact of quantitative easing on the volatility of US and European corporate bond markets

A cross-country analysis

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Objectives

This paper seeks to first and foremost evaluate the nuances that differentiate quantitative easing (QE), as employed in the last financial crisis, from conventional monetary policies, with updates for the recent round of QE by the European Central Bank (ECB). Such differences then facilitate an investigation of whether QE by the Federal Reserve System and the ECB reduced volatility of domestic and international corporate bonds. We simultaneously assess potential transmission channels that could explain how any of the discovered effects transpired.

Summary

A review of literature and central bank data reveals technical intricacies of QE and interest rate targeting, and of US and Europe QE. The popular volatility modelling framework EGARCH, enhanced with exogenous variables to capture QE effects, is applied to broad-based Bloomberg US and European corporate bond indices.

Conclusions

QE is potent in reversing bond market turbulence that the 2008 financial crisis left in its wake, both on domestic and cross-border scales, consistent with the signaling channel. The portfolio balancing channel is evident for US QE only, and both asset purchase intensity and policy announcement are found to be ineffectual in reducing volatility, at least under this model specification.

Key words: *Quantitative easing, Financial Crisis, Corporate bond, Volatility, EGARCH, Transmission channels*

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Table of Contents

1. INTRODUCTION	5
2. LITERATURE REVIEW	6
2.1 Quantitative easing and associated financial conditions	7
2.1.1 The Zero Lower Bound	7
2.1.2 The breakdown of financial intermediation	9
2.2 Quantitative easing versus short-term interest rates instruments	9
2.2.1 Definition of quantitative easing	10
2.2.2 Comparison between QE and short-term interest rates instruments	11
2.3 Overview of ECB and Fed QE programs	12
2.3.1 Nonstandard monetary policy and QE programs in the euro area	12
2.3.2 Asset purchase programs by the Federal Reserve System	14
2.3.3 Differences between ECB and US nonstandard measures	15
2.4 The impact of QE on corporate bonds	17
2.4.1 International effects of QE programs	19
2.4.2 QE and corporate bond volatility	22
3. METHODOLOGY	25
3.1 Quantitative easing and conditional volatility	25
3.2 Data and summary statistics	29
3.2.1 Summary of events of interests	30
3.2.2 Bond return and summary statistics	33
4. EMPIRICAL RESULTS	36
4.1. Impact of Fed and ECB QE on domestic corporate bonds	37
4.2. Impact of Fed and ECB QE on international corporate bonds	42
5. ROBUSTNESS TESTS	44
5.1. Model diagnostics	44
5.2 Robustness tests	45
5.2.1 Controlling for macroeconomic volatility	45
5.2.2 Adjusted list of announcements	46
6. CONCLUSION	46
6.1 Implication for International Business	47
6.2 Limitation and suggestion for future research	48
7. REFERENCE LIST	49
8. APPENDICES	56
Appendix 1: Model diagnostics	56
Appendix 2: Robustness test results	57

1. INTRODUCTION¹

In October 2017, it was announced that the European Central Bank (ECB) would halve the size of its formidable bond buying program. Such change in monetary policy direction is reminiscent of the “Taper tantrum” that saw transient panic in the US markets when the Federal Reserve made an announcement in a similar vein. It signifies the end of an era in which unconventional monetary policy has been the central tenet of central banks’ policy framework. A reasonable question would be whether the market has been too entrenched in its expectation of prolonged accommodative monetary policy. Given various positive indicators at the time of the announcement, is such dependence healthy? Does quantitative easing’s role in ameliorating market turbulence have sound foundation or is it based purely on psychological signaling?

This thesis sets out to evaluate the power of quantitative easing (QE) to influence corporate bond volatility in two of the world’s biggest markets, the United States and the Euro area. Given their size, it would be no surprise that they also affect each other and other smaller but highly dependent markets. Spillover effect is hence also a major part of the research. The focus on the corporate bond market is justified by the fact that it, along with households, constitutes the private market that is the ultimate target of any kind of monetary policy. It is responsible for a large portion of both corporate financing and investment opportunities. Price and return stability in this area is thus of utmost interest to central bankers, who know that it would directly influence the macroeconomy.

By employing an extended EGARCH model with exogenous variables to broad-based corporate bond indices, this thesis discovers a few key lessons. QE in both areas are found to exert clear negative impacts on their respective domestic markets as well as each other’s markets with respect to volatility. In other words, QE periods witnessed general decrease in return volatility, while periods immediately following them were more volatile. But not all QE programs exhibited the desired behavior in the sample

¹ I would first like to thank Professor Roman Stepanov for his various suggestions that helped improve the clarity and accuracy of this research and, crucially, for his assistance in retrieving key data from Bloomberg.

period, which comprises both the Great Recession of 2008 and the European sovereign debt crisis. The ability of daily amount of assets purchased under the programs and the announcements to generate changes in volatility is generally either small or statistically insignificant. However, related changes in government securities price or returns are able to induce rather big changes in return volatility, attesting to the existence of the portfolio balance channel for QE.

The remainder of this thesis is structured as follows: Section 2 presents relevant literature that explores the theory and foundation of the effect of QE on financial markets. Section 3 outlines the econometric model and relevant data to answer the research questions. Section 4 presents and discusses the empirical results while Section 5 subjects such results to further robustness testing. Section 6 concludes.

2. LITERATURE REVIEW

There exists broad academic consensus that monetary policy, as implemented by central banks, plays a vital role in preserving a healthy economy. When economic activity declines due to adverse shocks from crises, this role becomes ever more prominent. The 2008 financial crisis exemplifies a situation in which central bank policy decisions, though insufficient to fully counter the consequences, alleviated financial and macroeconomic conditions and averted a full-scale collapse comparable to the 1930 Great Depression. Further, due to its severity, the last crisis also prompted all major central banks, including the Federal Reserve System (Fed), the Bank of England, and the European Central Bank (ECB), to utilize unprecedented measures that represented clear aberrations from their standard toolkit. A large body of literature has since investigated the impact of such unconventional monetary policies (UMPs) on various aspects of the financial market as well as the real economy. This thesis contributes to existing research by focusing on the volatility of the corporate bond markets. Specifically, it seeks to answer 3 key questions:

- 1) Do the size and timing of quantitative easing policies of the European Central Bank affect the volatility of domestically traded corporate bonds in the eurozone?
- 2) Does ECB bond purchase have a spillover effect on the volatility of US corporate bonds?
- 3) Does US bond purchase have a spillover effect on the volatility of eurozone corporate bonds?

Accordingly, the literature review will be structured as follows: *Section 2.1* delineates the conditions that justify the usage of UMPs, rather than conventional policies, in the first place. *Section 2.2* differentiates between quantitative easing and orthodox monetary policy. These 2 sections provide the context for further analysis answering the research questions. *Section 2.3* compares UMPs by the ECB and the Fed and provides potential explanations as to the differences or otherwise in results obtained for research questions 2 and 3. *Section 2.4* outlines the key theoretical and empirical research to which this thesis is most related, namely those on volatility and international effects of QE.

2.1 Quantitative easing and associated financial conditions

2.1.1 The Zero Lower Bound

Although UMP itself may vary in forms depending on each central bank, conventional monetary policy usually only refers to the manipulation of short-term interest rates at which central banks provide funds to banks or the interbank money market. According to Joyce et al. (2012), central banks base their determination of rates on a variety of macroeconomic signals and crucially on the so-called Taylor rule. In normal times, and even in mild recessions, these key policy rate decisions have a well-documented effect of maintaining low and stable inflation – 2% for most developed economies.

The severity of the 2008 crisis, however, meant that the Taylor rule would recommend negative interest rates. As Fawley and Neely (2013) note, assuming unconstrained choices, rational agents can, and will, always hold non-interest-bearing cash instead

of depositing it in negative rate banks. Therefore, short-term interest rate is said to have a Zero Lower Bound (ZLB), and conventional monetary policy was restricted as such in the crisis when the ZLB became binding. For practical reasons, however, central banks do not necessarily drive rates precisely to zero, but instead keep them a little above zero (Rogers et al., 2014). Indeed, interest rates in the euro area and the UK remained slightly positive even in periods where the ZLB was considered effectively binding (e.g. during 2010 and 2011, figure 1). However, some studies (e.g. Fahr et al. (2013)) argue against this conclusion, especially in the case of the euro area, leading to differences in comparison between UMPs of different areas, which is discussed in Section 2.3.

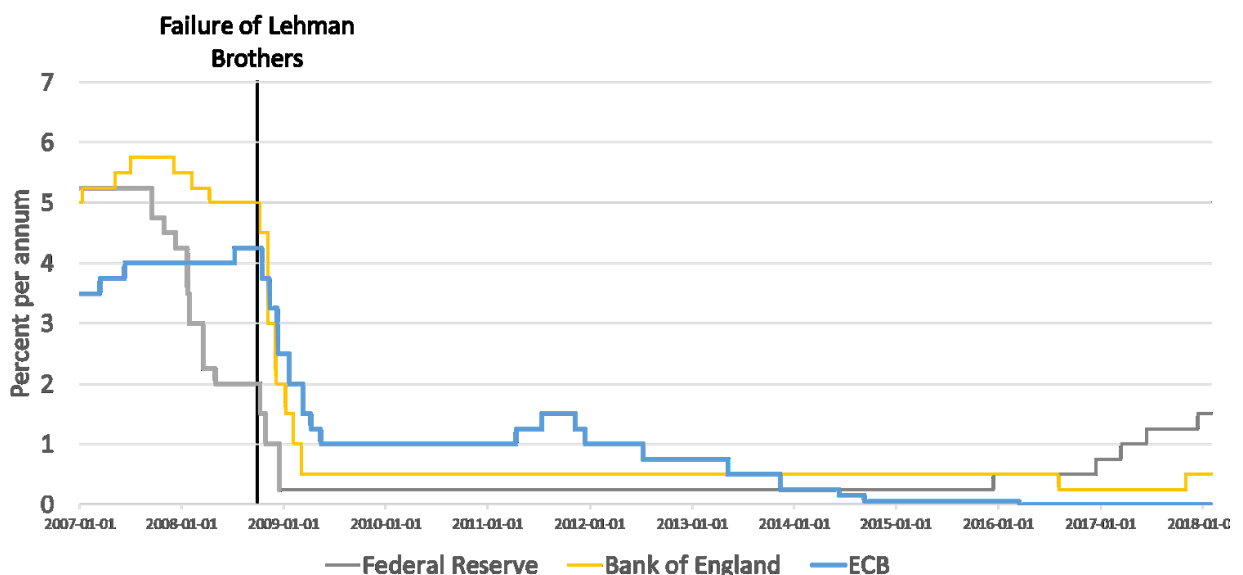


Figure 1: Evolution of key policy rates

Notes: Effective as of 16 December 2008, the target Fed Funds rate by the Federal Reserve is to be expressed as a range, e.g. 0-0.25% from 16 December 2008 to 16 December 2015. The grey line represents the upper limit of that range from 16 December 2008 onwards.

Source: Bank of England, Federal Reserve, ECB

In such situation, monetary policy works via manipulation of future rate expectations using UMPs, which aim to replace now ineffectual conventional policies (Lenza et al., 2010). Curdia and Woodford (2011) employ an extended New Keynesian model to prove the efficacy of credit easing, a specific form of UMP, when financial markets become disrupted enough to enforce the ZLB. Although they do not provide specific analysis, they also implicitly support the use of quantitative easing in similar

circumstances. As demonstrated next, such disruption occurred primarily in the financial sector.

2.1.2 The breakdown of financial intermediation

Giannone et al. (2011) identifies the collapse of financial intermediation as an important step that propagated the deleterious impact of the 1930 Great Depression. Financial intermediaries are central to the transmission of monetary policy to the macroeconomy in all regions, but especially so in the euro area. They fulfil this role by providing loans to the private sector, thereby transforming changes in key policy rates to changes in market rates, which in turn help price all fixed income securities.

After the collapse of Lehman Brothers, solvency concerns about other banks arose in the interbank market. According to Giannone et al. (2012), information asymmetry exacerbated the situation, leading to adverse selection, resulting in some institutions being barred from the interbank market altogether due to their heightened credit risk. Heider et al. (2009), by modeling the interbank market, suggest that such stigmatization can result in the freezing of the interbank market, as it indeed did. If one institution refuses to provide wholesale funding to its counterparties, other institutions may feel pressured into doing likewise, culminating in a rapid spiral of forced deleveraging (Giannone et al., 2012).

Moreover, to the extent that banks are perturbed by their solvency, they are incentivized to hoard cash instead of lending them out. Both reasons seriously impaired the transmission channel of monetary policy, further demanding central banks to consider other alternatives. Unsurprisingly, as discussed below, these unconventional alternatives aimed to either replace or recover financial intermediation in both the US and the euro area, despite implementation differences.

2.2 Quantitative easing versus short-term interest rates instruments

To properly understand the impact of UMPs on financial markets, this section seeks to compare UMPs to previously mentioned conventional interest rate innovations.

2.2.1 Definition of quantitative easing

Despite a decade's worth of research on unconventional alternatives at the ZLB, there seems to be inconsistency in academics' definition of what constitutes UMPs. According to Bernanke et al. (2004) and as summarized by Lehto (2014), the alternatives can be roughly categorized into 3 groups:

- Expectations management via communication strategies: e.g. by signaling commitment to a future interest rates path
- Quantitative easing (QE): Expansion of monetary base, specifically the central bank balance sheet, by providing banks with excess reserves
- Credit easing (CE): Changes in the composition of the central bank balance sheet by purchasing unconventional assets.

