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Quantitative Easing and the Supply of Safe Assets: Evidence from International Bond Safety Premia

Jens H. E. Christensen[†]

Nikola N. Mirkov[‡]

Xin Zhang[*]

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Abstract

Through large-scale asset purchases, widely known as quantitative easing (QE), central banks around the world have affected the supply of safe assets by buying quasi-safe bonds in exchange for truly safe reserves. We examine the pricing effects of the European Central Bank's bond purchases in the 2015-2021 period on an international panel of bond safety premia from four highly rated countries: Denmark, Germany, Sweden, and Switzerland. We find statistically significant negative effects for all four countries. This points to an important international spillover channel of QE programs to bond safety premia that operates by increasing the amount of truly safe assets.

JEL Classification: E43, E47, G12, G13, F42

Keywords: term structure modeling, convenience yields, unconventional monetary policy, European Central Bank

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[†] Corresponding author: Federal Reserve Bank of San Francisco, 101 Market Street MS 1130, San Francisco, CA 94105, USA; phone: 1-415-974-3115; e-mail: jens.christensen@sf.frb.org.

[‡] Belgrade Banking Academy; e-mail: nikola.mirkov@bba.edu.rs.

[*] Sveriges Riksbank; e-mail: xin.zhang@riksbank.se.

1 Introduction

The widespread use of large-scale asset purchases among central banks, a policy commonly known as quantitative easing (QE), calls for a better understanding of its transmission to financial markets. In particular, its impact on the prices and market dynamics of safe assets would seem to merit further investigation. When a central bank operates a QE program, it effectively reduces the supply of safe assets available to the public.[1] At the same time, though, it pays for the assets with reserves, which are overnight safe claims that only banks can hold. Hence, the overall impact on the supply of—and demand for—safe assets is unclear.

Although a large literature has provided theoretical frameworks and empirical evidence showing how central banks' QE programs may affect domestic and foreign bond markets as well as exchange rates,[2] the contribution of this paper is to expand on the role played by central bank reserves for the transmission of QE. In particular, we emphasize that the expansion of reserves may have additional implications for the pricing of safe assets in settings with significant heterogeneity in terms of the safety and liquidity of those assets. To explain the workings of this mechanism, we build on the analysis in Bechtel et al. (2021, henceforth BERV) and note that a QE program can be seen as a swap of one safe asset, typically a government bond, in exchange for another safe asset, namely the equivalent amount of reserves. Hence, in principle, the total supply of safe assets available to financial market participants may vary little on net over the course of the operation of a QE program. Under such ideal conditions there should be no significant additional effects on the pricing of safe assets beyond those already documented in the literature and discussed in Section 2. While this theoretical equivalence between safe assets and central bank reserves is likely to apply to the United States,[3] BERV argue that it does not hold for the euro area with the wide dispersion in safety across its various government bond markets. Specifically, they show that the European Central Bank's (ECB) bond purchases under its Public Sector Purchase Porgramme (PSPP) have included large volumes of what they refer to as "quasi-safe" assets such as Italian, Portuguese, and Spanish government bonds.[4] As a consequence, the total supply of truly safe assets in the euro area is more likely than not to have increased as a result of the ECB's QE operations. All else being equal, this added supply should lower the excess price that safe assets can command in the bond markets, a convenience premium we refer to as the safety premium; see Christensen and Mirkov (2022, henceforth CM).[5]

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[1] By law, most central banks are not allowed to buy and hold risky debt as part of their normal operations. For example, the U.S. Federal Reserve may only acquire U.S. Treasury securities or government-sponsored mortgage-backed securities outside of emergency contingencies.

[2] For examples, see Kolasa and Wasalowski (2020), Motto and Özen (2022), Malliaropulos and Migiakis (2023), and Gourinchas et al. (2023), among many others.

[3] U.S. Treasury securities and government-sponsored mortgage-backed securities are both widely viewed as highly safe assets and represent the vast majority of securities purchased by the U.S. Federal Reserve under its various QE programs.

[4] These are safe assets that are prone to become information-sensitive in times of crisis.

[5] See also Longstaff (2004) and Krishnamurthy and Vissing-Jorgensen (2012).

The empirical contribution of the paper is to test this hypothesis using safety premium estimates for four highly rated countries: Denmark, Germany, Sweden, and Switzerland.[6] We selected these four countries for two notable reasons. First and foremost, all four countries are closely related to the euro area, but to varying degrees. Germany is one of the core members in the euro area. Denmark is not part of the euro area but maintains a long-established peg of the Danish krone to the euro. Although Sweden and Switzerland are outside the euro area with floating exchange rates, they both have strong economic ties with it through trade and their financial systems. Second and of practical relevance, all four countries have well-developed government bond markets, which provide the requisite high-quality bond price information needed for the estimation of our yield curve models. Furthermore, as the ECB's QE policy was designed and operated to affect economic conditions in the euro area, including in Germany, our study hence provides both a domestic and a cross-border perspective on the effects of QE on bond safety premia. Importantly, our findings confirm that ECBs QE purchases appear to have lowered significantly the safety premia in all four countries. Given that three of these countries are not part of the euro area and their domestic safe asset and central bank reserve supplies therefore were unaffected by the QE purchases, our results highlight an important international spillover channel that works through investors' perceptions about the available supply of "truly safe" assets at an international, or even global, level.

In terms of the basic mechanics at play, we note that, due to equal regulatory treatment, a bank in the euro area is indifferent between selling a safe and a quasi-safe asset. For example, a Belgian bank will see no difference in meeting its regulatory requirements whether it sells a German or Italian bond to the ECB in a QE auction. By extension, a logic similar to the one laid out in Christensen and Krogstrup (2019, 2022) applies and entails that there is likely to be a minimum of financial market impact if the central bank solely buys safe assets from banks in exchange for central bank reserves, a point also emphasized by BERV. As a consequence, our novel reserve-induced safety premium effects only arise provided the purchases of quasi-safe assets are executed with non-bank entities. In that case, banks balance sheets are expanded and the outstanding amount of truly safe assets in the hands of financial market participants increases as central bank reserves are considered superior to the quasi-safe assets acquired by the central bank.[7]

To estimate the safety premia in each bond market, we use an arbitrage-free dynamic term structure model augmented with a bond-specific risk factor. The identification of the bond-specific risk factor comes from its unique loading for each individual bond, as in Andreasen et al. (2021, henceforth ACR). Our analysis uses prices of individual bonds rather than the more

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[6] Given that our conjecture is about the relative supply of safe and quasi-safe assets, any price effects arising through this mechanism should be limited to the safety premia of the safe assets. This explains why we do not examine other components in the prices of safe assets such as the expectations or term premium components.

[7] In addition, the increase in reserves and banks' balance sheets may give rise to reserve-induced portfolio balance effects on the term premia of the safe assets as discussed in Christensen and Krogstrup (2019, 2022), a question we leave for future research.

usual input of yields from fitted synthetic curves. The underlying mechanism assumes that, over time, an increasing proportion of the outstanding inventory is locked up in portfolios of buy-and-hold investors. Given forward-looking investor behavior, this lock-up effect means that a particular bond's sensitivity to the market-wide bond-specific risk factor will vary depending on how seasoned the bond is and how close to maturity it is. In a careful study of nominal U.S. Treasuries, Fontaine and Garcia (2012) also find a pervasive bond-specific factor that affects all bond prices with loadings that vary with the maturity and age of each bond. By observing a cross section of bond prices over time—each with a different time since issuance and time to maturity—we can identify the overall bond-specific risk factor and each bond's loading on that factor.

While CM already used this approach to estimate safety premia for the Danish and Swiss government bond markets, we provide updated results for these two markets. More importantly, to the best of our knowledge, we are the first to provide estimates of such safety premia for the German and Swedish government bond markets. Furthermore, even though our four samples have different start dates determined by data availability or other practical considerations, they all run through the end of 2021. Hence, our analysis includes the recent COVID-19 pandemic period, during which numerous central banks, including the ECB, acquired significant volumes of safe and quasi-safe assets.[8]

In all four markets, we find large and time-varying bond-specific premia. Given that these markets are significantly less liquid than U.S. Treasury markets, maybe with the exception of the German bund market, we follow CM and refer to these convenience premia as safety premia. The estimated average safety premium is 0.15 percent, 0.62 percent, 0.54 percent, and 0.66 percent in the Danish, German, Swedish, and Swiss markets, respectively. Hence, in light of the very low interest rate levels prevailing in all four countries at the time of the ECB's QE operations, the safety premium represents a non-negligible part of the yield earned by bond investors during this period.

To study the relationship between changes in our estimated safety premium series and the amount of quasi-safe assets that has been replaced by safe reserves, we rely on panel regressions with our safety premium series as the dependent variables and the ECB's asset holdings measured as a percentage of nominal GDP in the euro area as the key explanatory variable. Given the fact that the ECBs bond purchases under the PSPP followed a fixed distribution key across countries during the period under analysis, the latter can be assumed to serve as a proxy for the amount of quasi-safe assets in the euro area that has been replaced by safe reserves. Importantly, we include a range of relevant control variables to account for factors that matter for the individual safety premium series independent of the operation of the QE program. We find that the ECB's asset holdings measured as a percentage of nominal GDP in the euro area has a statistically and economically significant negative impact on the

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[8] For example, the U.S. Federal Reserve increased its asset holdings by about 4.5 trillion dollars between December 2019 and December 2021; see https://www.federalreserve.gov/releases/h41/default.htm.

safety premia in all four countries. In other words, the larger the supply of truly safe assets, the lower the safety premia, and therefore, the lower the prices and the higher the yields of those safe assets.

We explain these findings by emphasizing this novel QE transmission channel centered around investors' perceptions about the relative supply of safe assets in and across the safest government bond markets in the euro area and its neighboring countries.[9,10] The ECB's cumulative asset purchases likely reduced the relative scarcity of Danish, Swedish, and Swiss bonds by increasing the absolute amount of safe assets across European financial markets.[11] For Germany, the sign of the effect is unclear ex ante though, because it would depend on the *perceived* change in the available amount of German bonds relative to the *perceived* changes in the available amount of safe assets in the euro area and neighboring countries.

In terms of magnitudes, our panel regression results indicate that asset purchases by the ECB equivalent to 1 percent of nominal GDP in the euro area tends to lower the safety premia by about 0.35 basis points. Given that the ECB increased its bond holdings by as much as 40 percent of GDP between early 2015 and the end of 2021, our results imply that this is likely to have reduced safety premia on net by 0.12 percent, a considerable number given the very low interest rate levels prevailing during this period. Next, we run time series regressions for each of the four countries' safety premia individually. The results confirm that the ECB QE programs reduced the safety premium in all four countries. Interestingly, the impact of the ECB QE asset purchases on the safety premia varies notably across countries. While the bond markets in Denmark and Switzerland seem to respond in fairly similar ways to added supply of safe asset equivalents with a safety premium decline of about -0.33 basis point per percentage point increase in ECB holdings as a share of nominal GDP, the German and Swedish bond markets exhibit a much stronger reaction with a decline that is about four and five times larger, respectively. Hence, the pricing power of German and Swedish government bonds appear to be much more sensitive to changes in the global supply of safe assets.

The remainder of the paper is structured as follows. Section 2 offers a brief summary of the related literature, while Section 3 contains the description of our international panel of government bond prices. Section 4 details the no-arbitrage term structure model we use and summarizes our estimation results. Section 5 describes the calculation of the safety premia and examines their determinants. Finally, Section 6 concludes the paper.

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[9] Caballero et al. (2017) and references therein focus on the demand and supply of safe assets relative to other assets, while our study is about the relative pricing power across different safe assets as measured through the lens of our estimated safety premium series.

[10] The existence of the safety premia we examine may ultimately be rooted in the aggregate demand for safe assets to meet money-like convenience services; see Krishnamurthy and Vissing-Jorgensen (2012, 2015), Greenwood and Vayanos (2010), and Greenwood et al. (2015), among many others.

[11] The ECB asset purchases should arguably be the dominating factor underlying any major changes in the relative scarcity of bonds across the European markets during the 2015-2021 period. The only exception to this general statement is Sweden, where the Riksbank operated its own QE programs during much of this period. Therefore, in our analysis, we make sure to carefully control for the Swedish safe asset purchases flowing from these programs.

2 Related Literature and Other QE Channels

The analysis in this paper relates to several important strands of literature. Most directly, it speaks to the voluminous literature on the financial market effects of central bank large-scale asset purchases. Second, our results relate to research on financial market convenience and safety premia. Finally, the paper contributes to the rapidly growing literature about the economic consequences of the COVID-19 pandemic.

In the following, we briefly relate our analysis to the other main transmission channels emphasized in the literature about the financial market effects of QE.

One key channel through which QE transmits to interest rates is known as the signaling channel emphasized by Christensen and Rudebusch (2012) and Bauer and Rudebusch (2014), whereby bond yields can decline because the introduction of a QE program is interpreted by investors as a signal that interest rates will be low for longer than already anticipated. Since this channel operates mainly through the expectations component of bond yields, it is unlikely to affect the safety premia we consider in this paper.

Another important transmission mechanism is the supply- and reserve-induced portfolio balance channel discussed at length in Christensen and Krogstrup (2019, 2022). This channel works by forcing investors to substitute their investments away from the safe assets purchased by the central bank and into riskier assets with either longer duration or greater credit and liquidity risks. Hence, the effects from this channel materialize through a lowering of the general term premium component of bond yields and therefore also falls outside of our analysis. A similar argument applies to the local supply effects stressed by D'Amico and King (2013). These effects materialize as flow effects at the time of the central bank purchases and also mainly affect the term premium component of bond yields. See also Malliaropulos and Migiakis (2023) for portfolio balance effects on sovereign bond markets.

Finally, the liquidity effects flowing from QE asset purchases highlighted by Christensen and Gillan (2022) are limited to the classes of assets targeted by the QE program and operate through a lowering of the liquidity premium component of bond yields caused by a tilt in the bargaining power away from buyers and towards sellers. Clearly, bonds in Denmark, Sweden, and Switzerland were not targeted by the ECB's QE purchases. Hence, by definition, they cannot have been affected through this liquidity channel and, even for the German bonds, they are already trading at a convenience premium. This suggests that the bargaining power in this market is already favorable to sellers, although some marginal effect through this channel cannot be ruled out.[12]

Beyond the frequently cited channels listed above, there are other potential mechanisms for QE to work. For example, Hattori et al. (2016) stress that central bank asset purchases

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[12] Effects from the liquidity channel on German bond prices would boost the German safety premia and go against the negative effects we document. Hence, our estimated effects for Germany are likely to be lower bound estimates of the true safety premium effect of the increase in the supply of safe assets.

have the potential to provide insurance against macroeconomic tail risks by limiting the downside risk to asset prices. However, these effects are economy-wide in nature and would impact all asset classes instantaneously upon announcement thanks to the forward-looking behavior of investors and hence should matter little for our safety premia. Also, it may affect the perception and pricing of risk, leading to a so-called "risk-taking channel," as discussed in Borio and Zhu (2012), which also would not apply to the safe assets considered in our bond safety premium series. Moreover, Kolasa and Wasalowski (2020) demonstrate that asset purchase programs of foreign central banks can affect international capital movements and exchange rate adjustments. Finally, Gourinchas et al. (2023) show that QE purchases lower bond yields and depreciate the currency through changes in the risk premia in currency and bond markets.

In addition to emphasizing a novel transmission of QE to bond prices, our study also relates to the recent literature that stresses the role of reserves and the friction that only banks can hold them; see Christensen and Krogstrup (2019, 2022), BERV, and Kandrac and Schlusche (2021), among several others.

3 The International Government Bond Data

A limited number of developed countries are so highly rated that their government debt can command a safety premium; among them are Denmark, Germany, Sweden, and Switzerland.[13] In this section, we describe the data from each of these four government bond markets that we use in our empirical analysis.

To estimate the factors in our yield curve model, we use the prices of standard fixed-coupon government bonds. These are all marketable, non-callable bonds denominated in the local currency that pay a fixed rate of interest annually. With the exception of the Swiss data, which have been kindly provided by staff at the Swiss National Bank, the remaining data has been downloaded from Bloomberg. Hence, the start date for the sample for each country is determined by the data availability from these two sources.

Figure 1a shows the yields to maturity series for all Danish government bonds in our sample, which runs from January 1995 through the end of December 2021. This represents an update of the Danish government bond price sample analyzed in CM. Figure 1b illustrates the yields to maturity for all German government bonds in our sample, which covers the period from January 1999 through the end of December 2021. Figure 1c shows the yields to maturity series for all Swedish government bonds in our sample from January 1999 to December 2021. We note that the start dates for these two markets were chosen to align with the launch of the euro in January 1999. In comparison to the other three markets, the Swiss government bond market is small, even relative to the Swiss economy. As of January 7, 2021,

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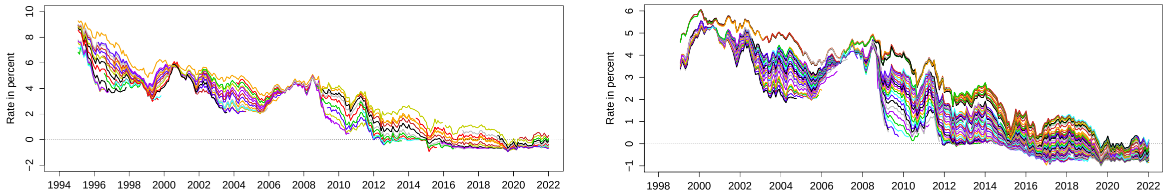
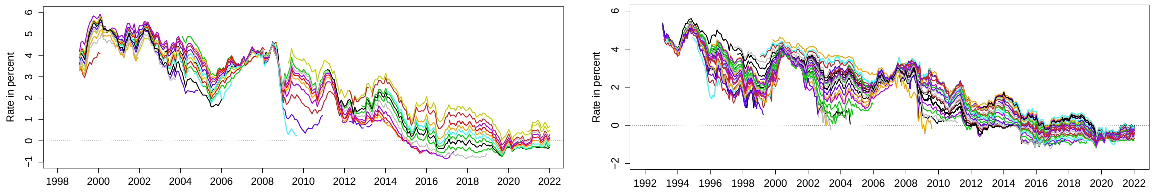
[13] During our key period of analysis from 2015 to 2021, all four countries held a triple-A rating with a stable outlook from all major rating agencies.