In the case of CE, conventional assets are understood as Treasury securities. Since the latter two measures are not mutually exclusive, Bernanke (2009) further differentiates between QE (as practiced by the Bank of Japan the early 2000s) and CE by stating that while QE focuses on the *quantity* of bank reserves (the central bank's *liabilities*), CE stresses the *composition* of loans and securities (the central bank's *assets*). If CE does not also involve the expansion of the monetary base, it fits Lenza et al.'s (2010) description of *qualitative easing*. Since this was not the case in the period sampled, this thesis is not interested in this concept. Joyce et al. (2012) and Curdia and Woodford (2011) define CE as the provision of credit directly to the private sector via purchases of private sector assets. This captures the fact that CE, as practice by the Fed, extends the purchases to include corporate bonds, agency debt, and mortgage-backed securities - so-called "unconventional assets." Giannone et al. (2011) add some nuances by characterizing QE as "purchases of assets in functioning and liquid market", although it is unclear what qualifies as "functioning" and "liquid." It can be inferred from Joyce et al (2012) that this might refer to the market for

government bonds/bills. In this 2008 crisis, however, Ueda (2009) argues that many central banks employed a mixture of both.

The differentiation between QE and CE with respect to the composition of assets purchased could be important in explaining the impact of policy on the corporate bond market, whose assets were purchased in CE and not QE regimes (according to the *strict* definitions above). For practical purposes, however, **quantitative easing (QE)** in this paper hereinafter refers to the expansion of the monetary base via purchases of government and non-government securities.

2.2.2 Comparison between QE and short-term interest rates instruments

Precisely because of its relative novelty, and that its creation was not supported by previous academic research, there exists relatively less historical evidence and empirical research substantiating QE's efficacy. Traditional frameworks to assess monetary policy have also proved unsuccessful (Fahr et al., 2013). Among existing literature, however, most academics concur that QE has been successful in lowering medium to long-term bond yields (Gagnon et al. (2011), Krishnamurthy and Vissing-Jorgensen (2011), Hamilton and Wu (2012), Joyce et al. (2012), among others). Consequently, QE has the effect of flattening the yield curve when the short-term rate is at the ZLB. This is in sharp and most significant contrast with conventional monetary policy, which targets short-term interest rates. It should hence have muted influence on the other end of the yield curve, which is in fact more relevant for investment decision making and is the desired target of monetary policy. This puzzle about standard policy that Bernanke and Gertler (1995) point out has been partially resolved by QE.

Regardless, QE is certainly not without shortcomings. A report titled "Quantitative easing: Implications for bond market volatility" (2012) points out that QE serves as the monetization of government deficit via the creation of bank reserves. Evidently, the ensuing loss of foreign investors' confidence in the national currency could cause an exchange rate collapse, and, if uncontained, a sovereign crisis. Joyce et al. (2010) emphasizes that UMPs such as QE should only be deployed so long as the ZLB constrains the potency of traditional methods, not as a panacea.

Another crucial aspect where QE differs from its orthodox peer is its overt emphasis on quantity. As Hamilton and Wu (2012) suggest (but have not empirically tested), doubling the amount of asset purchased could double the effect on yields and, naturally, the amount of bank reserves. Meanwhile, in normal times, orthodox policy targeting key interest rates functions via open market operations in which central banks sell or buy securities from the banking sector, thereby influencing the level of reserves the sector holds at central banks. Crucially, these fluctuations in reserves are the by-product, not the intended effect, of monetary policy (Joyce et al., 2010). Furthermore, these market operations are designed to exert negligible impact on asset prices since their size is small compared to the overall Treasury securities market (Gagnon et al., 2011). For QE, the opposite is true: its unprecedented proportion had a strong impact on yields and ultimately asset prices.

2.3 Overview of ECB and Fed QE programs

Despite sharing the fundamental characteristics just outlined, QE programs by the ECB and the Fed are by no means identical. Differences in financial structures of both parties necessarily warrant different designs of asset purchase programs. Such differences are not as drastic between the Fed and the Bank of England as they are between the Fed and the ECB, justifying the comparison between the latter.

2.3.1 Nonstandard monetary policy and QE programs in the euro area

Details of both conventional and unconventional measures implemented by the ECB since the onset of the crisis are not only readily available from its website but also well-documented in literature (see Lenza et al. (2010), Giannone et al. (2011, 2012), Fawley and Neely (2013), among others). Notwithstanding, since the ECB abstained from outright major asset purchases for a long period, its early measures, though unconventional in nature, cannot be characterized as QE. Later measures, notably the large-scale asset purchase programs, are scarcely researched due to their relatively more recent implementation. Yet it is these measures that are of utmost interest to this

thesis as they are directly comparable to those practiced in the US and provide some contrast to the policies implemented earlier in the euro area itself. However, an overview of *all* ECB UMPs is presented next, followed by a comparison to that of the US.

After Lehman Brothers collapsed, and before the initiation of QE, Joyce et al. (2012) identify repo operations as ECB's distinct tool. Essentially, the ECB buys the security while simultaneously agreeing to sell it again if needed (Lenza et al., 2010). They describe this trade as a "collateralized loan of central bank liquidity." Prior to the collapse, this provision was conducted via one-week repos with variable rate tender. After the collapse, the ECB embarked on a **fixed rate full allotment (FRFA)** regime, where liquidity was provided in *unlimited* amount at price conditions determined by the ECB (Giannone et al., 2011). Due to heightened demand for liquidity in a dysfunctional market, this created a significant increase in ECB balance sheet size, though negligible when compared to that of the Fed. Further, the list of eligible collateral and the average maturity of repos were also expanded, up to 36 months in the case of the latter (Lenza et al., 2010).

On May 7, 2009, the ECB introduced the €60 billion covered bond purchase program (CBPP) to alleviate the stress on the covered bond market. This represented only 2.5% of the outstanding bonds (Fawley and Neely, 2013). Further, then-ECB President Jean-Claude Trichet explicitly emphasized that CBPP was not QE, nor would it expand the ECB balance sheet. Subsequent programs (CBPP2 launched in November 2011 and the on-going CBPP3 in October 2014) also pale in comparison to the size of Fed asset purchase programs. However, they involve more significant private sector asset purchases than any other central banks (*ibid.*), which should have a direct impact on such sector (Gagnon et al., 2011), including the corporate bond market as investigated in this thesis.

In May 2010, the ECB announced the Securities Markets Program (SMP), which was later replaced by Outright Monetary Transactions. Both programs aimed to address the European sovereign debt crisis by purchasing government debt in the secondary market (Fawley and Neely, 2013). Crucially, as the ECB clarified, they did not have a

specific target purchase amount, nor would they expand the monetary base. Like the CBPPs, they did not constitute QE.

While most of the aforementioned programs are *sterilized* (Valiante, 2017) in the sense that their net impact on the monetary base is trivial, the asset purchase programs (APPs) introduced after November 2014 involved the expansion of the ECB balance sheet in non-trivial amounts compared to US QE programs. Therefore, they fit the above definition of QE. These programs comprise of CBPP3 as well as the Asset-backed securities purchase program (ABSPP - introduced November 2014), Public sector purchase program (PSPP – March 2015), and Corporate sector purchase program (CSPP – June 2016). As illustrated in figure 2, PSPP overwhelmingly constitutes the bulk of purchases.

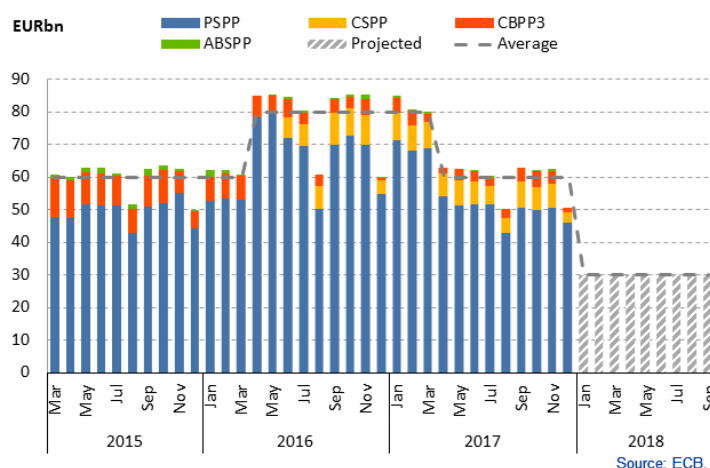


Figure 2: ECB Asset purchase programs monthly net purchases, by program

Because these programs represent relatively recent developments in the ECB policy framework, little empirical research has been done to study their impact. Valiante (2017) is a rare example, using a difference-in-differences approach to show that PSPP has significantly impacted long-term interest rates, thereby soothing the market and flattening the yield curve.

2.3.2 Asset purchase programs by the Federal Reserve System

Belke et al. (2017) present a concise, up-to-date summary of all UMPs conducted in the US in response to the crisis. Rather than reiterating, this paper shall only emphasize the key feature: large scale asset purchase programs. These programs, starting in November 2008 and ending in October 2014, accumulated \$4.4 trillion in assets (Figure 3). The analyses to be conducted, however, will also consider the Maturity Extension Program (MEP), in which the Fed financed the purchase of 6-30 years Treasury bonds with the sale of bonds whose maturities were less than 3 years. As its name suggest, MEP “extends” Fed’s portfolio maturity with little to no changes to its balance sheet (Belke et al., 2017).

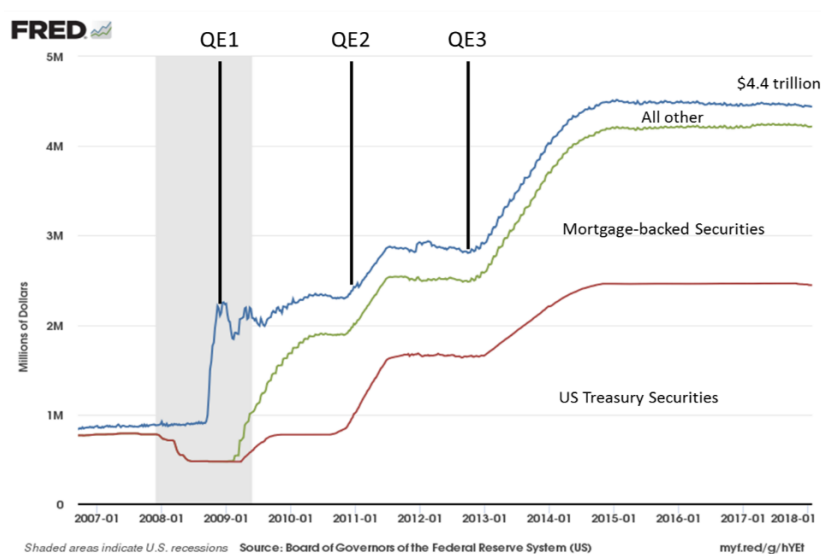


Figure 3: Evolution of the Federal Reserve Balance Sheet

2.3.3 Differences between ECB and US nonstandard measures

As a whole, the Fed’s asset purchase programs expanded its balance by about \$3.5 trillion, roughly 20% of 2014’s GDP (ibid.). Compared to the pre-crisis period, the balance sheet has increased more than five-fold. This increase dwarfs the increase of the ECB’s balance sheet in the periods preceding its asset purchase programs (Figure 4). However, it is also evident from Figure 4 that the ECB had had a significantly larger balance sheet at the onset of the crisis. Hence, as Lenza et al. (2010) argue, the expansion of monetary base via nonstandard operations to accommodate larger demand for central bank liquidity was proportionally smaller. As such, the size of the increase could be attributed to different starting conditions.

Similarly, they also point out that the ECB had also been carrying out large repos operations, with allotments up to €300 billion, dwarfing the Fed's \$30 billion. It had always had access to nearly 2000 counterparties in the interbank market compared to the Fed's meager 20. Finally, whereas the Fed limited eligible collateral primarily to US Treasuries and government agency bonds, the ECB had accepted a wide array, including asset-backed securities. Consequently, the paper concludes that few alterations to existing framework were needed for the ECB to accommodate increasing stress in the market. For the US, more substantial measures were warranted.

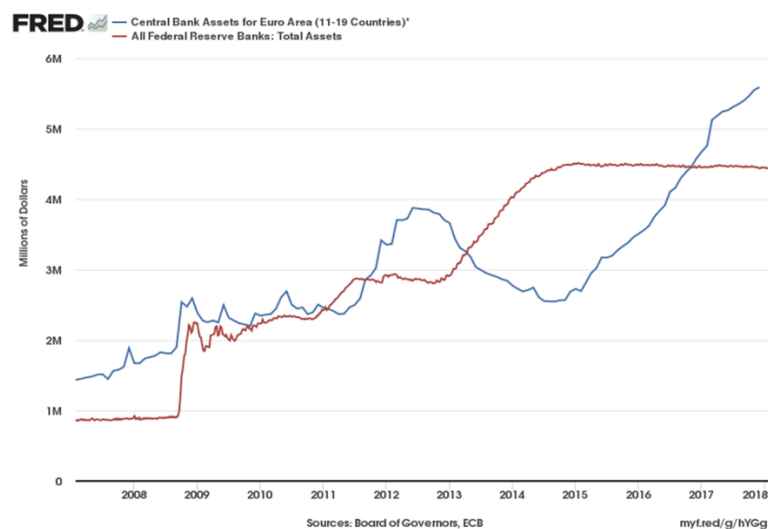


Figure 4: Evolution of the ECB and the Fed Balance sheets

The ECB also differed from the Fed in its choice to deal overwhelmingly with the interbank market, rather than extending its facilities to a broader range of counterparties. Perhaps ECB President Trichet provides the best explanation by indicating in his 2009 speech the “profound differences in their financial structures.” Specifically, while the banking sector in the euro area provides 70% of firms’ external financing, the figure is considerably smaller in the US, where market-based sources play an integral role. The ECB was then left with no choice but to opt for direct central bank intermediation as the collapse of financial intermediation would have a detrimental impact on the macroeconomy.

That being said, it eventually adopted outright purchase programs, including private sector assets, that resulted in the rapid expansion of its monetary base (Figure 4). Valiante (2017) suggests existing measures were insufficient to boost the bank lending that is so essential for improved economic growth and inflation, which contradicts early theoretical findings by Lenza et al. (2010). Lehto (2014) attempts to explain such late adoption by citing burdensome politics as a factor that precludes the ECB's freedom to adopt early and sizeable QE programs, instead opting for collateralized lending. Indeed, recent APPs are crucially constrained by the 25% limit, prohibiting holdings exceeding 25% of total eligible debt securities from an issuing national state (Claeys et al., 2015). This stems from the restrictions set forth by the Lisbon Treaty that prevent the Eurosystem from conducting purchases that can be conceived as sovereign bailouts or monetary financing (Rogers et al., 2014). Thus, per Claeys et al.'s (2015) calculations, the programs may have to end prematurely, with total purchases less than the planned amount, to avoid breaking this rule. This diminished quantity, along with the focus on the financial sector, might well create a more muted influence on the corporate market than the Fed's program.