(a) Denmark (b) Germany



(c) Sweden (d) Switzerland

Figure 1: **Yield to Maturity of Government Bonds**
Illustration of Danish, German, Swedish, and Swiss government bond yields to maturity. The Danish sample starts in January 1995. The German and Swedish samples start in January 1999, while the Swiss sample starts in January 1993. All samples end in December 2021.

the total amount of outstanding Swiss government bonds was CHF67 billion, or less than 10 percent of Swiss nominal GDP in 2020. Thus, these bonds are among the safest in the world. Our Swiss government bond price data are collected daily by staff at the Swiss National Bank and are available back to the 1980s. However, we follow CM and start the data sample in January 1993, when the data appear to be systematically reliable across all available bonds.[14] Figure 1d shows the Swiss government bond prices converted into yield to maturity.

In general, yield levels in all four countries have trended lower the past 20-25 years and fell below zero by the end of our sample. Furthermore, business cycle variation in the shape of the yield curves is pronounced around the lower trends in all four markets. Note that these yield curves tend to flatten ahead of recessions and steepen during the initial phase of economic recoveries.

Regarding the important question of a lower bound on interest rates, the ECB kept its conventional policy rate well below zero for an extended period. Thanks to the high credit quality of the bonds we examine, their yields were frequently even lower. As a consequence, in most cases, short- and medium-term bond yields in our samples were significantly below zero with no visible lower constraint. Thus, it is not clear that one would need to impose a lower bound to model these data. Empirically, it is challenging to determine whether an unconstrained Gaussian model approach is more appropriate than a model approach enforcing a lower bound in such cases; see Andreasen and Meldrum (2019) for a detailed discussion. Here, we choose to focus on models with Gaussian dynamics, which can easily handle negative

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[14] Our sample represents an update of the Swiss bond data used by Christensen at al. (2022) and CM.

interest rates.

4 Model Estimation and Results

In this section, we first detail the augmented arbitrage-free Nelson-Siegel model, referred to as the AFNS-R model, that serves as the benchmark in our analysis before we describe the restrictions imposed to achieve econometric identification of the model. We then report the estimation results for all four countries and compare the model fit.

4.1 The AFNS-R Model

To begin, let $X_t = (L_t, S_t, C_t, X_t^R)'$ denote the state vector of the four-factor AFNS-R model also used by CM. Here, L_t denotes a level factor, while S_t and C_t represent slope and curvature factors. Finally, X_t^R is the added market-wide bond-specific risk factor.

The instantaneous risk-free rate is defined as

$$r_t = L_t + S_t. \tag{1}$$

The risk-neutral $\mathbb{Q}$-dynamics of the state variables used for pricing are given by

$$\begin{pmatrix} dL_t \\ dS_t \\ dC_t \\ dX_t^R \end{pmatrix} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & \lambda & -\lambda & 0 \\ 0 & 0 & \lambda & 0 \\ 0 & 0 & 0 & \kappa_R^{\mathbb{Q}} \end{pmatrix} \left[\begin{pmatrix} 0 \\ 0 \\ 0 \\ \theta_R^{\mathbb{Q}} \end{pmatrix} - \begin{pmatrix} L_t \\ S_t \\ C_t \\ X_t^R \end{pmatrix} \right] dt + \Sigma \begin{pmatrix} dW_t^{L,\mathbb{Q}} \\ dW_t^{S,\mathbb{Q}} \\ dW_t^{C,\mathbb{Q}} \\ dW_t^{R,\mathbb{Q}} \end{pmatrix},$$

where Σ is a lower-triangular matrix.

Based on the $\mathbb{Q}$-dynamics above, zero-coupon bond yields preserve a Nelson and Siegel (1987) factor loading structure

$$y_t(\tau) = L_t + \left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau}\right) S_t + \left(\frac{1 - e^{-\lambda\tau}}{\lambda\tau} - e^{-\lambda\tau}\right) C_t - \frac{A(\tau)}{\tau}, \tag{2}$$

where $\frac{A(\tau)}{\tau}$ is a convexity term that adjusts the functional form in Nelson and Siegel (1987) to ensure absence of arbitrage (see Christensen et al. (2011)).

Importantly, due to bond-specific premia in our four government bond markets, individual bond prices are sensitive to the variation in the bond-specific risk factor X_t^R. As a consequence, the pricing of the bonds in each market is not performed with the standard discount function above, but rather with a discount function that accounts for the bond-specific risk:

$$\overline{r}_t^i = r_t + \beta^i (1 - e^{-\lambda^{R,i}(t - t_0^i)}) X_t^R, \tag{3}$$

where t_0^i denotes the date of issuance of the specific security and β^i is its sensitivity to the variation in the market-wide bond-specific risk factor. Furthermore, the decay parameter $\lambda^{R,i}$ is assumed to vary across securities as well.

As shown in Christensen and Rudebusch (2019), the net present value of one unit of currency paid by bond i at time $t+\tau$ has the following exponential-affine form

$$\begin{aligned} P_t^i(t_0^i,\tau) &= E^{\mathbb{Q}}\Big[e^{-\int_t^{t+\tau}\overline{r}^i(s,t_0^i)ds}\Big] \\ &= \exp\Big(B_1^i(\tau)L_t + B_2^i(\tau)S_t + B_3^i(\tau)C_t + B_4^i(t_0^i,t,\tau)X_t^R + A^i(t_0^i,t,\tau)\Big). \end{aligned}$$

This implies that the model belongs to the class of Gaussian affine term structure models. Note also that, by fixing $\beta^i = 0$ for all i, we recover the AFNS model.

Now, consider the whole value of the bond issued at time t_0^i with maturity at $t+\tau$ that pays a coupon C annually. Its price is given by[15]

$$P_t^i(t_0^i,\tau) = C(t_1-t)E^{\mathbb{Q}}\Big[e^{-\int_t^{t_1}\overline{r}^i(s,t_0^i)ds}\Big] + \sum_{j=2}^{N} CE^{\mathbb{Q}}\Big[e^{-\int_t^{t_j}\overline{r}^i(s,t_0^i)ds}\Big] + E^{\mathbb{Q}}\Big[e^{-\int_t^{t+\tau}\overline{r}^i(s,t_0^i)ds}\Big]. \quad (4)$$

So far, the description of the AFNS-R model has relied solely on the dynamics of the state variables under the $\mathbb{Q}$-measure used for pricing. However, to complete the description of the model and to implement it empirically, we will need to specify the risk premia that connect these factor dynamics under the $\mathbb{Q}$-measure to the dynamics under the real-world (or physical) $\mathbb{P}$-measure. It is important to note that there are no restrictions on the dynamic drift components under the empirical $\mathbb{P}$-measure beyond the requirement of constant volatility. To facilitate empirical implementation, we use the essentially affine risk premium specification introduced in Duffee (2002). In the Gaussian framework, this specification implies that the risk premia Γ_t depend on the state variables; that is,

$$\Gamma_t = \gamma^0 + \gamma^1 X_t,$$

where $\gamma^0 \in \mathbf{R}^4$ and $\gamma^1 \in \mathbf{R}^{4\times 4}$ contain unrestricted parameters.

Thus, the resulting unrestricted four-factor AFNS-R model has $\mathbb{P}$-dynamics given by

$$\begin{pmatrix} dL_t \\ dS_t \\ dC_t \\ dX_t^R \end{pmatrix} = \begin{pmatrix} \kappa_{11}^{\mathbb{P}} & \kappa_{12}^{\mathbb{P}} & \kappa_{13}^{\mathbb{P}} & \kappa_{14}^{\mathbb{P}} \\ \kappa_{21}^{\mathbb{P}} & \kappa_{22}^{\mathbb{P}} & \kappa_{23}^{\mathbb{P}} & \kappa_{24}^{\mathbb{P}} \\ \kappa_{31}^{\mathbb{P}} & \kappa_{32}^{\mathbb{P}} & \kappa_{33}^{\mathbb{P}} & \kappa_{34}^{\mathbb{P}} \\ \kappa_{41}^{\mathbb{P}} & \kappa_{42}^{\mathbb{P}} & \kappa_{43}^{\mathbb{P}} & \kappa_{44}^{\mathbb{P}} \end{pmatrix} \left(\begin{pmatrix} \theta_1^{\mathbb{P}} \\ \theta_2^{\mathbb{P}} \\ \theta_3^{\mathbb{P}} \\ \theta_4^{\mathbb{P}} \end{pmatrix} - \begin{pmatrix} L_t \\ S_t \\ C_t \\ X_t^R \end{pmatrix} \right) dt + \Sigma \begin{pmatrix} dW_t^{L,\mathbb{P}} \\ dW_t^{S,\mathbb{P}} \\ dW_t^{C,\mathbb{P}} \\ dW_t^{R,\mathbb{P}} \end{pmatrix}.$$

This is the transition equation in the extended Kalman filter estimation of the AFNS-R model.

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[15] This is the clean price that does not account for any accrued interest and that maps to our observed bond prices.

4.2 Model Estimation and Econometric Identification

Due to the nonlinear relationship between state variables and bond prices in equation (4), the model cannot be estimated with the standard Kalman filter. Instead, we use the extended Kalman filter as in Kim and Singleton (2012); see Christensen and Rudebusch (2019) for details. Furthermore, to make the fitted errors comparable across bonds of various maturities, we scale each bond price by its duration. Thus, the measurement equation for the bond prices takes the following form

$$\frac{P_t^i(t_0^i,\tau^i)}{D_t^i(t_0^i,\tau^i)} = \frac{\widehat{P}_t^i(t_0^i,\tau^i)}{D_t^i(t_0^i,\tau^i)} + \varepsilon_t^i.$$

Here, $\widehat{P}_t^i(t_0^i,\tau^i)$ is the model-implied price of bond i, $D_t^i(t_0^i,\tau^i)$ is its duration, which is calculated before estimation, and ε_t^i represents independent and Gaussian distributed measurement errors with mean zero and a common standard deviation σ_ε. See Andreasen et al. (2019) for evidence supporting this formulation of the measurement equation.

Furthermore, since the market-wide bond-specific risk factor is a latent factor that we do not observe, its level is not identified without additional restrictions. For the Danish market, we let the first 30-year bond issued on April 6, 1994, and maturing on November 10, 2024, with 7 percent coupon have a unit loading on this factor, that is, $\beta^i = 1$ for this bond. For the German market, we use the first 30-year bond issued on July 4, 1997, and maturing on July 4, 2027, with 6.5 percent coupon and let it have a unit loading on the bond-specific risk factor. For the Swedish market, we let the 12-year government bond issued on July 22, 1991, with maturity on May 5, 2003, and a coupon rate of 10.25 percent have a unit loading. Finally, for the Swiss market, we follow CM and let the first 30-year, 4 percent coupon Swiss Confederation bond, which was issued on April 8, 1998, and matures on April 8, 2028, have a unit loading on this factor. These choices imply that the β^i sensitivity parameters measure sensitivity to the bond-specific risk factor relative to that of the benchmark bond in each market.

Finally, we note that the $\lambda^{R,i}$ parameters can be hard to identify if their values are too large or too small. As a consequence, we impose the restriction that they fall within the range from 0.0001 to 10, which is without practical consequences. Also, for numerical stability during model optimization, we impose the restriction that the β^i parameters fall within the range from 0 to 250.

4.3 Estimation Results

In this section, we briefly summarize the estimation results of the AFNS-R model applied to the four government bond markets in our sample. In the interest of simplicity, we limit the focus to a version of the AFNS-R model where $K^{\mathbb{P}}$ and Σ are diagonal matrices. As shown in ACR, these restrictions have hardly any effects on the estimated bond-specific premia, because they are identified from the model's $\mathbb{Q}$-dynamics, which are independent of $K^{\mathbb{P}}$ and

Parameter	Denmark		Germany		Sweden		Switzerland	
	Est.	SE	Est.	SE	Est.	SE	Est.	SE
$\kappa_{11}^{\mathbb{P}}$	0.0028	0.0169	0.0258	0.0951	0.0295	0.0665	0.0066	0.0296
$\kappa_{22}^{\mathbb{P}}$	0.0032	0.0281	0.5112	0.2389	0.2288	0.2215	0.1700	0.1230
$\kappa_{33}^{\mathbb{P}}$	0.0130	0.0739	0.2213	0.1600	0.1582	0.1742	0.5393	0.2627
$\kappa_{44}^{\mathbb{P}}$	0.0863	0.1368	0.3854	0.2388	0.4118	0.2581	0.0067	0.0333
σ_{11}	0.0059	0.0002	0.0075	0.0003	0.0063	0.0002	0.0034	0.0001
σ_{22}	0.0122	0.0009	0.0172	0.0019	0.0131	0.0009	0.0085	0.0005
σ_{33}	0.0158	0.0010	0.0193	0.0011	0.0198	0.0010	0.0200	0.0014
σ_{44}	0.0058	0.0006	0.0133	0.0015	0.0051	0.0006	0.0099	0.0008
$\theta_1^{\mathbb{P}}$	0.1150	0.0298	0.0834	0.0246	0.0524	0.0308	0.0426	0.0162
$\theta_2^{\mathbb{P}}$	0.1122	0.0509	-0.0525	0.0187	-0.0111	0.0229	-0.0247	0.0108
$\theta_3^{\mathbb{P}}$	-0.0959	0.3655	-0.0309	0.0286	-0.0429	0.0341	0.0114	0.0111
$\theta_4^{\mathbb{P}}$	0.0131	0.0227	0.0052	0.0177	-0.0025	0.0042	0.1080	0.2710
λ	0.3111	0.0060	0.1774	0.0023	0.5884	0.0078	0.1838	0.0029
$\kappa_R^{\mathbb{Q}}$	1.8698	0.0902	0.8879	0.0289	1.5066	0.0617	2.5191	0.1110
$\theta_R^{\mathbb{Q}}$	-0.0021	0.0002	-0.0080	0.0006	-0.0021	0.0002	-0.0059	0.0004
σ_ε	0.0004	3.1×10^{-7}	0.0003	1.7×10^{-7}	0.0003	4.5×10^{-7}	0.0007	2.3×10^{-7}

Table 1: **Estimated Dynamic Parameters**
The table shows the estimated dynamic parameters for the international panel of AFNS-R models, each estimated with a diagonal specification of $K^{\mathbb{P}}$ and Σ.

only display a weak link to Σ through the small convexity adjustment in yields.

Table 1 reports the estimated dynamic parameters. We do see differences across markets, which should be expected given that both the sample period and cross-sectional coverage vary from country to country. This affects the estimated persistence of the state variables as well as their estimated volatilities. It also impacts the value of λ, in particular given that this parameter determines the rate of decay in the yield factor loading of the slope factor in the model; a high value of λ implies a rapid decay of the slope factor loading and suggests that the estimated model puts more emphasis on fitting the short end of the yield curve.

Table 2 reports the summary statistics for the fit to all bonds in the sample from the four model estimations broken down into maturity buckets. Also reported are the number of fitted errors observed in each maturity bucket in each market. In general, we note the very strong fit of the AFNS-R model to the entire yield curve in each of the four government bond markets. This demonstrates that the model is able to produce a very accurate fit in all four markets.

5 The Government Bond Safety Premium

In this section, we analyze the government bond safety premia implied by the estimated AFNS-R models described in the previous section. First, we formally define the bond safety

Maturity bucket	Denmark			Germany			Sweden			Switzerland		
	Obs.	Mean	RMSE	Obs.	Mean	RMSE	Obs.	Mean	RMSE	Obs.	Mean	RMSE
0-2	771	0.43	8.77	937	-4.32	8.51	467	-0.96	6.49	848	0.06	9.34
2-4	688	0.57	5.46	1,200	1.09	3.88	506	1.03	5.29	984	0.36	5.89
4-6	512	0.33	6.29	1,305	3.06	5.09	472	-0.99	4.47	1000	-0.80	5.46
6-8	415	0.30	4.91	1,369	3.50	6.02	435	-0.41	3.07	906	0.41	4.49
8-10	372	0.61	5.63	1,385	3.85	6.23	415	-0.89	3.99	838	0.44	4.09
10-12	243	-0.58	5.50	193	1.98	4.66	241	0.24	4.12	650	0.40	3.79
12-14	24	3.38	5.39	146	-0.17	1.90	72	0.76	1.91	393	0.36	3.59
14-16	24	0.61	5.66	178	1.50	3.18	64	-0.08	2.46	252	0.83	4.86
16-18	26	0.96	2.05	174	2.46	4.23	45	0.32	2.98	222	0.71	4.70
18-20	48	0.10	1.14	210	4.56	7.41	46	-0.05	2.41	239	0.92	5.28
20-22	48	0.01	0.71	234	4.84	7.21	28	0.02	1.83	141	0.78	4.95
22-24	47	0.29	1.14	258	4.87	6.69	26	2.33	3.06	151	-1.43	4.33
24-26	48	0.46	1.69	281	6.57	8.53	35	0.15	2.69	131	-0.66	5.87
26-28	48	0.12	2.74	305	7.22	9.43	25	0.31	3.85	133	-2.73	6.52
28-30	46	3.00	10.21	301	6.71	8.86	24	0.13	5.48	111	-2.88	5.65
30<	33	0.19	3.79	207	5.31	7.78	2	n.a.	n.a.	443	0.30	5.65
All bonds	3,393	0.42	6.35	8,683	2.64	6.36	2,903	-0.26	4.59	7,442	0.08	5.64

Table 2: **Summary Statistics of Fitted Errors for Government Bond Yields**
This table reports the number of observations (Obs.), the mean pricing errors (Mean) and the root mean-squared pricing errors (RMSE) of government bond prices for the international panel of AFNS-R models, each estimated with a diagonal specification of $K^{\mathbb{P}}$ and Σ. The pricing errors are reported in basis points and computed as the difference between the implied yield on the coupon bond and the model-implied yield on this bond. Each data sample is monthly and described in Section 3.

premia and describe their historical evolution in each market. Second, we examine their interpretation by contrasting them to other convenience yields considered in the literature before we proceed to a regression analysis to study their determinants and whether the ECB safe-asset purchases have affected them.