Fahr et al. (2013) use a DSGE model to estimate the hypothetical impact of US QE, were it to be implemented in the eurozone, and provide supportive conclusion for its usage. However, they caution that this result would hold only under the assumption that monetary policy transmission is not impaired, which is not as applicable to the euro area as it is the US. Despite all these differences, many authors (such as Fahr et al., 2013, Lenza et al., 2010, Giannone et al., 2012) agree that they arise from the different structure of the financial systems across the Atlantic, and that the two areas share more similarities than often argued.

2.4 The impact of QE on corporate bonds

The bond market is the linchpin of a well-functioning economy. They account for a considerably portion of institutional investors' portfolio. From a corporate finance perspective, it is preferable to obtain financing via debt to equity. As indicated, the bond market, either the interbank market or the corporate bond market, accounts for

most of external financing in Europe and the US (Trichet, 2009). Therefore, it is hardly any surprise that most research on QE focuses on its impact on the bond market, rather than the equity market.

Nevertheless, this body of literature predominantly studies relatively riskless assets, namely Treasury securities, with fewer academics studying the impact on riskier instruments such as corporate bonds. A probable explanation is that QE programs entail primarily purchases of such risk-free assets. As such, their impact should be most pronounced for the markets of those assets. For example, Krishnamurthy and Vissing-Jorgensen (2011) imply that purchases of mortgage-backed securities in US QE1 drive large reductions in mortgage rates. Regarding announcement effects, Rogers et al. (2014) prove that assets that central banks intend to buy witnessed the most dramatic move in prices. On the international level, due to imperfect correlation between global bond returns, the reduction in US bond yields due to an announcement of US bond purchase should be greater than that in foreign bond yields (Neely, 2011).

Regardless, Joyce et al. (2012) rightly point out that the ultimate target of monetary policy is the private market, i.e. households and corporations. The spillover effect from the purchased assets to private assets that were largely left untouched is partially established within QE research. According to portfolio balance theory, investors consider different asset classes as (imperfect) substitutes. The QE-induced reduction in yields of purchased assets such as Treasury or mortgage-backed securities renders other classes, such as corporate bonds, more attractive (Gagnon et al, 2011). The ensuing increase in demand for these substitutes bids up their prices and lowers their yields. However, the paper finds that this spillover effect is not as sturdy as the original impact on the purchased assets. Although the ECB, via CBPPs or CSPP, does purchase private assets outright, the quantity is not comparable to that for sovereign-backed, safer securities. Similarly, Rogers et al. (2014), who survey the US, UK, euro area, and Japan, find that the spillover from bond yields to other asset prices is most pronounced for the US.

A few papers directly assess the impact of unconventional policies on the corporate sector rather than abstracting from investigations of government bonds. Lo Duca et al. (2015) establish a connection between the rise in global corporate bond issuance,

especially in emerging markets, and US QE. They argue that the issuance serves as a tool to fill the supply “gap” created by large-scale asset purchases by the Fed. A reasonable inference is that QE successfully increased investors’ risk appetite and stimulated demand for riskier assets. Approaching from a different aspect, Gilchrist and Zakrajšek (2013) employ both the event-style regression and identification through heteroskedasticity to quantify the effect of US QE announcements on corporate credit risk of both the financial and non-financial sector. However, their results only indicate a reduction in corporate credit risk for the non-financial sector, including corporations, using the latter method.

Despite uncertainty in findings, both papers above contribute to relatively underresearched areas within the QE literature: the former studies the international effect of QE and the latter tackles a rather novel dependent variable – credit risk. These two aspects are also the main contributions of this thesis, which studies the impact of US and ECB QE on corporate bond volatility, considering cross-country spillovers. It also updates the narrative to include the newly implemented ECB asset purchase programs.

2.4.1 International effects of QE programs

Compared to the domestically-oriented research, the literature for the international effect of QE, especially US QE, is smaller yet growing. Neely (2010) is one of the pioneers in the topic. His paper is strongly related to Gagnon et al. (2011), retaining the focus on long-term risk-free yields and the portfolio balance channel. Just as Gagnon et al. (2011) use the portfolio balance channel to explain the spillover effect from purchased assets to other assets, Neely (2010) applies the same channel for foreign assets with attractive yields. Also using an event study, he concludes that US QE announcements immediately reduced long-term US and foreign bond yields and simultaneously depreciated the dollar. Figure 5 generally validates this conclusion, with long-term government bond yields plunging at or in anticipation of the commencement of US QE and only rebounded during US QE3 when recovery was well underway. Overall, yields of all economies saw drastic reductions vis-à-vis the pre-QE levels, except for Japan, which has always had stable, low interest rates.

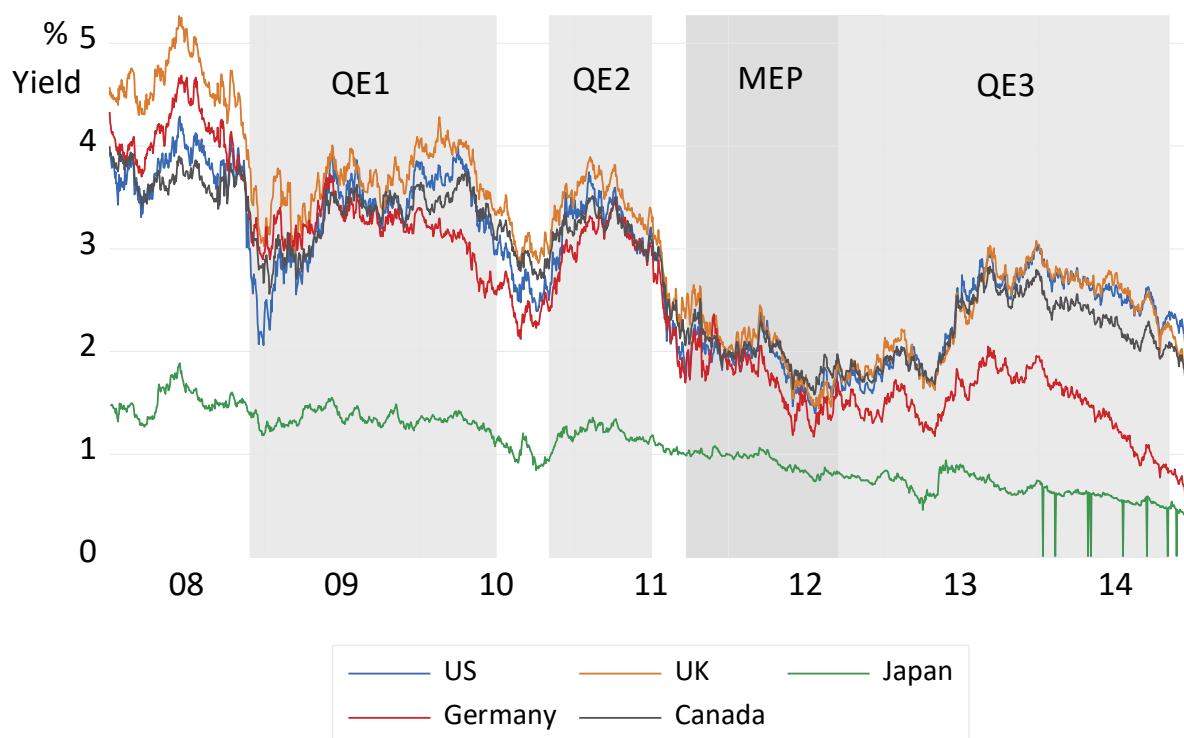


Figure 5: Evolution of select 10-year government bond yields over the course of US QE.

Source: Investing.com

Subsequent studies expand the narrative to consider other transmission channels, namely the signaling channel, and the cross-country conditions that best support each channel (Bauer and Neely, 2014)². They find that while signaling effects are most prominent for countries with strong yields response to US conventional monetary announcements like Canada, portfolio balance channel is the key transmission mechanism for countries whose yields covary with US yields (Germany, Australia).

The international signaling channel rests on the premise that a central bank's policy is informative of that of its foreign counterpart (ibid). Indeed, such policy rate linkage is evident in reality, especially for countries that are very economically integrated. In fact, it contributed to the propagation of the crisis in the first place, consistent with theory of financial contagion. Financial contagion refers to the "significant increase in cross-market linkages after a shock to an individual country" (Dornbusch et al.,

² For a detailed discussion of all QE transmission channels, see Krishnamurthy and Vissing-Jorgensen (2011)

2000). It is the propagation of that (mostly negative) shock to linked economies, resulting in the covariance of exchange rates, equity prices, bond spreads, and capital flows. One of its fundamental cause is competitive devaluations, wherein crisis-induced devaluation of a country's currency puts pressure on another currency in terms of export competitiveness in a third market. Subsequently, both currencies exhibit strong comovements that could lead to a full-blown currency war (ibid). As acknowledged in section 2.2.2, QE as a tool to address the crisis and contagion may actually risk increasing the likelihood of such a disastrous event. However, as Bauer and Neely (2014) indicate, that shortcoming may be more than compensated for by the fact that exchange rate stabilization, i.e. restrained devaluation, can engender closer alignment of central banks' policies, thereby catalyzing the salutary effects of the signaling channel. Along with perceivably very strong regional economic ties, it might culminate in clear Canadian yield response to US monetary policy, as mentioned above. Therefore, although contagion largely denotes deleterious shocks, its transmission mechanism may also help administer the cure that is QE.

A promising explanation for the strong portfolio balancing channel between US QE and Germany and Australia, again drawing on financial contagion theory, is the solid financial link between the countries via large cross-holdings. As per Kaminsky and Reinhart (1998), the interregional holdings serve as strategic hedging against macroeconomic risks that is essential for global financial portfolio diversification. It could be these holdings that caused considerable covariance in the excess returns of these government bonds, as discovered in Bauer and Neely (2014). German and Australian bonds could also be viewed as relatively good substitutes for US bonds, whose supply is drastically slashed under QE programs. With higher contagion likelihood and stronger portfolio balancing, we can therefore expect higher volatility response to foreign large-scale asset purchases from these country pairs.

From a different perspective, these financial linkages expedited the increase in illiquidity in international interbank market, thus helping the crisis spread. Brunnermeier and Pedersen (2008) note that a shock to investor's funding constraints, causing liquidity demand to overpower supply, increases market volatility via a rise in risk aversion and liquidation of positions, culminating in even more illiquidity. Allen and Gale (2000) further stress that this liquidation takes place first

and foremost with claims on other regions, denying liquidity to those who need it the most. This is the fundamental cause of international financial contagion via the liquidity channel because of cross-holdings. Importantly, however, central bankers can again utilize this channel to deliver QE. To the extent that illiquidity causes spikes in cross-region volatility, the pumping of liquidity via central bank asset purchases into the markets should reduce volatility in all regions.

Overall, while the signaling and portfolio balancing channels explain how QE has its international effects, expected and observed variations in those effects between countries are best accounted for by the linkages between them. The stronger the link, the more pronounced QE's impact on the market's bond volatility.

On a different but related note, Craine and Martin (2008) find that US conventional monetary policy surprise impacts the Australian market but surprises from Australia have little relevance for the US equity market. This asymmetry apparently also applies for UMPs, with the influence of US shocks on non-US (British, European, Japanese) yields much more considerable than those of non-US shocks on US yields (Rogers et al., 2014).

2.4.2 QE and corporate bond volatility

The key contribution of this thesis is the emphasis on a new dependent variable – bond volatility. An increase in investor perception of volatility will make them demand more premium to hold long-term government bonds, which in turn makes government financing less accessible (Steeley & Matyushkin, 2014). Since government spending constitutes a significant portion of GDP in major economies, this dampens the very economic growth that QE is designed to stimulate. For the riskier corporate bonds, the effect may be even more drastic. Cai and Jiang (2008) demonstrates that corporate bond volatility has strong predictive power of corporate excess returns.

As shown by Figure 6, the US Treasury market volatility, measured by the MOVE index, has been on a steady decline since its peak in the financial crisis. This downward trend in bond market volatility may be attributed to successful implementation of QE for several reasons. First, the market may interpret central

banks' activist role in the market as a sign of a stable future path of interest rates—consistent with the signaling channel, reducing uncertainty around the key input to bond pricing. Second, due to documented soothing effect of QE, it can also affect volatility via the reduction of credit risk and default risk premia (Gilchrist and Zakrajšek, 2013). In other words, the market may feel more assured given the intermediation by central banks. Third, via the portfolio balance channel discussed, QE increases demand for relative high-yield corporate bonds, thus potentially creating more stability in demand. These bases for the investigation of corporate bond volatility is summarized in the conceptual framework below (Figure 7).

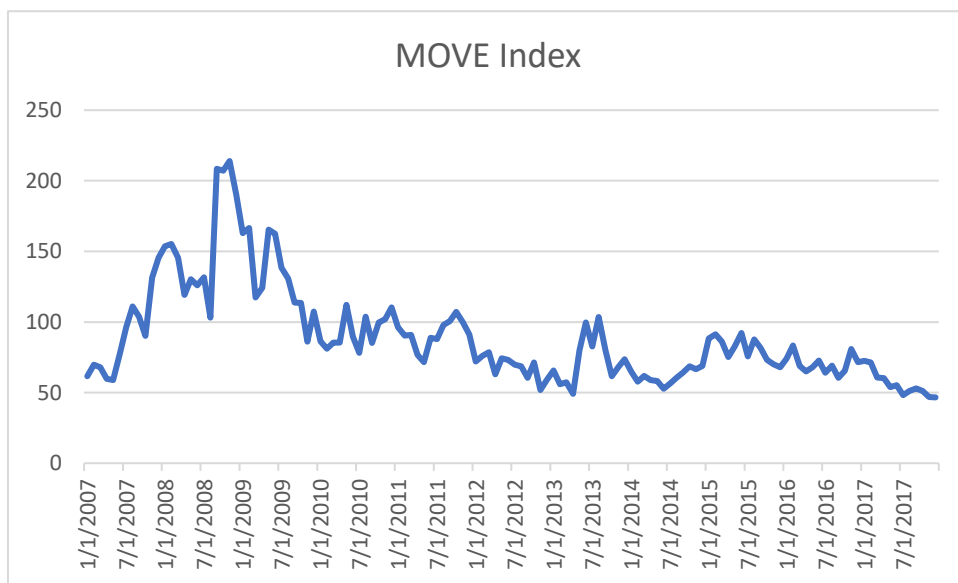


Figure 6: Merrill Lynch Option Volatility Estimate (MOVE) Index. Source: Bloomberg

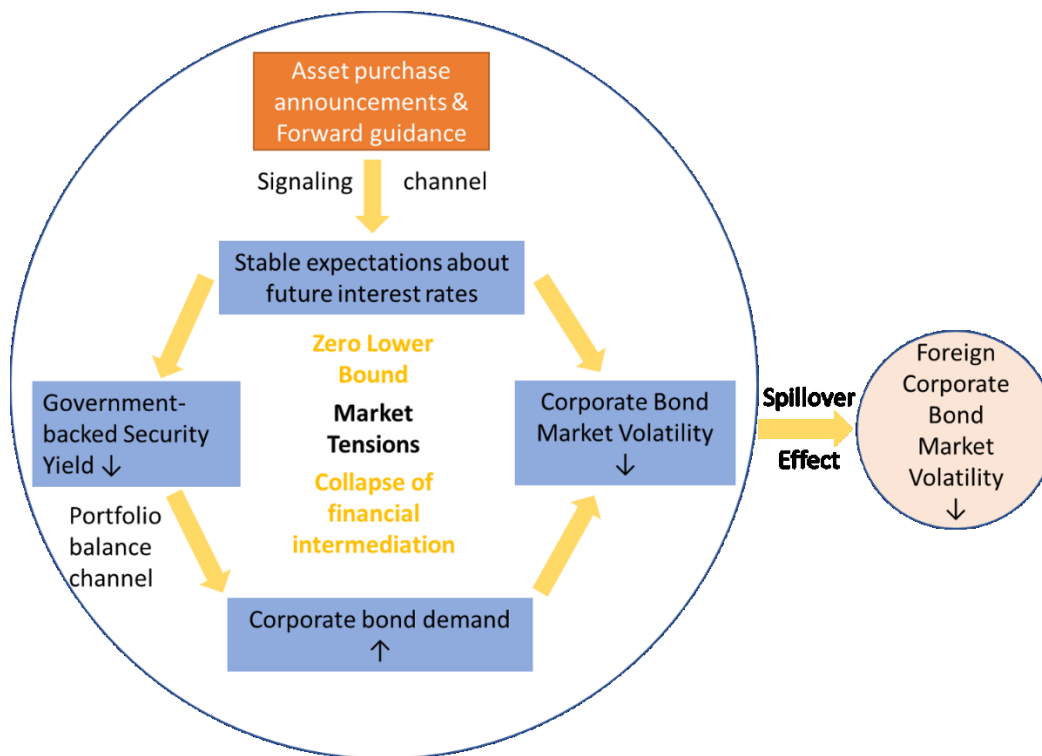


Figure 7: Conceptual Framework

Table 1 provides a summary of the key research on which this thesis draws significantly. Generally, research on volatility heavily utilizes generalized autoregressive conditional heteroskedasticity (GARCH) models. Those focusing specifically on QE find that it has a negative impact on volatility. However, results have focused more on equity market than bond markets, and none pertains to the corporate bond market. The very recent European APPs are also not considered.

Paper	Focus	Methodology	Conclusion
Tan and Kohli (2011)	Impact of US QE on US stock market volatility	AR (1) for VIX and GARCH (1,1) for S&P 500 as well as modified CEV model	US QE1 and QE2 reduced stock market volatility, but their conclusion increases volatility
Shogbuyi and Steeley (2017)	QE by BoE and Fed and UK, US, Germany, France,	Univariate and multivariate GARCH	QE reduced equity volatility, domestically and internationally, but UK QE actual purchase

	Japan equity markets		days saw volatility increases
Steeley and Matyushkin (2014)	UK QE and the gilt market return volatility	GARCH and event study	QE reversed the six-fold increase in gilt volatility when the crisis starts
Steeley (2017)	Volatility of stocks, short-term and long-term UK bonds	GARCH (1,1)	UK QE ^{1,2,3} reduced stocks and bond volatility to pre-crisis levels
Christiansen (2003)	Volatility spillover from US and aggregate European bond markets into individual bond markets	AR-GARCH. Countries divided into European Monetary Union (EMU) and non - EMU countries.	For EMU countries, own country and EU effects significant while US effect negligible.
Hamao et. al. (1990)	Stock market price change and international price volatility effects	MA (1) – GARCH (1,1)	US and UK volatility had spillover effect on the Japanese market

Table 1: Summary of key research on QE and volatility/volatility spillovers

3. METHODOLOGY

3.1 Quantitative easing and conditional volatility

Following the convention in volatility modelling, this thesis will utilize the popular *generalized autoregressive conditional heteroscedasticity* (GARCH) family of statistical processes, first introduced by Engle (1982) and Bollerslev (1986), to jointly model the mean and variance processes of corporate bond returns, with emphasis evidently placed on the latter. In particular, an extended version of the standard GARCH – the exponential GARCH (EGARCH) (Nelson, 1991)– is used. We will begin with a brief overview of the ARCH models before specifying the model to be fitted to the data.

The key motivation for Engle's (1982) seminal work introducing the ARCH model is to provide a tool to forecast volatility. One would desire to do this exercise for either risk management, asset allocation, or derivatives pricing and strategy (Reider, 2009). Before ARCH, academics had practically ignored the need to forecast volatility in favor of mean returns (Engle, 2001). ARCH tackles an intrinsic assumption in the least square models – homoscedasticity of the error term, i.e. constant volatility. In practice, by casting even a cursory look at *some* financial time series data, such as those to be examined here, one could find evidence contradicting this. Volatility clustering, meaning some periods are riskier than others, is an acknowledged stylized fact about time series (Cont, 2001). Instead of assuming homoscedasticity, Engle (1982) attempts to capture and model heteroscedasticity of asset returns, thereby providing a measure for *conditional, non-constant* volatility. In addition, the model also captures other facts about asset returns, namely autocorrelation of squared returns, volatility mean reversion, and excess kurtosis (Reider, 2009).

In the basic ARCH(1) process,

$$R_t = \mu + \epsilon_t$$

$$\epsilon_t \mid \Omega_{t-1} \sim N(0, \sigma_t^2) \text{ where}$$

$$\sigma_t^2 = \alpha_0 + \alpha_1 \epsilon_{t-1}^2 \text{ with } \alpha_0 > 0 \text{ and } 1 > \alpha_1 \geq 0$$

ϵ_t is the error term that captures excess return whose conditional variance σ_t^2 is a positive linear function of the squared of last period's error term. It is assumed to be conditionally normal here, but that assumption could be changed to Student's t or GED distributions, both of which can have fat tails. From the model, one can extract this conditional variance series and forecast ahead for as long as is needed. Bollerslev (1986) then generalizes the model to create GARCH by also permitting lagged conditional variance to influence the current conditional variance. Therefore, under a GARCH (1,1) specification,

$$\sigma_t^2 = \alpha_0 + \alpha_1 \epsilon_{t-1}^2 + \beta_1 \sigma_{t-1}^2 \text{ where } \alpha_0 > 0, \alpha_1, \beta_1 \geq 0 \text{ and } \alpha_1 + \beta_1 < 1$$

Note that the nonnegativity constraints imposed on the parameters in both ARCH and GARCH ensure that σ_t^2 can never be negative. Nelson (1991), in his paper introducing EGARCH, argues that these constraints are "often violated by estimated coefficients" and "may unduly restrict the dynamics of the conditional variance process". Further, they could have destabilizing effects on the estimation of model parameters. It therefore makes sense to replace these constraints. In EGARCH, the same nonnegativity requirement of σ_t^2 is satisfied by taking the natural log of σ_t^2 without having to impose any constraints of the parameters as in the linear version.

Further, since σ_t^2 is a function of past **squared** error ϵ_{t-1}^2 , only the size and not the sign of that lagged error term, which also proxies for shock and its resultant excess return, impacts current variance. Thus, the underlying assumption is that ϵ_t – the shock – is symmetric in its effect on volatility. In reality, many researchers, starting with Black (1976), find that market declines seem to cause higher volatility than do market increases of equivalent magnitude. This is particularly true for broad-based equity and bond market indices, as those studied here (Engle, 2001). EGARCH addresses this inconsistency by modelling both the *sign* and the *size* of the shock. Overall, its main advantages over GARCH are two-fold: 1) It simplifies GARCH by removing problematic constraints 2) It enhances GARCH with a term that captures an additional stylized fact about returns – asymmetry of shocks.

With a good understanding of the underlying model, we now proceed to specify it. The basic model is specified as follows:

$$R_{i,t} = \alpha_{i,0} + \sum_{j=1}^p \theta_{i,j} D_{i,j,t} + \alpha_{i,1} QEInt_{i,t} + \alpha_{i,2} QEAnn_{i,t} + \alpha_{i,3} Gov_{i,t} + d_{i,1} R_{i,t-1} + \epsilon_{i,t} \quad (1)$$

$\epsilon_{i,t} | \Omega_{t-1} \sim G(0, \sigma_{i,t}^2, \kappa)$ where

$$\ln(\sigma_{i,t}^2) = \omega_i + \alpha_i \left[\frac{|\epsilon_{i,t-1}|}{\sqrt{\sigma_{i,t-1}^2}} - \sqrt{\frac{2}{\pi}} \right] + \gamma_i \frac{\epsilon_{i,t-1}}{\sqrt{\sigma_{i,t-1}^2}} + \beta_i \ln(\sigma_{i,t-1}^2) + \sum_{j=1}^p \phi_{i,j} D_{i,j,t} + \lambda_{i,1} QEInt_{i,t} + \lambda_{i,2} QEAnn_{i,t} + \lambda_{i,3} Gov_{i,t} \quad (2)$$

where $R_{i,t}$ represents the log return on the corporate bond index at time t , $i \in [US, EU]$. In spillover analyses, the regressors remain the same (except for AR terms) while the

dependent variable is changed to the return of the other party. Ω_{t-1} denotes the information set that comprises all available information at time $t - 1$. Though unexpected, the European return series do exhibit autocorrelations as discussed below. This warrants the inclusion of the AR(1) term in equation (1). As mentioned, the key contribution of EGARCH is its ability to capture asymmetry in the impact of positive and negative shocks. In equation (2), the second term indicates the *size* of the shock while the *sign* of the shock is captured by the third term. In line with observations of asymmetry skewed towards negative shocks, γ is therefore expected to be *negative* and α *positive*.

Exogenous variables are added to both the conditional mean and conditional variance equations to capture the effect of quantitative easing. First, a set of dummy variables denote periods of asset purchases, taking value 1 in those periods and 0 otherwise. For the US, 4 dummy variables ($p = 4$) represent QE1 (November 25, 2008 to June 30, 2010), QE2 (November 3, 2010 to June 30, 2011), MEP (September 21, 2011 to December 31, 2012), and QE3 (September 13, 2012 to October 31, 2014). For the eurozone, 6 dummy variables ($p = 6$) represent CBPP (July 2, 2009 to June 30, 2010), CBPP2 (November 3, 2011 to 31 October 2012), CBPP3 (20 October 2014 – present), ABSPP (21 November, 2014 – present), PSPP (March 9, 2015 – present), CSPP (June 8, 2016 – present). As mentioned, though the small size of the CBPPs may disqualify them as true QE, they are still relevant because they involve outright purchases of private sector assets.

Second, the variable $QEInt_t$, first used by Shogbuyi and Steeley (2017), indicates the intensity or size of the asset purchases. Unlike the original paper, it is not separated according to different QE periods. The value of the variable on day t is calculated by taking the ratio of purchases on that day to the daily average of all prior purchases.

Third, announcement effects are also accounted for by another dummy variable, $QEAnn_t$, taking value 1 on days with QE-related policy announcements and zero otherwise. Ideally, a standard event study, as employed by numerous studies about QE mentioned above, may better capture this effect, although the vast majority only pertains to bond returns. Steeley and Matyushkin (2014) is a rare case that conducts a volatility-based event study. However, to include other factors, they also have to use

a regression-based setting with the dummy variable. Details about announcements of interest are provided in Table 2. Since the Fed releases its FOMC announcements at 14:15 EST, their influence on European markets only manifests on the subsequent business day (Abad and Chuliá, 2013). Thus, when modelling spillover from the US to Europe, the variable is lagged by one period.

Finally, following Rogers et al. (2014), the model includes a variable related to government bond yields (Gov), proxying for monetary policy surprises. The intent is to measure the spillover from government securities, the most purchased assets, to private sector assets such as corporate bonds, the final target of any QE program. The variable is thus a testament to the existence of the portfolio balance channel. Based on wide consensus of QE research on government bonds mentioned in the previous section, central banks' power to impact their government bond yields is taken as axiomatic. The variable is measured as daily changes in government bond yields/prices. For the US, the chosen security is the 10-year Treasury futures. A positive change in its price means a reduction in the 10-year rate and a more accommodative monetary policy, such as QE. Hence the associated coefficient λ_3 is expected to be *negative*, i.e. a price increase/rate decrease reduces volatility. For the eurozone, the daily change in the Italian-German 10-year bond spread is used to reflect the unique supranational nature of the region³. Contrary to the US, the negative change in the spread means QE has successfully reduced the risk premia required to hold the riskier Italian bond. The associated coefficient should then be *positive*.