5.1 The Estimated Bond Safety Premium

We now use the estimated AFNS-R models to extract the safety premium in each government bond market. To compute this premium, we first use the estimated parameters and the filtered states $\{X_{t|t}\}_{t=1}^{T}$ to calculate the fitted bond prices $\left\{\hat{P}_t^i\right\}_{t=1}^{T}$ for all outstanding securities in a given market. These bond prices are then converted into yields to maturity $\left\{\hat{y}_t^{c,i}\right\}_{t=1}^{T}$ by solving the fixed-point problem

$$\begin{aligned} \hat{P}_t^i &= C(t_1 - t)\exp\left\{-(t_1 - t)\hat{y}_t^{c,i}\right\} + \sum_{k=2}^{n} C\exp\left\{-(t_k - t)\hat{y}_t^{c,i}\right\} \\ &\quad + \exp\left\{-(T - t)\hat{y}_t^{c,i}\right\}, \end{aligned} \tag{5}$$

for $i = 1, 2, ..., n_t$, meaning that $\left\{\hat{y}_t^{c,i}\right\}_{t=1}^{T}$ is approximately the rate of return on the ith bond if held until maturity (see Sack and Elsasser (2004)). To obtain the corresponding yields with correction for the safety premium, a new set of model-implied bond prices are computed from the estimated AFNS-R model but using only its frictionless part, i.e. with

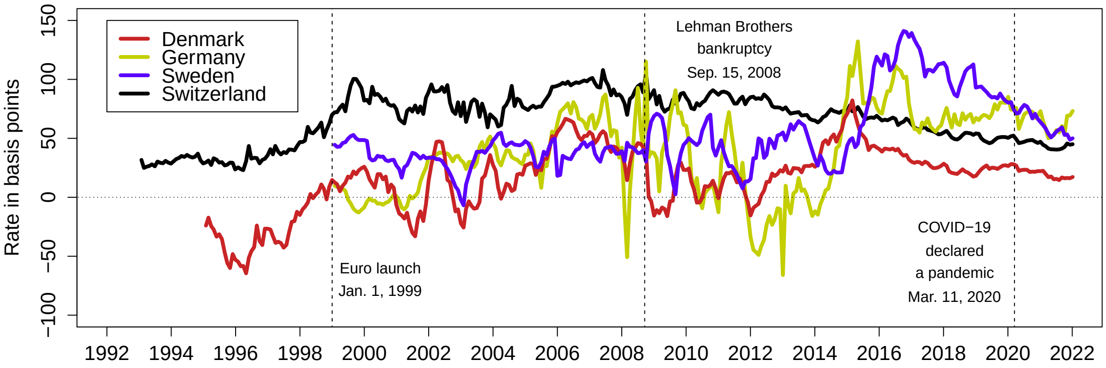

Figure 2: **Average Estimated Government Bond Safety Premia**
Illustration of the average estimated bond safety premium for each observation date implied by the AFNS-R model estimated with a diagonal specification of $K^{\mathbb{P}}$ and Σ using Danish, German, Swedish, and Swiss government bond prices. The German data is described in this paper and cover the period from January 31, 1999, to December 31, 2021. The Swedish data cover the same period, while the Danish and Swiss data follow the analysis of CM and start on January 31, 1995, and January 29, 1993, respectively. In all cases, the bond safety premia are measured as the estimated yield difference between the frictionless yield to maturity of individual bonds with the market risk factor turned off and the corresponding fitted yield to maturity.

the constraints that $X^R_{t|t} = 0$ for all t, $\theta^{\mathbb{Q}}_R = 0$, and $\sigma_{44} = 0$. These prices are denoted $\left\{\tilde{P}^i_t\right\}_{t=1}^T$ and converted into yields to maturity $\tilde{y}^{c,i}_t$ by solving equation (5) in the same way as above. They represent estimates of the prices that would prevail in a world without any financial frictions or convenience premia. The safety premium for the ith bond is then defined as

$$\Psi^i_t \equiv \tilde{y}^{c,i}_t - \hat{y}^{c,i}_t, \tag{6}$$

where $\tilde{y}_t$ is the frictionless yield and $\hat{y}_t$ the fitted yield.

For each market we calculate the average of the estimated premia for each observation date, denoted $\overline{\Psi}^j_t$ for country j. These monthly averages of estimated safety premia for our four bond markets are shown in Figure 2.

As for magnitudes, Switzerland has the highest safety premium among our four series with an average of 0.66 percent, closely followed by Germany and Sweden with average safety premia of 0.62 percent and 0.54 percent, respectively, while Denmark has lower safety premia, which average 0.15 percent. This ranking seems reasonable given that Switzerland has a long history of being considered a safe haven country in times of crisis, while Germany has the most liquid government bond market in the euro area.

One notable difference between the German, Swedish, and Swiss safety premia on one hand and the Danish safety premia on the other is observed during the financial crisis, when key crisis events like the onset of the crisis itself in the summer of 2007 and the bankruptcy of Lehman Brothers in September 2008 coincided with spikes in the former safety premia, while they tend to be associated with declines in the Danish safety premium. We speculate that Denmark's peg to the euro was viewed by global investors as less of a safe haven during this period.

In the late 1990s, both Danish and Swiss safety premia increased notably. CM associate these increases with the launch of the euro on January 1, 1999. Hence, the introduction of the euro appears to have affected investors' perceptions about the relative scarcity of safe assets in neighboring non-euro member countries like Denmark and Switzerland.

Moreover, we note that the German and Swedish safety premium series exhibit a unique behavior in the 2015-2017 period, which coincided with the asset purchase programs operated by the ECB and the Riksbank at the time; see Christensen and Zhang (2024) for details and analysis of the latter.

Lastly, the onset of the COVID-19 pandemic in spring 2020 left at most a short-lived mark on the safety premia in these four government bond markets.

5.1.1 Interpretation of the Estimated Bond Safety Premia

Before proceeding to our empirical analysis, we want to briefly elaborate on the interpretation of the estimated bond safety premia.

In our approach, we estimate the convenience premia embedded in the bond prices in each government bond market using a standard dynamic term structure model augmented with a bond-specific risk factor with a unique loading structure that varies with the maturity and age of each bond. By observing a cross section of bond prices over time—each with a different time-since-issuance and time-to-maturity—the overall bond-specific risk factor and each bond's loading on that factor are identified and distinguished from the conventional fundamental risk factors in the model. Hence, our approach is very direct and does not rely on observing any additional information beyond the panel of bond prices itself.

This direct way of estimating bond-specific risk premia contrasts with the existing literature where liquidity and convenience premia are identified and measured by comparing different securities that share key characteristics. A notable example is Longstaff (2004), who uses bonds issued by the Resolution Funding Corporation (Refcorp) and compares their yields to those of regular U.S. Treasury securities. Given that both bonds are fully backed and guaranteed by the U.S. Treasury Department, there is no credit risk involved, and for sure no credit risk *differential* to consider. Hence, when Refcorp bonds systematically trade with a positive yield spread it must be for other reasons. Longstaff (2004) argues that the positive spread is due to the extreme liquidity of U.S. Treasuries and interprets the positive yield spread as a convenience premium in favor of U.S. Treasuries. However, it could equally well be an illiquidity discount in the prices of Refcorp bonds, even though Longstaff (2004) tries to rule that out. Crucially, this type of analysis does not in itself tell us the source of the yield spread, which can come from either market or be a mix of effects in both markets.

In the European context, researchers have examined the yields of bonds issued by Kreditanstalt für Wiederaufbau (KfW) in Germany and compared them to the yields of German bunds (the class of bonds we examine in this paper), see De Santis (2014) and references therein for examples. Similar to the analysis by Longstaff (2004), it is the case that both of these classes of bonds are fully backed and guaranteed by the same entity, the German government. Thus, there are again no credit risk *differentials* to consider. As a consequence, KfW-bund yield spreads should contain a minimum of safety premia as they cancel out in the yield spread calculation. Instead, KfW-bund yield spreads mainly represent a measure of the relative liquidity risk premia across the two bond markets. In contrast, our estimated bond-specific risk premia likely reflect both liquidity risk discounts and safety price premia. Importantly, we only observe the net effect, which is a large price premium that makes us refer to them as safety premia. For that same reason we are implicitly assuming in the regression analysis in the next section that most of the variation in our estimated safety premium series are driven by variation in the underlying unobserved true safety premia.

These observations suggest that there may only be a weak link between our estimated German bund safety premia and KfW-bund yield spreads. To test that conjecture, we regress our estimated German bund safety premium series on KfW-bund yield spreads with two, five, seven, and ten years to maturity constructed as described in Appendix A. The results of these regressions are reported in Table 3. First, for the regressions with the individual KfW-bund yield spread series, we note the significant coefficients for short- to medium-term maturities. However, as we go past the five-year maturity point, the statistical significance declines quickly with no relationship statistically detectable at the ten-year maturity. Importantly, despite the statistical significance, the adjusted R^2-values are small in all four regressions. Crucially, including all four spread series as explanatory variables increases the adjusted R^2 to 0.17, but all four regression coefficients are now statistically insignificant. Thus, there does not seem to be a robust relationship between the KfW-bund yield spreads and our estimated German bund safety premium series.

The negative coefficients in the individual regressions imply that increases in the KfW-bund yield spreads, say, from a flight-to-liquidity away from KfW bonds and towards German bunds tend to coincide with declines in our estimated German bund safety premia. This finding is consistent with the view that our estimated German bund safety premium series is the net effect of underlying unobserved positive safety premia somewhat tempered by offsetting negative liquidity premia. Hence, when there are flight-to-liquidity spikes in the German bond markets, there is some tendency to see moderation in the estimated safety premia. However, we stress that this effect is very modest based on the low adjusted R^2-values and the fact that the statistically significance is entirely absent in the regression with

	1	2	3	4	5
Constant	88.657***	91.502***	87.357***	81.399***	85.738***
	(4.684)	(5.176)	(5.457)	(4.863)	(5.512)
KfW-bund yield spread (2yr)	-0.575***				-0.079
	(0.210)				(0.437)
KfW-bund yield spread (5yr)		-0.535***			-2.750
		(0.196)			(2.139)
KfW-bund yield spread (7yr)			-0.300		3.109
			(0.183)		(3.063)
KfW-bund yield spread (10yr)				-0.076	-0.932
				(0.147)	(1.287)
Adj. R^2	0.128	0.092	0.031	0.000	0.172

Table 3: **Regressions of German Safety Premia on KfW-Bund Yield Spreads**
Reported are results of standard ordinary least squares regressions with the average estimated German bund safety premium as the dependent variable and KfW-bund yields spreads with two, five, seven, and ten years to maturity as the explanatory variables. Standard errors computed by the Newey-West estimator (with four lags) are reported in parentheses. All samples are monthly covering the period from January 31, 1999, to December 31, 2021. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

all four KfW-bund yield spreads.

Based on this evidence we draw two conclusions. First, the convenience yield spreads analyzed in the existing literature based on prices for bonds backed by the same ultimate guarantor mainly, if not outright exclusively, reflect relative liquidity premia. They only contain a minimum of safety premia as those cancel out in the spread calculation by construction. Second, as a corollary, a direct stand-alone analysis like ours that only relies on the observed bond prices is needed to measure the safety premia embedded in the prices of highly rated bond markets. This underscores the strength of our empirical approach.

Finally, regarding the robustness of the individual safety premium series, we point to CM. For the estimated Swiss safety premia we use, their paper documents that those safety premium estimates are insensitive to varying the data frequency as daily, weekly, and monthly data produce similar results. Furthermore, their paper considers the most parsimonious and the most flexible unconstrained version of the AFNS-R model and reports little change in the estimates. Lastly, their paper allows for varying degrees of stochastic volatility in the frictionless level, slope, and curvature factors, which does not affect the results much either. We take these results to demonstrate that the safety premium series are very robustly estimated. Mechanically, this robustness is due to the fact that the safety premia are identified from the cross section of bond prices on each observation date.

After this closer look at the interpretation and robustness of our estimated safety premium series, we can turn our attention to the key question about the connection between them and the supply of safe assets.

5.2 Regression Analysis

We measure the average treatment effect of the ECB's QE asset purchases on the safety premia within a panel regression framework. In particular, the regression equation for the safety premium from country j takes the form:

$$\overline{\Psi}_t^j = \alpha + \delta_{pspp} d_t^{pspp} + \delta_c' D_t + \sum_{l=0}^{L} \delta_l' X_{j,t-l} + \gamma_j + \epsilon_{j,t}. \tag{7}$$

Here, d_t^{pspp} is the stock of bonds acquired by the ECB through the PSPP, expressed as a percentage of nominal GDP in the euro area;[16] D_t and X_t are vectors of control dummies and continuous control variables, respectively; L is the number of lags included; γ_j is the country fixed effects; and $\epsilon_{j,t}$ is a random residual. The estimate of δ_{pspp} measures the effect on the safety premia of a 1 percentage point change in the stock of bonds held by the ECB under the assumption that the confounding variables in the vector $X_{j,t}$ are exogenous and that $E[\epsilon_{j,t}|X_{j,t}] = 0$.

We control for a host of confounding factors. Specifically, we consider the CBOE Volatility Index (VIX), the TED spread, the 10-year on-the-run premium in U.S. Treasuries, and the spread between the Italian and each country's 10-year government bond yield to proxy for investors' risk aversion, financial market uncertainty, and related demand for safe-haven assets;[17] we use each country's debt-to-GDP ratio to control for effects tied to the supply of government bonds;[18] and the overnight interest rate in each country serves as a proxy for the opportunity cost of holding money and the associated liquidity premia of government bonds, as explained in Nagel (2016). For each country, we include the average government bond age and the one-month realized volatility of the 10-year government bond yield as additional proxies for bond liquidity following the work of Houweling et al. (2005). Inspired by the analysis of Hu et al. (2013), we include a noise measure of the government bond prices in each country to control for variation in the amount of arbitrage capital available in each market. We add the overnight federal funds rate to proxy for the U.S. safe-asset liquidity premium as in Nagel (2016), and we consider the MOVE volatility index to proxy for risk aversion in global bond markets. In addition, we include the domestic QE program in the case of Sweden because the Swedish QE program is highly correlated with the ECB purchases. Omitting the Swedish QE variable could lead to contaminated estimates for the ECB QE effect. Finally,

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[16] In principle, this measure should only include the amount of quasi-safe assets that have been acquired by the ECB and replaced with safe reserves, i.e., bonds issued by high-risk countries in the periphery of the euro area, and should hence exclude safe bonds issued by highly rated countries in the core of the euro area. However, in the absence of that granular data, we use the entire stock of purchased government-backed securities as a proxy for the amount of replaced quasi-safe assets. Provided the ratio of quasi-safe assets in the ECB's portfolio is close to being constant, which is a reasonable assumption given the fixed distribution key for the purchases, there should be little bias in the estimated parameter. Please see Appendix B for detailed information on the ECB QE programs.

[17] See Grisse and Nitschka (2015).

[18] See Krishnamurthy and Vissing-Jorgensen (2012).

	1	2	3	4
α	87.150***	51.064***	61.555***	53.602***
	(3.053)	(12.136)	(11.583)	(9.682)
δ_{pspp}	-0.371***	-0.316***	-0.362***	-0.388***
	(0.045)	(0.048)	(0.054)	(0.038)
controls	No	Yes	Yes(Δ)	Yes(6 lags)
Country FE	YES	YES	YES	YES
No of obs	328	328	328	304
Adj. R^2	0.801	0.881	0.848	0.955

Table 4: **Average Treatment Effects of ECB Asset Purchases**
The table reports the coefficient estimates from regression (7) together with their respective robust standard errors. The first column reports the regression without controls, the second column reports the estimates with the set of control variables, the third column contains the results including controls in first differences, and the last column contains controls with L set to six lags. The last three rows report the use of country fixed effects, the number of observations, and the adjusted R^2. The underlying safety premium sample starts in January 1995 for Denmark, in January 1999 for both Germany and Sweden, and in January 1993 for Switzerland. In all four cases, the samples end in December 2021. Note that we only run the regression for the period since January 2015 after the ECB had launched its first QE program. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

we add a few dummy variables in D_t, including a dummy variable to control for the introduction of the euro in January 1999, a dummy variable to indicate whether the country under investigation is in a negative interest rate environment, and a dummy variable for the Swiss safety premium that takes the value of one in the period of minimum exchange rate control by the Swiss National Bank from September 2011 to January 2015 and zero otherwise.

Table 4 reports the results in which column (1) contains the outcomes without any controls, while columns (2)-(4) report the regressions conducted by using the control variables in levels, the control variables in first differences, and the control variables with six lags, respectively. We stress that the sample used in these regressions starts in January 2015 after the ECB had launched its first actual QE program on January 22, 2015, to focus squarely on the period with active bond purchases. We note that the coefficient on the ECB QE purchase variable is negative and statically significantly so in all four regressions, in particular in the most conservative specification (4) with six lags included. Moreover, the sizes of the estimated coefficients are all similar and not statistically different from each other. Specifically, we find that an increase in the ECB QE bond purchases equal to 1 percentage point of nominal GDP in the euro area will lead to an average decline in the safety premium across the four countries between 0.32 basis point and 0.39 basis point, where the largest estimate for the safety premium decline comes from the most conservative regression with lagged control variables, reported in column (4). Importantly, the significance of these results are robust and hold up when we cluster the standard errors at the country level as documented in Appendix C.