Results are subject to both diagnostic and robustness tests, whose results can be found under section 5. The next section provides a brief description of the time series and event data, including rationales for said robustness tests.

3.2 Data and summary statistics

³ Rogers et al. (2014) provides full rationale as to the usage of this unique variable, while Won et al. (2013) establish a relationship between surprise changes in a country's credit spread on the volatility of its bond market.

3.2.1 Summary of events of interests

Table 2A and 2B present announcements by the ECB and the Fed that could potentially amount to monetary policy surprises. Choosing events to be included itself is a tradeoff. While the inclusion of impertinent event dates could distort inferences about transmission channels, omitting relevant dates weakens the statistical tests but does not lead to any biases, at least when analyzing channels (Krishnamurthy & Vissing-Jorgensen, 2011). Announcements in Table 2 are therefore selected based on examination of QE studies utilizing the event study approach, e.g. Lehto (2014), Christensen and Rudebusch (2012), Fawley and Neely (2013), Gagnon et al. (2011), Fratzscher et al. (2017). This not only ensures the validity of the selection but also makes results more comparable.

A potential weakness in the event set is the inclusion of both accommodative and restrictive policy announcements. Specifically, announcements about the ending of a particular asset purchase program, or the reduction in its size, could be greeted with spikes in volatility, depending on the prevailing macroeconomic condition. Indeed, when Fed's Chairman Ben Bernanke referred to the tapering of US QE in 2013, investors rapidly withdrew their money from the bond market in panic, resulting in a noticeable surge in US Treasury Yield now known as "Taper Tantrum." Therefore, it is possible that results for announcement effect are subject some degree of bias. Robustness tests in section 5.2 will correct for this.

The section will also add an additional macro-level indicator, namely the stock market volatility, as a control variable. The variable is meant to capture swings in the overall economy that might or might not be a direct result of QE implementation. Alternatively, it can account for volatility transmission between stock and bond markets. Steeley (2006) finds that the correlation between UK bond and equity markets is significantly negative.

TABLE 2A: Selected European Central Bank's asset purchase program-related announcements

Date	Related Program	Event	Description
7-May-09	CBPP	Governing Council (GC) Press release	The ECB will conduct purchases of €60 billion of euro-denominated covered bond
4-Jun-09	CBPP	GC Press release	The full technical modalities of the CBPP are decided upon
10-May-10	SMP	GC Press release	The ECB announces the sterilized SMP to intervene in dysfunctional euro area public/private debt securities markets
30-Jun-10	CBPP	GC Press release	CBPP fully implemented as scheduled. Purchased bonds to be held until maturity.
26-Jul-12	OMT	Draghi speech	ECB President Mario Draghi's London "whatever it takes to save the euro" speech
02-Aug-12	OMT	Press conference	ECB President Draghi emphasizes that "the euro is irreversible", announcing extended sovereign debt purchase program
6-Sep-12	SMP/OMT	GC Press release	Technical modalities for OMT announced
6-Oct-11	CBPP2	GC Press release	The ECB will conduct new purchases of €40 billion of euro-denominated covered bond
3-Nov-11	CBPP2	GC Press release	The full technical modalities of the CBPP2 are decided upon
4-Sep-14	CBPP3/ABSPP	Press conference	ABSPP and CBPP3 announced
2-Oct-14	CBPP3/ABSPP	GC Press release	The full technical modalities of the CBPP3 and ABSPP are decided upon
22-Jan-15	PSPP	GC Press release	The ECB expands its existing purchases to include euro area government, agency and institution bonds. Combined monthly purchase amount is €60 billion.
10-Mar-16	CSPP	GC Press release	CSPP is added to the APP
21-Apr-16	CSPP	GC Press release	The ECB decides on the main technical parameters of the CSPP
8-Dec-16	APP	GC Press release	APP is extended until at least December 2017, but monthly amount to be reduced by €20 billion to €60 billion as of April 2017
26-Oct-17	APP	GC Press release	APP is extended until at least December September 2018, but monthly amount to be halved to €30 billion as of January 2018

TABLE 2B: Selected Federal Reserve System's asset purchase program-related announcements			
Date	Related Program	Event	Description
25-Nov-08	QE1	FOMC Statement	The first large scale asset purchase announcement. Fed set to purchase \$100 billion of agency debt and \$500 of MBS.
1-Dec-08	QE1	Bernanke speech	Fed's Chairman Ben Bernanke hints at substantial purchases of Treasury securities
16-Dec-08	QE1	FOMC Statement	FOMC reiterates Bernanke's suggestion of potential long-term Treasury purchases
28-Jan-09	QE1	FOMC Statement	FOMC again says it is ready to expand QE1 and include Treasuries
18-Mar-09	QE1	FOMC Statement	QE1 expanded with purchases of agency debt, MBS, and Treasuries of \$100, \$750, and \$300 billion respectively
12-Aug-09	QE1	FOMC Statement	Purchases to be conducted at a slower pace and finished in late October, not mid-September
23-Sep-09	QE1	FOMC Statement	FOMC announces the gradual slowing of MBS/agency debt purchases, which are set to be completed by late 2010:Q1
4-Nov-09	QE1	FOMC Statement	Size of agency debt purchases reduced from \$200 to \$175 billion
10-Aug-10	QE1	FOMC Statement	The Fed will reinvest principal payments from agency debt and MBS in long-term Treasuries to maintain the balance sheet
27-Aug-10	QE2	Bernanke speech	The Fed is "prepared to provide additional monetary accommodation...if it proves necessary."
21-Sep-10	QE2	FOMC Statement	Per the Committee's projections, "inflation is likely to remain subdued for some time before rising" to the target level
12-Oct-10	QE2	FOMC Minutes	FOMC members hint at looming additional accommodative policy
15-Oct-10	QE2	Bernanke speech	The possibility of a second round of QE is reiterated
3-Nov-10	QE2	FOMC Statement	FOMC announces \$600 billion - QE2, comprising of \$75 billion per month Treasury purchases
22-Jun-11	QE2	FOMC Statement	QE2 finished as planned
21-Sep-11	MEP	FOMC Statement	MEP announced. Principal payments of agency debt and MBS now reinvested in MBS.
20-Jun-12	MEP	FOMC Statement	MEP length, but not its size, extended to the end of 2012
22-Aug-12	QE3	FOMC Minutes	FOMC members suggest that "additional monetary accommodation would likely be warranted fairly soon..."
13-Sep-12	QE3	FOMC Statement	The Fed announces open-ended QE3, which include \$40-billion-per-month MBS purchases until the outlook for the labor market improves
12-Dec-12	QE3/MEP	FOMC Statement	FOMC decides to expand QE3 by continuing to purchase \$45 billion of Treasuries per month but will not sterilize the purchase via the sale of short-term securities
19-Jun-13	QE3	Bernanke speech	In light of positive economic data, Bernanke suggests the "tapering" of QE3 from \$85 billion to \$65 billion in September 2013
18-Dec-13	QE3	FOMC Statement	3 months late of the initial date, the FOMC announces the official "tapering" of \$20 billion in both MBS and Treasuries
29-Oct-14	QE3	FOMC Statement	The Fed votes to end asset purchase program and states its confidence in economic improvement

Table 2: Selected ECB and Fed QE Announcements

3.2.2 Bond return and summary statistics

Daily closing observations of the Bloomberg Barclays US Corporate Bond (LUACTRUU) and Bloomberg Barclays Euro-Aggregate (LECPTREU) indices from 2008:Q1 to 2017:Q4 were taken from Bloomberg. Standard log returns are then calculated, serving as the key dependent variable in equation (1). QE transaction-level data are publicly available from the ECB and Fed websites. It is used to calculate the intensity of asset purchases. For the ECB, detailed purchase data are unavailable, so purchase amounts are inferred as the difference in daily holdings of purchase programs. Finally, government bond yields of the US, Germany, and Italy are collected from investing.com. Since GARCH estimation requires continuous variables, all missing values are linearly interpolated.

	US	EU
Mean%	0.00021	0.00018
Median%	0.00037	0.00024
Maximum%	0.02057	0.00844
Minimum%	-0.02094	-0.00891
Std. Dev.%	0.00336	0.00168
Skewness	-0.312	-0.708
Kurtosis	5.715	6.336
Jarque-Bera	841.651	1424.992
Probability	1.73E-183	0.000000
Augmented Dickey- Fuller	-10.416	-20.764
Probability	0.000000	0.000000

Table 3: Summary statistics of bond returns 2-Jan-08 to 29-Dec-17 (2603 observations)

Summary statistics for the two bond return series are provided in Table 3. It seems that US corporate bond returns are twice as volatile as their European counterpart. Both return series are negatively skewed and leptokurtic, reflecting the well-known fat-

tailed nature of asset returns (e.g. Cont, 2001). Along with the Jarque-Bera statistics, kurtosis and skewness indicate strong departure from normality.

In addition, the series exhibit some characteristics that would make them potential candidates for GARCH modelling. First, the Augmented Dickey-Fuller test statistics soundly rejects the null hypothesis of the series having unit roots under all test specifications (regarding trend and intercept). Therefore, stationarity, a key assumption in GARCH models, is satisfied. Weak-sense stationarity, essentially a lack of trend as indicated by constant unconditional mean and variance, is a vital assumption for time series analysis because it is indispensable for meaningful forecasting, which any model is arguably designed to do. Without stationarity, the accuracy of the model will be time-variant because the probability density function changes and forecasts are, as a rule, impossible. In this investigation, nonstationary data might exhibit a different behavior that does not revert to a long-term mean after it is subject to a shock in the crisis. Such a change in behavior is very hard to model. For example, if volatility consistently increases over time after the shock, so will its sample mean and variance, meaning all models will always underestimate the mean and variance in future periods. Even for current data, the coefficients may be spurious, indicating significant correlation where there is none.

Second, Figure 8 further shows signs of volatility clustering, which GARCH is specifically designed to model.

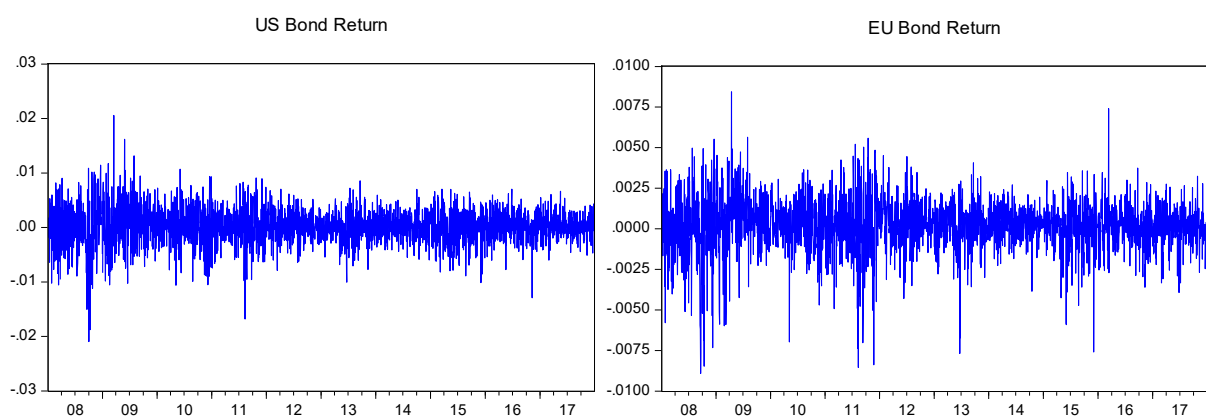


Figure 8: US and EU Bond Return (Log)

However, the clearest sign of good model fitness is evidence of time varying variance structure of the error term, i.e. heteroscedasticity. Excess kurtosis, as discussed, could be a symptom of such structure (Steeley and Matyushkin, 2014). More powerful still, Bollerslev (1986) shows that one can meaningfully utilize the autocorrelation and partial autocorrelation for the squared process to examine time series behavior in equation (2). As such, autocorrelation of squared returns will be examined next along with autocorrelation in absolute returns.

According to Table 4, the US return series exhibit no autocorrelation, as to be expected. Perhaps most dramatic is the significant, positive autocorrelation of EU daily bond returns, meaning that one can potentially exploit historical prices to make economic profit. This seemingly contradicts the efficient market hypothesis. One potential explanation is that component bond returns take different amounts of time to react to new information (Shogbuyi & Steeley, 2017). Granted, though significant, the level of autocorrelation is only unexpectedly large for the first two orders (>10%) and decays rapidly afterwards. An AR(1) term is included in the mean equation for the EU return series to correct for this.

Table 4: Autocorrelation of returns

This table provides the autocorrelation coefficients for daily US and EU bond returns up to lag 10 and the probability associated with their respective Q-statistics

	AC(1)	AC(2)	AC(3)	AC(4)	AC(5)	AC(6)	AC(7)	AC(8)	AC(9)	AC(10)
US										
Return	-0.025	-0.007	0.03	0.021	-0.014	0.022	0.000	0.019	0.007	0.060
	(0.195)	(0.407)	(0.24)	(0.258)	(0.328)	(0.312)	(0.419)	(0.434)	(0.52)	(0.062)
EU										
Return	0.152	0.103	0.079	0.078	0.034	0.034	-0.003	0.025	0.029	0.02
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

Table 5 presents the autocorrelation of the squared returns, which is more relevant to predict the behavior in the variance process, i.e. equation 2, that the thesis is attempting to model. All squared returns exhibit significant autocorrelations that are much larger in magnitude compared to those in Table 4. The first order autocorrelation

is 27.2% for the eurozone and 20.3% for the US. Though not extremely high, such significant, positive autocorrelation of squared returns is rare when studying economic time series. It is a clear implication of ARCH effects in the variance process (Engle, 2001).

Table 5: Autocorrelation of squared returns

This table provides the autocorrelation coefficients for daily US and EU **squared** bond returns up to lag 10 along with the probability associated with their respective Q-statistics

	AC(1)	AC(2)	AC(3)	AC(4)	AC(5)	AC(6)	AC(7)	AC(8)	AC(9)	AC(10)
US										
Return	0.203	0.142	0.097	0.086	0.148	0.208	0.211	0.203	0.231	0.094
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
EU										
Return	0.272	0.253	0.135	0.153	0.116	0.081	0.124	0.105	0.119	0.106
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)

4. EMPIRICAL RESULTS

After tentative indications of model fitness are observed, the paper now proceeds to fit the specified model in equation 1 and 2 to the data. This section conducts parameter estimation for four different EGARCH specifications, capturing both domestic and international spillover effect of QE programs by the Fed and the ECB. All parameters are estimated by maximum likelihood using the Berndt-Hall-Hall-Hausman (BHHH) algorithm and Marquardt steps in EViews (Berndt et al., 1974).

Table 6: Estimated parameters of the **mean** process (Equation 1)

This table provides the results from the maximum likelihood estimation of the parameters of the model

$R_{i,t} = \alpha_{i,0} + \sum_{j=1}^p \theta_{i,j} D_{i,j,t} + \alpha_{i,1} QEInt_{i,t} + \alpha_{i,2} QEAnn_{i,t} + \alpha_{i,3} Gov_{i,t} + d_{i,1} R_{i,t-1} + \epsilon_{i,t}$, where $\epsilon_{i,t} | \Omega_{t-1} \sim G(0, \sigma_{i,t}^2, \kappa)$ and

$$\ln(\sigma_{i,t}^2) = \omega_i + \alpha_i \left[\frac{|\epsilon_{i,t-1}|}{\sqrt{\sigma_{i,t-1}^2}} - \sqrt{\frac{2}{\pi}} \right] + \gamma_i \frac{\epsilon_{i,t-1}}{\sqrt{\sigma_{i,t-1}^2}} + \beta_i \ln(\sigma_{i,t-1}^2) + \sum_{j=1}^p \phi_{i,j} D_{i,j,t} + \lambda_{i,1} QEInt_{i,t} + \lambda_{i,2} QEAnn_{i,t} + \lambda_{i,3} Gov_{i,t}$$

$R_{i,t}$ is the daily log return of the corporate bond market i index at time t , $i \in [US, EU]$. The information set Ω_{t-1} includes all available information at time $t - 1$. The dummy variables $D_{i,j,t}$ denotes QE phases: QE1, QE2, QE3, MEP in the US; CBPP, CBPP2, CBPP3, ABSPP, PSPP, CSPP in Europe. The variable $QEInt_{i,t}$ is the intensity of

daily asset purchases. $QEAnn_{i,t}$ is another dummy variable, taking value one on QE announcement dates (Table 2) and zero otherwise. US dates are lagged by one period when they influence European returns. The variable Gov measures the pass through from changes in yields/prices of government securities. Probabilities associated with z-statistics are provided in parentheses below their estimated coefficients.

All estimated coefficients except α_3 and d_1 are $\times 10^2$											
	Constant	QE Phases					QE Intensity	QE Announcement	Government securities	AR(1)	
	α_0	θ_1	θ_2	θ_3	θ_4	θ_5	θ_6	α_1	α_2	α_3	d_1
US Quantitative Easing											
			-	-							
US	0.0107 (0.000)	0.0228 (0.024)	0.0198 (0.028)	0.0022 (0.604)	0.0127 (0.044)			0.0068 (0.426)	-0.0017 (0.002)	0.8261 (0.000)	
EU	0.010 (0.002)	0.016 (0.107)	-0.022 (0.071)	0.011 (0.024)	0.020 (0.004)			0.012 (0.164)	0.045 (0.076)	0.176 (0.000)	0.083 (0.000)
Europe Quantitative Easing											
EU	0.025 (0.000)	0.011 (0.145)	0.003 (0.686)	0.010 (0.540)	-0.004 (0.822)	-0.016 (0.099)	-0.005 (0.590)	0.000 (0.852)	0.004 (0.923)	0.008 (0.000)	0.065 (0.001)
US	0.019 (0.032)	0.028 (0.165)	0.025 (0.095)	-0.065 (0.194)	0.106 (0.057)	-0.030 (0.312)	-0.009 (0.650)	0.000 (0.902)	-0.092 (0.195)	0.019 (0.000)	

Table 6 reports the estimation results for the conditional mean process while Table 7 displays the parameters for the conditional variance process. Both tables are divided into an upper and lower panel, which focus on the impact of US and Europe QE respectively. The following section focuses on the domestic effect of those programs. International effects then follow. In each of those discussions, results for the conditional mean process (Table 6) come first, although the emphasis is obviously on those in Table 7.

4.1. Impact of Fed and ECB QE on domestic corporate bonds

The conditional mean equation (Table 6) is first examined. As US QE programs were heavily anticipated, and those in Europe even more so as they followed both US QE and a period of policy inefficacy, it is expected that the bulk of the impact will be in the variance process. For the eurozone, most QE periods do seem to have insignificant impact on the mean of bond returns. The US is different in that except for QE3, all

other programs are associated with an increase in bond returns, consistent with the portfolio balancing channel. As investors seek to replenish their portfolios as relative supply of government securities shrinks, corporate bonds might well have been an ideal candidate, even more so than equities (Joyce et al., 2017). However, PSPP, the ECB's largest purchase program produces effects that seemingly contradict portfolio balance theory, despite being very comparable to US QE1. That period is characterized with a negative, albeit barely significant ($p=0.099$) response in corporate bond returns, indicating a reduction (rather than an increase) in corporate bonds demand, price, and hence returns. The cause may lie in the eurozone's supranational nature, wherein purchases are conducted in uneven amounts in countries of different financial market sizes.

Purchase intensity is insignificant for both markets (α_1 , Table 6). Only US QE announcements are generally accompanied by a reduction in returns (α_2 , Table 6). Changes in prices/yields of government securities apparently also have very significant influences on corporate bond returns (α_3 , Table 6). An increase in the price of US 10-year Treasury Futures, which reflects investors' expectation of a rate cut, either directly or via QE, causes US corporate bond returns to rise. European markets once again witness surprising results. Specifically, if the Italian-German yield spread increases – signifying worsening conditions, investors are more likely to exhibit “flight-to-quality” rather than risk-taking behaviors by investing in relatively riskier assets like corporate bonds as the coefficient seems to imply. However, relative to the US, the magnitude of this coefficient is drastically smaller.

Unsurprisingly, the variance process (Table 7) offers more telling evidence. Almost all EGARCH parameters are highly significant. γ is negative, implying volatility asymmetry in which negative shocks have larger impacts than positive ones of the same size. The coefficient associated with the past conditional variance (GARCH effect) suggests volatility is quite persistent, especially in Europe where $\beta = 0.941$. As figure 9 demonstrates, both markets witnessed a massive spike in volatility in 2008 after the collapse of Lehman Brothers marked the official start of the crisis.

Regarding the variables related to QE periods (ϕ , Table 7), the expected result would be that those periods witness a reduction in volatility, either to pre-crisis level or even

below that. Accordingly, we should expect the coefficient to be statistically insignificant or significantly negative. Results in Table 7 suggest that this is true for most QE periods, as does the visualization in Figure 9. In the US, while QE2 and QE3 drive bond volatility down to levels below those prior to their implementation, volatility in the MEP and QE1 periods is not significantly different from the level pre-crisis. In the eurozone, the results are qualitatively similar. A crucial exception is, again, PSPP in the eurozone, which seem to cause an increase in volatility. This is also in contradiction with previous QE studies (e.g. Shogbuyi and Steeley, 2017, Tan and Kohli, 2011), although these studies never examined corporate bonds. One possible explanation is that while PSPP mitigated the consequences of the crisis, especially in the government bond market, private financial market and macroeconomic indicators suggested that the economy was still fragile (Joyce et al., 2011), possibly due to its slow pass-through (Peersman, 2011). But the fact that PSPP both reduced return and increased volatility may suggest intrinsic structural flaws. Criticism of the program is not inexistent, see e.g. van Lerven (2016). One should keep in mind, however, that ECB's programs are yet to be completed and critique such as this at this point may not be justified. Besides, it can be seen clearly from Figure 9 that spikes in the PSPP period eventually subsided, although it may not be wholly ascribed to the program alone as it is conducted in tandem with 3 other asset purchase programs. In fact, since CSPP involves outright purchases of corporate debt, it could be a more likely cause of volatility decline.

While not significant in Europe, the intensity of asset purchases (λ_1 , Table 7) in the US is an integral factor affecting corporate bond volatility. One could interpret this as solid proof of the “quantitative” aspect that differentiates QE and the associated boom in central banks' balance sheets from mere qualitative changes in their composition. Intuitively, large asset purchases should induce more portfolio balancing (and hence more volatility.) This is supported by several authors (see section 2.2.2) who advocate increasing the size of asset purchases and, to a lesser extent, the fact that “tapering” announcements shook markets so much. On the other hand, the negative effect on volatility does temporarily reverse the overall increase in price stability that is central to QE, or any other monetary policies. It is thus imperative that such volatile episodes discontinue eventually, which they fortunately do in reality. The insignificance of the

variable for the eurozone might stem from errors that occur in its inference and calculations, given that explicit purchase data is not readily available.

QE-related announcements (λ_2 , Table 7), appear to cause, or at least not effectively resolve, market uncertainty. On the one hand, investors could perceive announcements of prolonged accommodative policy (which could characterize most announcements in Table 2) as a sign of sluggish recovery of the economy. On the other hand, as mentioned in Section 3.2.1, the inclusion of some restrictive policies in the variable could produce some perverse effect on interpretation. However, results in Table 7 concur with authors who do have a diverse set of announcements such as Steeley and Matyushkin (2014) and Abad and Chuliá (2013). Other authors redress the potential conflict in direction of impact with an event study, which treats each event separately instead of aggregating their effect. In the aggregate setting of a regression analysis, Joyce and Tong (2012), by using intra-day data, successfully captured the impact of the variable on bond yields. In a later section, this paper will redo the estimation with only those announcements deemed accommodative.

Table 7: Estimated parameters of the variance process (Equation 2)

This table provides the results from the maximum likelihood estimation of the parameters of the model $R_{i,t} = \alpha_{i,0} + \sum_{j=1}^p \theta_{i,j} D_{i,j,t} + \alpha_{i,1} QEInt_{i,t} + \alpha_{i,2} QEAnn_{i,t} + \alpha_{i,3} Gov + d_{i,1} R_{i,t-1} + \epsilon_{i,t}$, where $\epsilon_{i,t} | \Omega_{t-1} \sim G(0, \sigma_{i,t}^2, \kappa)$ and

$$\ln(\sigma_{i,t}^2) = \omega_i + \alpha_i \left[\frac{|\epsilon_{i,t-1}|}{\sqrt{\sigma_{i,t-1}^2}} - \sqrt{\frac{2}{\pi}} \right] + \gamma_i \frac{\epsilon_{i,t-1}}{\sqrt{\sigma_{i,t-1}^2}} + \beta_i \ln(\sigma_{i,t-1}^2) + \sum_{j=1}^p \phi_{i,j} D_{i,j,t} + \lambda_{i,1} QEInt_{i,t} + \lambda_{i,2} QEAnn_{i,t} + \lambda_{i,3} Gov$$

$R_{i,t}$ is the daily log return of the corporate bond market i index at time t , $i \in [US, EU]$. The information set Ω_{t-1} includes all available information at time $t - 1$. The dummy variables $D_{i,j,t}$ denotes QE phases: QE1, QE2, QE3, MEP in the US; CBPP, CBPP2, CBPP3, ABSPP, PSPP, CSPP in Europe. The variable $QEInt_{i,t}$ is the intensity of daily asset purchases. $QEAnn_{i,t}$ is another dummy variable, taking value one on QE announcement dates (Table 2) and zero otherwise. US dates are lagged by one period when they influence European returns. The variable Gov measures the pass through from changes in yields/prices of government securities. Probabilities associated with z-statistics are provided in parentheses below their estimated coefficients.

Consta- nt	EGARCH(1,1)						QE Phases				QE	Government securities
	α	γ	β	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	Intens- ity	Announ- cement	
ω	α	γ	β	ϕ_1	ϕ_2	ϕ_3	ϕ_4	ϕ_5	ϕ_6	λ_1	λ_2	λ_3
US Quantitative Easing												
US	-3.762	0.494	-0.104	0.740	-0.046	-0.229	-0.120	-0.050		0.285	1.860	-38.448

	(0.000)	(0.000)	(0.000)	(0.000)	(0.485)	(0.007)	(0.011)	(0.341)		(0.000)	(0.000)	(0.000)	
EU	-0.660	0.159	-0.070	0.959	-0.022	-0.006	-0.026	-0.041		0.033	0.004	-1.525	
	(0.000)	(0.000)	(0.000)	(0.000)	(0.179)	(0.739)	(0.016)	(0.966)		(0.058)	(0.976)	(0.621)	
Europe Quantitative Easing													
EU	-0.932	0.212	-0.043	0.941	-0.039	0.000	-0.131	0.028	0.100	-0.025	0.000	0.623	0.826
	(0.000)	(0.000)	(0.005)	(0.000)	(0.059)	(0.996)	(0.006)	(0.609)	(0.014)	(0.159)	(0.615)	(0.003)	(0.028)
US	-0.126	0.058	-0.007	0.993	-0.006	-0.007	-0.028	0.047	-0.024	0.001	0.000	-0.065	1.049
	(0.000)	(0.000)	(0.377)	(0.000)	(0.113)	(0.014)	(0.212)	(0.077)	(0.010)	(0.847)	(0.305)	(0.570)	(0.000)