	1	2	3	4	5	6	7	8
α	29.983***	30.476	53.908*	213.513***	-54.109*	9.474	88.509***	2.898
	(10.779)	(22.125)	(31.403)	(71.469)	(31.052)	(34.089)	(9.139)	(30.754)
δ_{pspp}	-0.373***	-0.320***	-0.697***	-1.378**	-1.528***	-1.766***	-0.290***	-0.323***
	(0.064)	(0.062)	(0.233)	(0.662)	(0.383)	(0.211)	(0.028)	(0.057)
δ_{se}					5.379***	3.328***		
					(1.266)	(0.712)		
controls	Standard	6 lags	Standard	6 lags	Standard	6 lags	Standard	6 lags
Country	DEN	DEN	GER	GER	SWE	SWE	SWI	SWI
No of obs	82	76	82	76	82	76	82	76
Adj. R^2	0.886	0.936	0.540	0.753	0.847	0.968	0.929	0.926

Table 5: **Country-Specific Treatment Effects of ECB QE**
The table reports the coefficient estimates from regression (7) with the set of control variables, but run for each country separately. We use Newey-West standard errors with four monthly lags. The underlying safety premium sample starts in January 1995 for Denmark, in January 1999 for both Germany and Sweden, and in January 1993 for Switzerland. In all four cases, the samples end in December 2021. Note that we only run the regression for the period since January 2015 after the ECB had launched its first QE program. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

We further analyze the data using separate country-specific regressions with Newey-West standard errors. These results are reported in Table 5. The findings are qualitatively similar to the panel regression results, but we can see that the effects of the ECB QE program vary across the countries in our sample. The Swiss safety premium is reduced by approximately 0.3 basis point for ECB QE purchases of additional bonds equivalent to 1 percent of euro area GDP, which is the smallest effect across the four countries in the sample. The largest impact on the safety premium is found in Sweden. In particular, Swedish bond safety premia are materially affected by the ECB asset purchase program, as columns (5) and (6) in Table 5 suggest. An increase in the ECB bond purchases equal to 1 percent of euro area GDP will reduce the safety premium by between 1.53 basis points and 1.77 basis points. Interestingly, the domestic QE purchases by the Riksbank have the opposite effect with significant positive effects.[19] Note that these positive coefficients are loadings on the Swedish QE purchases measured as a percentage of Swedish nominal GDP. Hence, they are not directly comparable to the results for the ECB QE purchases other than in terms of their interpretation. Importantly, all these results are economically significant. Hence, the country-specific results confirm that the ECB asset purchase program had important negative influences on the safety premium dynamics in Denmark, Germany, Sweden, and Switzerland.

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[19] We take these positive coefficients to imply that the Riksbank's domestic QE bond purchases significantly increased the scarcity of Swedish government bonds and thereby helped offset the negative effects flowing from the increase in truly safe assets caused by the ECB's QE program; see Christensen and Zhang (2024) for an analysis.

	1	2	3	4
α	45.144***	35.502***	30.329***	61.339***
	(0.846)	(6.191)	(4.544)	(8.045)
δ_{pspp}	0.245***	-0.135***	-0.137***	-0.118***
	(0.023)	(0.038)	(0.037)	(0.039)
controls	NO	YES	YES(Δ)	YES(6 lags)
Country FE	YES	YES	YES	YES
No of obs	1224	1224	1220	1200
Adj. R^2	0.409	0.608	0.576	0.611

Table 6: **Average Treatment Effects of ECB Asset Purchases: Full Sample**
The table reports the coefficient estimates from regression (7) together with their respective robust standard errors. The first column reports the regression without controls, the second column reports the estimates with the set of control variables, the third column contains the results including controls in first differences, and the last column contains controls with L set to six lags. The last three rows report the use of country fixed effects, the number of observations, and the adjusted R^2. The safety premium sample starts in January 1995 for Denmark, in January 1999 for both Germany and Sweden, and in January 1993 for Switzerland. In all four cases, the samples end in December 2021. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

5.2.1 Full Sample Results

For robustness we rerun the regressions using all available data from each country. In addition, we expand the measure of the ECB asset purchases to cover the period before their launch by simply inserting 0s for the earlier period.

First, we focus on the average estimated treatment effect using our full panel of data. These results are reported in Table 6. We note that the estimated average treatment effects are smaller when we use the full sample of data available for each country. Importantly, though, they remain negative and highly statistically significant for the empirically relevant cases where we include control variables. Furthermore, the adjusted R^2s all decline notably. This points to some instability over time in the empirical relationships between our dependent variables on one side and the control variables on the other. This makes us prefer the results from the 2015-2021 subsample that speaks most directly to the effects of the asset purchases and the associated increases in the supply of safe assets while they were taking place.

Second, we repeat the exercise for the individual safety premium series. Table 7 shows that the safety premia for the four countries are significantly negatively correlated with the ECB QE purchases for the full sample as well. An increase in the ECB QE program equal to 1 percent of nominal euro area GDP lowers the safety premium extracted from the respective government bond yield curves to varying degrees with estimates ranging from 0.42 basis point to 1.74 basis points, when controls are included. Interestingly, in general, the estimated effects are not smaller in this exercise. Rather, the results are qualitatively and quantitatively similar to those reported in Table 5. Overall, we take these results to underscore the robustness of

	1	2	3	4	5	6	7	8
α	-24.687*	-6.618	-61.924***	-118.490***	38.719**	44.230*	22.954***	21.784**
	(12.974)	(14.723)	(23.067)	(29.331)	(16.824)	(24.510)	(8.497)	(10.421)
δ_{pspp}	-0.422***	-0.426***	-0.438***	-0.557***	-1.914***	-1.737***	-0.540***	-0.509***
	(0.073)	(0.090)	(0.149)	(0.160)	(0.338)	(0.387)	(0.036)	(0.043)
δ_{se}					6.480***	5.984***		
					(1.088)	(1.291)		
controls	Standard	6 lags	Standard	6 lags	Standard	6 lags	Standard	6 lags
Country	DEN	DEN	GER	GER	SWE	SWE	SWI	SWI
No of obs	324	318	276	270	276	270	348	342
Adj. R^2	0.731	0.775	0.688	0.705	0.825	0.827	0.880	0.871

Table 7: **Country-Specific Treatment Effects of ECB Asset Purchases: Full Sample** The table reports the coefficient estimates from regression (7) with the set of control variables, but run for each country separately. We use Newey-West standard errors with four monthly lags. The safety premium sample starts in January 1995 for Denmark, in January 1999 for both Germany and Sweden, and in January 1993 for Switzerland. In all four cases, the samples end in December 2021. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

our findings.

To summarize, based on both joint panel and individual country-specific regressions, we find a strong and statistically significant negative correlation between our estimated safety premium series and the ECB's asset holdings as a share of nominal GDP in the euro area. Given that this measure of the ECB's asset holdings represents a proxy for the amount of quasi-safe assets that has been replaced by safe central bank reserves, we take these results to show that the resulting increase in the supply of truly safe assets lowered the excess price that very safe government bonds in and around the euro area can command in financial markets. Hence, our findings point to an important international transmission channel of QE that operates by altering the relative supplies of quasi-safe versus truly safe assets.

6 Conclusion

In this paper, we argue that central bank large-scale asset purchases can alter the relative supply of safe and quasi-safe assets in international bond markets and thereby affect the prices of safe assets. Specifically, when a central bank buys quasi-safe assets in exchange for truly safe reserves, the outstanding amount of safe assets increases, which may depress the excess price premia that highly safe assets can command in financial markets.

To test that conjecture, we use government bond prices from four highly rated countries to estimate their respective bond safety premium series and examine whether they were affected by the ECB's bond purchases under its PSPP during the 2015-2021 period, which included large volumes of quasi-safe bonds issued by governments in the periphery of the euro area.