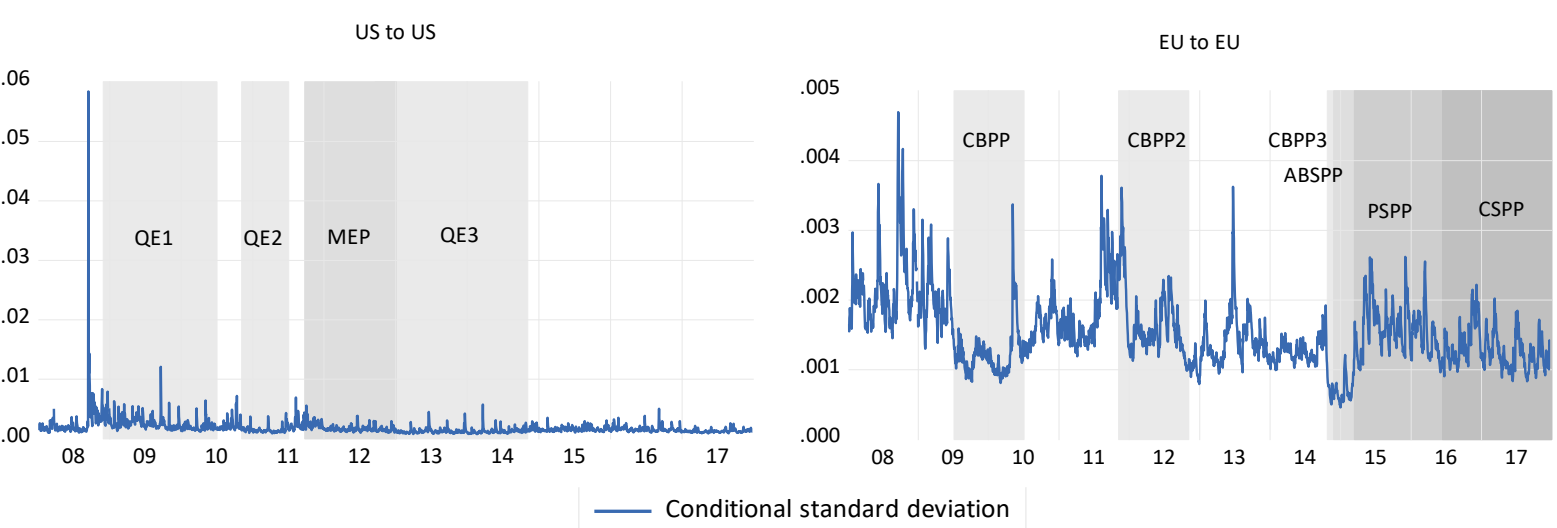


Figure 9: Conditional volatility of domestic QE

Finally, the pass-through effect from government securities (λ_3 , Table 7) is estimated to be significant and in the expected direction in both markets. US large-scale asset purchase programs have had the proven effect of reducing long-term government bond yields, as reflected in the increase in the price of US 10-year Treasury Futures over the sample period (Figure 10). A negative coefficient here suggests that volatility has generally declined during the same period and prices and returns have stabilized since the onset of the crisis. In Europe, QE's effect on the government bond market is proxied by the Italian-German yield spread. The spread did not peak in 2008, but rather at the height of the European sovereign debt crisis in 2011, and steadily declined afterwards. A positive coefficient implies that volatility in Europe has also declined. This is probably the most important piece of evidence substantiating the value of QE, as all central bankers would wish for their policies to impact the private sector and the real economy. The results also offer concrete proof of the portfolio balance channel

that crucially facilitates QE transmission to the desired target, i.e. the corporate sector in this instance.

4.2. Impact of Fed and ECB QE on international corporate bonds

The spillover effect of asset purchase programs is investigated next. From existing literature, asymmetry is expected, with US programs having larger effect on European markets rather than vice versa. The analysis benefits greatly from the fact that the Fed's and the ECB's programs largely do not coincide, unlike e.g. the US and the UK, allowing a quite clear separation of effects. This particularly pertains to the ECB's largest programs, CBPP3, ABSPP, PSPP, and PSPP, which only commenced after US QE3 had wrapped up in 2013 and were expected to have the largest impact.

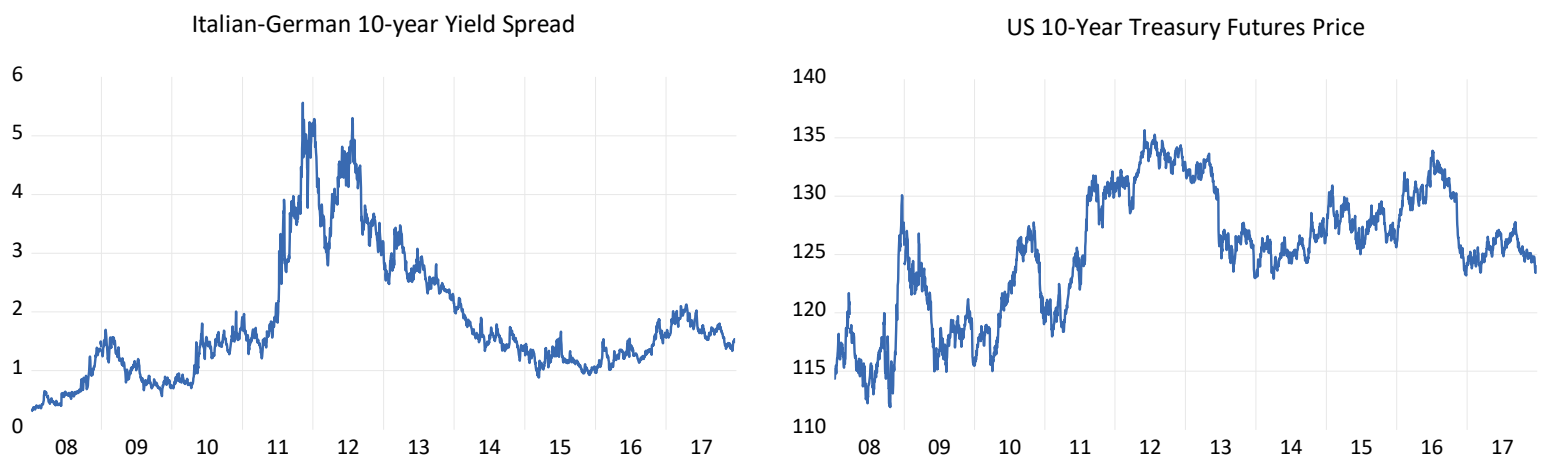


Figure 10: Evolution of selected government-related securities over sample period

In the conditional mean equation, the estimates (Table 6) suggest that US QE3 and MEP resulted in an increase in European return. QE1's influence on European corporate bonds was found to be insignificant and QE2 may have reduced returns ($p = 0.071$). ECB's CBPP2 and ABSPP witnessed a rise in US returns. In addition, the spillovers from both markets' government securities into the each other corporate bonds is significant. Their impacts also have the same sign/direction as they did for domestic markets. While such impact is drastically more muted for US QE, it surprisingly grows a little for European QE, implying that the programs affected foreign

markets even more than they did domestic markets. Granted, the coefficient is again much smaller in magnitude compared to US QE. Purchase intensity for both regions and announcement effect for the eurozone are insignificant.

The focus is once again on the time-varying variance process. As shown in Table 7 and Figure 11, all US QE periods saw a drop in eurozone corporate bond volatility to pre-crisis level, with QE3 reducing it even further. Equally potent, EU QE periods also saw a decrease in US bond volatility, either to pre-crisis level or below that. The exception is ABSPP, which actually saw an increase in US corporate bond volatility. However, the onset of ABSPP in November 2014 also coincided with a dramatic worsening of the global oil crash, which understandably culminated in turbulent financial markets. This might well have introduced some bias into the variable.

While European markets are not susceptible to US policy announcements (λ_2 , Table 7), they are very much so to the actual implementation of those policies (λ_1 , Table 7). The significant variable capturing US QE purchase intensity is still positive. The intensifying of US QE, therefore, seemed to unnerve investors in the European corporate bond market, resulting in heightened volatility. Both parameters are insignificant when measuring EU to US impact.

The pass-through effect from the sovereign debt market (λ_3 , Table 7) is again very significant, with reducing yield spread in Europe acting to calm market on the other side of the Atlantic. While US QE greatly benefited its own market, there is no indication that it might have helped European markets.

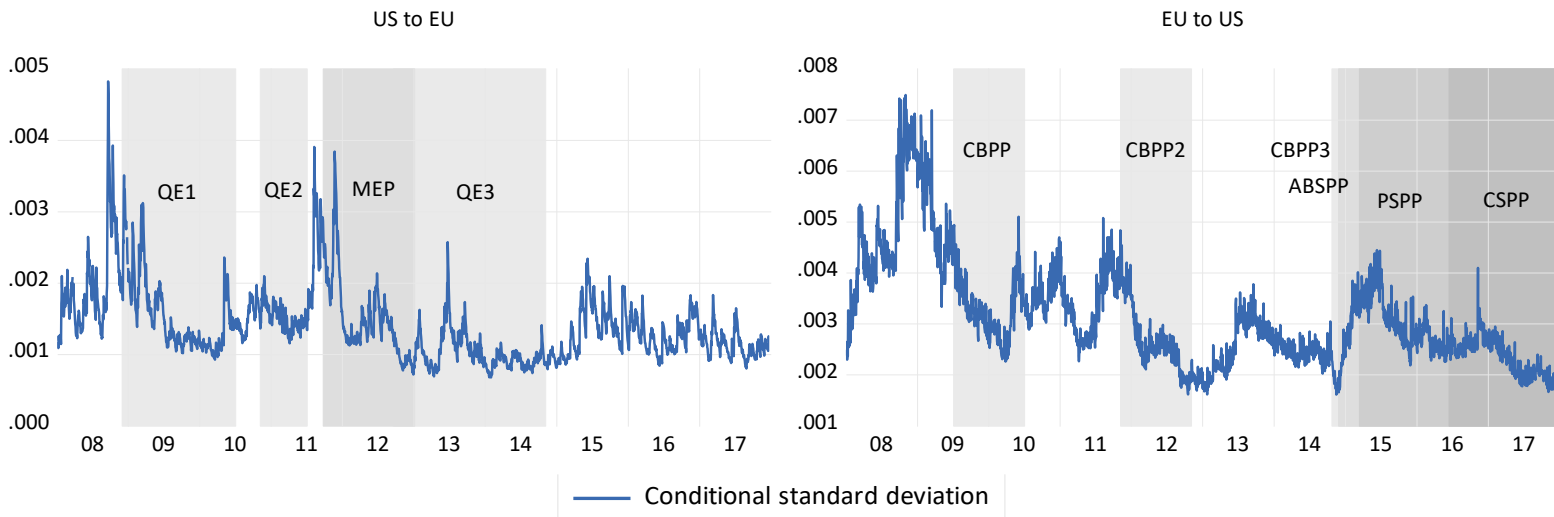


Figure 11: Conditional volatility of international QE

5. ROBUSTNESS TESTS

5.1. Model diagnostics

In this section several standard diagnostic tests are employed to ensure adequate goodness-of-fit. These include the autocorrelation of the standardized residuals and squared standardized residuals, the Lagrange multiplier test for remaining ARCH(1) effect, and the Jarque-Bera statistic for the distribution of the standardized residual, with the initial assumption being the Generalized error distribution (GED), which probably better captures the fat tail nature of asset returns. Results can be found under Appendix 1. Generally, the models do not seem to be mis-specified.

Though autocorrelation persists in the residuals, it has been reduced to small enough levels to be of negligible practical significance. Further, while it may indicate small issues in the conditional mean process, our focus is on volatility in the variance process. Here, no ARCH effects remain, as confirmed by the Ljung-Box Q statistic, and the ARCH-LM test for most cases. For the EU to US equation, the ARCH-LM statistic rejects the null hypothesis of “no remaining ARCH effect”, suggesting an additional ARCH lag. The EGARCH(1,2) (with no asymmetric effect, since it was insignificant in the original specification) specification removes any residual ARCH

effect without qualitatively changing previous conclusions. The Jarque-Bera results state that all residuals do not abide by Gaussian distribution, which affirms the initial assumption that the errors follow the GED.

5.2 Robustness tests

5.2.1 Controlling for macroeconomic volatility

Volatility of the stock market of the region being impacted is added as a control variable in both equations. It is represented by broad-based volatility indices: VIX in the US, and VSTOXX in the eurozone. The variables are found to be significantly negative for US QE and insignificant for EU QE. US corporate bond returns are thus more susceptible to market volatility. In the variance process, they are significantly positive, in line with expectations that stock market volatility will induce volatility in the bond market (Steeley, 2006).

Original results are by and large resilient to the added control variable, as shown in Appendix 2. Notable changes include the US operation intensity and the EU portfolio balance channel proxy. Both are rendered insignificant by the new variable. Volatility in both regions are therefore not subject to changes in the size of daily purchases in US QE, as previously found. European asset purchases seem to be transmitted not via the portfolio balance channel, but the signaling channel as evidenced by the dummy variables for the 6 QE periods. On the contrary, the portfolio balance channel that transmits the impact of US QE to European market is now significant, as is the domestic channel. The difference in the transmission channel between the two programs might be attributed to differences in the total size between US programs and early European programs. As stated, all covered bond purchase programs remove a meagre amount relative to the market compared to US QE, whose purchases eventually accumulated to 20% of GDP (Belke et al., 2017). Though PSPP is clearly of considerable proportions, it was not introduced until March 2015, which might explain why the variable has not proved robust under stress from a control variable.

5.2.2 Adjusted list of announcements

Heterogeneity in the impact of announcements has been identified as a potential factor introducing bias into the estimated coefficients and their significance. To eliminate the bias, the list in Table 2 is reduced to ensure that all events result in information of accommodative policy. Announcements of the slowing, i.e. “tapering”, or ending of asset purchases do not belong to this category. Accordingly, the following dates are removed:

- For the US: 12 August 2009, 23 September 2009, 4 November 2009, 10 August 2010, 22 June 2011, 19 June 2013, 18 December 2013, 29 October 2014.
- For the Eurozone: 30 June 2010, 8 December 2016, 26 October 2017

On September 18, 2013, the Fed defied its chairman’s previous statement about the tapering of QE and continued asset purchases at the same rate. This date is added to reflect potential (pleasant) market surprise.

Nevertheless, the results indicate no shifts in favor of QE announcements as a tool for tackling volatility and return. With respect to return, all QE-related announcements exert statistically insignificant effect. They also have the exact same impact as discussed in section 4 on conditional variance. Based on these results, the conclusion remains that announcements are at best ineffectual and at worst turbulence-causing, at least in the corporate bond market.

6. CONCLUSION

Overall, the analysis shows that QE is effective in reversing bond market turbulence that the 2008 financial crisis left in its wake. QE periods are characterized by significant reduction in volatility for both the markets studied, consistent with the signaling channel where central banks implicitly commit to prolonged accommodative policy. However, they may not respond to changes in the daily purchase rate, suggesting no

added benefit of concentrating purchases on particular days as opposed to smoothing them over the stated operation period. QE announcements are found to have no immediate soothing effect on the market, suggesting weakness of the signaling channel in this aspect. The portfolio balance channel is powerful for US programs only, where assets had always been purchased in very significant amounts. For Europe, evidence of such transmission mechanism is less sturdy, and assessment at this stage can be premature given that European programs are still ongoing as of this writing.

Granted, both central banks, the ECB and the Fed, are evidently quite influential in terms of generating meaningful impacts on each other's corporate bond markets, which should not be surprising given the integrated nature of global financial markets. Specifically, periods of purchase operations on both sides of the Atlantic witnessed significant drops in each other's bond market volatility, even after accounting for their own broad market volatility.

Europe's biggest purchase program, PSPP, while potentially beneficial for US investors, might have hurt its own market by both decreasing return and increasing volatility. This points to potential design flaws of the program, though one should wait until the conclusion of the program before making a complete critique.

6.1 Implication for International Business

From a policy maker's perspective, this thesis offers additional evidence in support of unconventional measures to address market turbulence in crises when standard policies have become impaired. QE is proved to be a potent tool in helping central bankers achieve their core pursuit of price stability. The yield curve, strongly affected by monetary policy such as QE, feeds into the pricing of all financial products, which in turn facilitate lending that fuels the global economy. Crucially, QE's ability to spill over into private markets means that it indirectly repairs corporate lending and thus help businesses develop. Spillover effects into foreign market is also noticeable, warranting increased cooperation between major central banks.

Given globalization and financial market integration, all international investors and corporations should pay close attention of central bank policy implementation, especially in major economies such as the US and the eurozone. This should not be limited to financial market investors just because QE directly affect such markets. The corporate bond market is the linchpin of a healthy economy. With spillover into this market established, players should naturally be concerned although admittedly they are relatively less directly affect by such substantial policy.

6.2 Limitation and suggestion for future research

While this paper attempts to capture the transmission channels that are central to QE, results should not be taken to provide definitive answers. Kojien et al. (2017) notes that inferring transmission channels from time series analysis of asset prices alone can be challenging. Instead, the directly relevant source of data is of movements in securities holdings, especially of institutional investors, which may better proxy for the flow of funds caused by portfolio balancing. The signaling channel, at least concerning QE announcements, is sensitive to the choice of relevant event dates and could be much harder to extract due to lack of clear relationships with a variable. While the event study methodology is allegedly more appropriate to investigate events, here the results are sensitive to the choice of event windows. Therefore, there potentially exists much possibilities in researching the avenues through which unconventional monetary policy works, which would be vastly useful for policy makers to design their programs to ensure the desired results. One could expand on the comprehensive work of Krishnamurthy and Vissing-Jorgensen (2011), who investigate channels from a US perspective, to explicitly include the supranational situation of the eurozone.

The channels themselves facilitate the investigation of *whether* QE had its desired effect, but not necessarily *why*. Future research could, for example, replicate this research on a security-level, where nuances in bond characteristics such as ratings and maturities can be captured. Literature merging theory of financial contagion, largely an instrument spreading destruction, and QE, a hopeful cure to a crisis, is still scarce. As discussed, the passage through which the crisis proliferates may also serve

as the way to administer corrective measures. How central bankers can manipulate typically vulnerable financial integration structures for their own utility is thus of special interest.

While the emphasis of this thesis is only on major economies, research of their effect on emerging markets is of equal importance. Particularly, major markets in Asia and South America deserve closer inspection as to whether the decisions of the ECB and the Fed have any bearing on the profitability of their investors.

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8. APPENDICES

Appendix 1: Model diagnostics

Table 8: Autocorrelation of squared residuals

This table provides the autocorrelation coefficients for the **squared** standardized residual of all four estimated models up to lag 10 along with the probability associated with their respective Q-statistics

	AC(1)	AC(2)	AC(3)	AC(4)	AC(5)	AC(6)	AC(7)	AC(8)	AC(9)	AC(10)
US to										
US	0.003 (0.888)	-0.002 (0.987)	-0.006 (0.991)	0.003 (0.998)	0.024 (0.904)	-0.008 (0.943)	-0.011 (0.958)	-0.001 (0.980)	0.062 (0.202)	-0.004 (0.269)
EU to										
EU	0.006 0.753	0.034 0.220	-0.017 0.283	-0.008 0.407	-0.020 0.414	-0.032 0.266	-0.007 0.355	-0.001 0.458	0.018 0.473	0.024 0.433
US to										
EU	0.027 (0.166)	0.051 (0.013)	-0.012 (0.028)	-0.010 (0.053)	-0.027 (0.047)	-0.022 (0.051)	-0.015 (0.070)	-0.006 (0.105)	0.010 (0.143)	0.018 (0.158)
EU to										
US	0.041 0.035	-0.012 0.090	-0.007 0.176	-0.004 0.289	0.013 0.362	0.007 0.471	0.047 0.120	0.026 0.104	0.055 0.012	-0.006 0.020

Table 9: Model statistics

This table provides general estimation statistics for the four models estimated

	US to US	EU to EU	US to EU	EU to US
Adjusted R squared	0.190	0.044	0.190	0.043
S.E of regression	0.002	0.002	0.002	0.003
Sum squared residual	0.006	0.007	0.006	0.028
Log likelihood	13587.440	13356.600	13587.440	11474.730
Durbin-Watson stat	1.904	1.780	1.904	2.023

Mean dependent variable	0.000	0.000	0.000	0.000
S.D dependent variable	0.002	0.002	0.002	0.003
Aikaike Information Criterion	-10.428	-10.247	-10.428	-8.798
Schwarz Criterion	-10.380	-10.191	-10.380	-8.744
Hannan-Quinn Criterion	-10.411	-10.227	-10.411	-8.779
ARCH LM probability	0.888	0.753	0.167	0.035
Jarque-Bera stat Standardized residuals	14125.09	680.37	604.66	151.95
(Probability)	(0.000)	(0.000)	(0.000)	(0.000)

Appendix 2: Robustness test results

Table 10: Estimated parameters of the **mean** process (Equation 1)

This table provides the results from the maximum likelihood estimation of the parameters of the extended model $R_{i,t} = \alpha_{i,0} + \sum_{j=1}^p \theta_{i,j} D_{i,j,t} + \alpha_{i,1} QEInt_{i,t} + \alpha_{i,2} QEAnn_{i,t} + \alpha_{i,3} Gov_{i,t} + \alpha_{i,4} Vol_{i,t} + d_{i,1} R_{i,t-1} + \epsilon_{i,t}$, where $\epsilon_{i,t} | \Omega_{t-1} \sim G(0, \sigma_{i,t}^2, \kappa)$ and

$$\ln(\sigma_{i,t}^2) = \omega_i + \alpha_i \left[\frac{|\epsilon_{i,t-1}|}{\sqrt{\sigma_{i,t-1}^2}} - \sqrt{\frac{2}{\pi}} \right] + \gamma_i \frac{\epsilon_{i,t-1}}{\sqrt{\sigma_{i,t-1}^2}} + \beta_i \ln(\sigma_{i,t-1}^2) + \sum_{j=1}^p \phi_{i,j} D_{i,j,t} + \lambda_{i,1} QEInt_{i,t} + \lambda_{i,2} QEAnn_{i,t} + \lambda_{i,3} Gov_{i,t} + \lambda_{i,4} Vol_{i,t}$$

$R_{i,t}$ is the daily log return of the corporate bond market i index at time t , $i \in [US, EU]$. The information set Ω_{t-1} includes all available information at time $t - 1$. The dummy variables $D_{i,j,t}$ denotes QE phases: QE1, QE2, QE3, MEP in the US; CBPP, CBPP2, CBPP3, ABSPP, PSPP, CSPP in Europe. The variable $QEInt_{i,t}$ is the intensity of daily asset purchases. $QEAnn_{i,t}$ is another dummy variable, taking value one on QE announcement dates (Table 2) and zero otherwise. US dates are lagged by one period when they influence European returns. The variable Gov measures the pass through from changes in yields/prices of government securities. The last variable, **Vol**, is the relevant stock market volatility, captured by volatility indices. Probabilities associated with z-statistics are provided in parentheses below their estimated coefficients.

All estimated coefficients except α_3 and d_1 are $\times 10^2$

	Constant	QE Phases						QE Intensity	QE Announcement	Government securities	Market volatility	AR(1)
	α_0	θ_1	θ_2	θ_3	θ_4	θ_5	α_3	α_1	α_2	α_3	α_4	d_1
US Quantitative Easing												
US	0.070 (0.000)	0.042 (0.000)	-0.032 (0.001)	-0.010 (0.024)	0.026 (0.000)			0.035 (0.000)	-0.164 (0.007)	0.831 (0.000)	-0.004 (0.000)	
EU	0.045 (0.000)	0.019 (0.066)	-0.028 (0.022)	0.004 (0.389)	0.030 (0.000)			0.025 (0.003)	0.042 (0.120)	0.181 (0.000)	-0.002 (0.000)	0.082 (0.000)
Europe Quantitative Easing												
EU	0.035 (0.001)	0.015 (0.071)	0.007 (0.395)	0.012 (0.394)	-0.004 (0.780)	-0.015 (0.138)	-0.010 (0.320)	0.000 (0.718)	0.003 (0.953)	0.008 (0.000)	0.060 (0.245)	-0.001 (0.003)
US	0.016 (0.445)	0.032 (0.149)	0.024 (0.122)	-0.065 (0.021)	0.099 (0.016)	-0.024 (0.494)	-0.004 (0.865)	0.000 (0.817)	-0.099 (0.097)	0.019 (0.000)	0.000 (0.901)	

Table 11: Estimated parameters of the variance process (Equation 2)

This table provides the results from the maximum likelihood estimation of the parameters of the extended model $R_{i,t} = \alpha_{i,0} + \sum_{j=1}^p \theta_{i,j} D_{i,j,t} + \alpha_{i,1} QEInt_{i,t} + \alpha_{i,2} QEAnn_{i,t} + \alpha_{i,3} Gov_{i,t} + \alpha_{i,4} Vol_{i,t} + d_{i,1} R_{i,t-1} + \epsilon_{i,t}$, where $\epsilon_{i,t} | \Omega_{t-1} \sim G(0, \sigma_{i,t}^2, \kappa)$ and

$$\ln(\sigma_{i,t}^2) = \omega_i + \alpha_i \left[\frac{|\epsilon_{i,t-1}|}{\sqrt{\sigma_{i,t-1}^2}} - \sqrt{\frac{2}{\pi}} \right] + \gamma_i \frac{\epsilon_{i,t-1}}{\sqrt{\sigma_{i,t-1}^2}} + \beta_i \ln(\sigma_{i,t-1}^2) + \sum_{j=1}^p \phi_{i,j} D_{i,j,t} + \lambda_{i,1} QEInt_{i,t} + \lambda_{i,2} QEAnn_{i,t} + \lambda_{i,3} Gov_{i,t} + \lambda_{i,4} Vol_{i,t}$$

$R_{i,t}$ is the daily log return of the corporate bond market i index at time t , $i \in [US, EU]$. The information set Ω_{t-1} includes all available information at time $t - 1$. The dummy variables $D_{i,j,t}$ denotes QE phases: QE1, QE2, QE3, MEP in the US; CBPP, CBPP2, CBPP3, ABSPP, PSPP, CSPP in Europe. The variable $QEInt_{i,t}$ is the intensity of daily asset purchases. $QEAnn_{i,t}$ is another dummy variable, taking value one on QE announcement dates (Table 2) and zero otherwise. US dates are lagged by one period when they influence European returns. The variable Gov measures the pass through from changes in yields/prices of government securities. The last variable, Vol , is the relevant stock market volatility, captured by volatility indices. Probabilities associated with z-statistics are provided in parentheses below their estimated coefficients.

	Constant	EGARCH(1,1)						QE Phases				QE Intensity	QE Announcement	Government securities	Market volatility
		ω	α	γ	β	ϕ_1	ϕ_2	λ_3	ϕ_4	ϕ_5	ϕ_6	λ_1	λ_2	λ_3	λ_4
US Quantitative Easing															
US	-9.422 (0.000)	0.551 (0.000)	0.007 (0.831)	0.378 (0.000)	-0.084 (0.508)	-0.168 (0.257)	-0.168 (0.048)	-0.003 (0.976)				-0.006 (0.953)	2.003 (0.000)	-61.676 (0.000)	0.048 (0.000)
EU	-2.050 (0.000)	0.194 (0.000)	-0.080 (0.000)	0.870 (0.000)	-0.039 (0.195)	0.048 (0.180)	-0.045 (0.029)	-0.018 (0.466)				-0.011 (0.716)	0.180 (0.402)	-12.565 (0.003)	0.008 (0.000)
Europe Quantitative Easing															
EU	-2.997	0.236	-0.066	0.802	-0.136	-0.006	-0.330	-0.016	0.332	-0.009	0.001	0.868	0.704		0.010

	(0.000)	(0.000)	(0.003)	(0.000)	(0.004)	(0.823)	(0.007)	(0.891)	(0.001)	(0.802)	(0.348)	(0.005)	(0.159)	(0.000)
US	-8.342	0.211	-0.033	0.349	-0.038	-0.139	-0.977	1.034	-0.019	-0.190	0.000	-0.483	0.012	0.033
	(0.000)	(0.000)	(0.325)	(0.017)	(0.657)	(0.070)	(0.003)	(0.004)	(0.904)	(0.062)	(0.877)	(0.353)	(0.987)	(0.000)