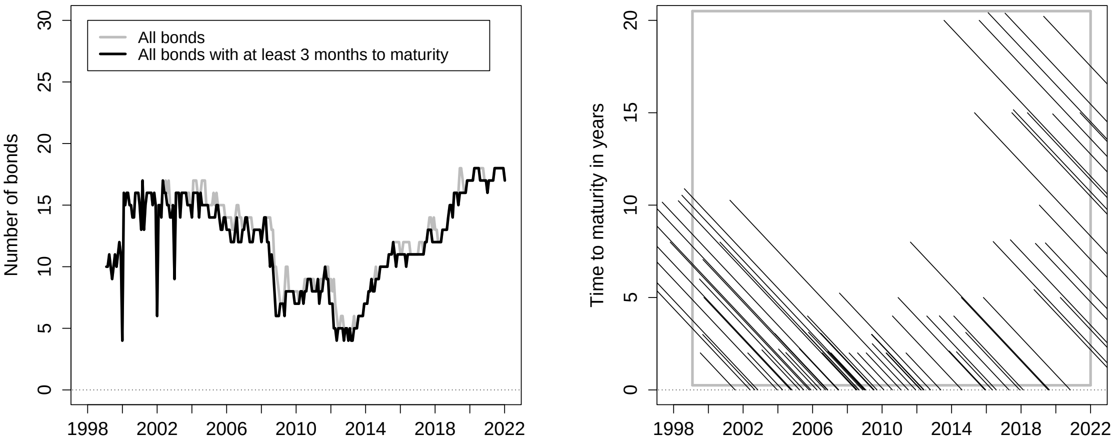
Using panel regressions with an extensive list of control variables, we find that asset purchases by the ECB equivalent to 1 percent of nominal GDP in the euro area tends to lower the safety premia by about 0.35 basis points. Given that the ECB increased its bond holdings by about 40 percent of GDP over the 2015-2021 period, these results suggest that the QE bond purchases lowered the safety premia in these four countries by as much as 0.12 percent, which is a notable amount given how low the overall interest rate level was during that period.

Importantly, a reduction in safety premia means a reduction in bond prices. Hence, the ECB QE purchases pushed *up* interest rate levels in these four countries. Whether this was offset by reductions in general term premia—the conventional way QE purchases are thought to affect bond markets—is not clear from our analysis, and we leave that question for future research.

Still, our results point to an important international transmission mechanism that works by replacing quasi-safe government bonds with truly safe central bank reserves and thereby affecting the perceptions about and the associated convenience premia tied to the *relative* scarcity of very safe government bonds. As a consequence, it would be interesting to explore whether our findings extend to other highly rated countries in Europe. However, we also leave that question for future research.

A Appendix: KfW Bond Data

In this appendix, we describe the data for the bonds issued by the German institute Kreditanstalt für Wiederaufbau (KfW) that we use in the empirical analysis in Section 5.1.1. The sample contains standard fixed-coupon bonds denominated in euros with pricing information available for at least half of the business days during the life of each bond. Finally, a few bonds with unreasonable and erratic price patterns were eliminated. We consider the resulting sample of 70 bonds to be representative of the market for KfW bonds during our sample period.



(a) Number of KfW bonds

(b) Distribution of KfW bonds

Figure A.1: **Overview of the KfW Bond Data**
Panel (a) reports the number of outstanding KfW bonds at a given point in time. Panel (b) shows the maturity distribution of the KfW bonds in the sample. The solid gray rectangle indicates the sample used in our analysis, where the sample is restricted to start on January 31, 1999, and limited to KfW bond prices with more than three months to maturity after issuance.

The number of outstanding KfW bonds over time in our sample is shown with a solid gray line in Figure A.1a. At the end of our sample period—which runs from January 1999 to December 2021—17 bonds were outstanding. However, as is widely recognized, prices of bonds near their maturity tend to be somewhat erratic. Therefore, to facilitate model estimation, we drop bonds from our sample when they have less than three months to maturity. Using this cutoff, the number of bonds in the sample is modestly reduced as shown with a solid black line in Figure A.1a.

Generally, the KfW has issued a variety of standard fixed-coupon bonds with original maturities ranging from 2 years to 20 years during our sample period. The maturity distribution of the 70 bonds in our sample is shown in Figure A.1b. Each bond is represented by a single downward-sloping line that plots its remaining years to maturity for each date. Overall, there

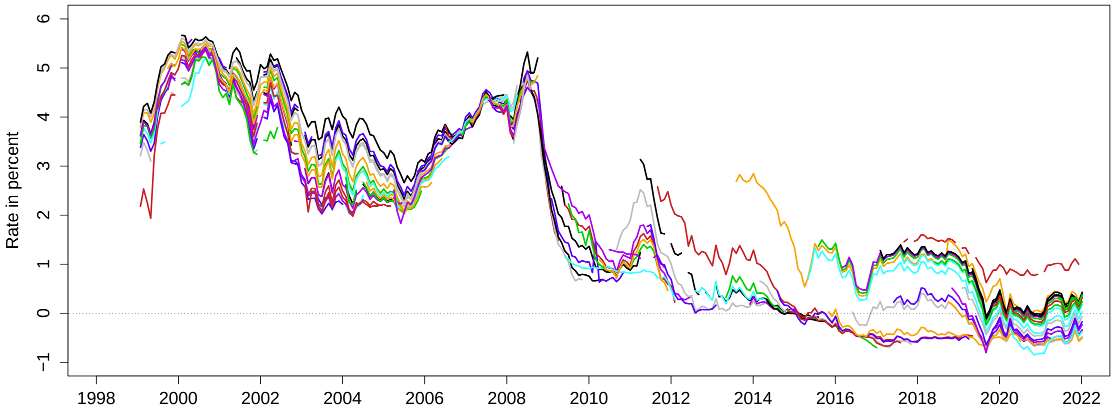


Figure A.2: **Yield to Maturity of KfW Bonds**

is significant variation in the maturity range covered by the outstanding bonds in our sample. However, our estimation method that uses all information in the entire panel of bond prices is well suited to handle this.[20]

Figure A.2 shows the KfW bond prices converted into yield to maturity. Several things are worth noting regarding these yield series. First, there is a trend lower in the general yield level during this period from roughly 5 percent in the early 2000s to around zero by the end of our sample. Second, there is pronounced business cycle variation in the shape of the yield curve around the lower trend. The yield curve tends to flatten ahead of recessions and steepen during the initial phase of economic recoveries. These characteristics are the practical motivation behind our choice of using a three-factor model for the KfW yield curve, adopting an approach similar to what is standard for U.S. and U.K. data; see Christensen and Rudebusch (2012).

To construct the spreads between the yields of KfW bonds and those of German bunds, we first obtain fitted German bund zero-coupon yields by estimating the arbitrage-free generalized Nelson-Siegel (AFGNS) model developed in Christensen et al. (2009) using our sample of German bund prices. We then obtain fitted KfW zero-coupon yields by estimating the simpler arbitrage-free Nelson-Siegel (AFNS) model described in Christensen et al. (2011) using the sample of KfW bond prices described above. By deducting the former from the latter at fixed two-, five-, seven-, and ten-year maturities, we get estimates of the yield spread at those constant maturities that we then regress on our estimated German bund safety premium with the results of these regressions reported in Table 3 in the main text.

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[20] Finlay and Wende (2012) examine prices from a limited number of Australian inflation-indexed bonds using the extended Kalman filter for estimation similar to our approach.

B Appendix: The ECB Quantitative Easing Programs

The QE programs implemented by the European Central Bank (ECB) starting in 2015 represented a monetary policy tool aimed at stimulating the economy and combatting deflationary pressures. The ECB's first outright QE program was officially announced in January 2015 and started operating in March 2015.[21] At its peak in 2022, the Eurosystem held assets totalling an amount equal to about 55% of euro area nominal GDP. The total stock of assets acquired under the QE program stood at €3,373 billion by the end of June 2023. The purchases were throughout allocated according to the Eurosystem national central banks' shares in the ECB's capital key, which reflect each countrys share in the total population and gross domestic product (GDP) of the euro area.

ECB introduced a number of quantitative easing programs, under the overarching umbrella program known as the Asset Purchase Programs (APP). There are four major asset purchase programs included in the APP: The public sector purchase program (PSPP), the corporate sector purchase program (CSPP), the asset-backed securities purchase program (ABSPP), and the third covered bond purchase program (CBPP3). Figure B.3 provides an overview of the net asset purchases made under these four programs. It is worth noticing that PSPP is by far the largest asset purchase program operated by the ECB. Furthermore, the other programs operated in assets such as corporate bonds that are not considered safe. To be conservative, we limit our focus to the PSPP program in the paper even though it is clear that purchases of risky assets like corporate bonds in exchange for safe reserves would expand the outstanding amount of truly safe assets as well.

Under the PSPP the ECB actively purchased public sector securities in two periods: 1) March 2015–December 2018; 2) November 2019–June 2022. The principal payments from maturing securities were reinvested fully until February 2023, and only partially since then. The PSPP security holdings consist of nominal and inflation-indexed government bonds issued by euro area countries, and bonds issued by recognised agencies, regional and local governments, international organisations, and multilateral development banks in the euro area. The majority of the securities held in the PSPP portfolio is in the form of government bonds and recognised agencies' bonds.

The primary goal of the ECB's QE programs was to bring the inflation rate to its 2% target and boost economic growth in the eurozone. Under the programs, the ECB purchased a substantial amount of government bonds and other eligible assets from eurozone countries. The ECB had certain selection criteria for the eligible assets. For instance, bonds had to be above a minimum credit rating and meet certain maturity requirements. This helped maintain the quality and safety of the assets acquired through the QE programs. These purchases have

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[21] On 22 January 2015, the ECB introduced the Public Sector Purchase Program (PSPP), which would supplement the Asset-Backed Securities and Covered Bonds Purchase Programs (ABSPP and CBPP3) already in place.

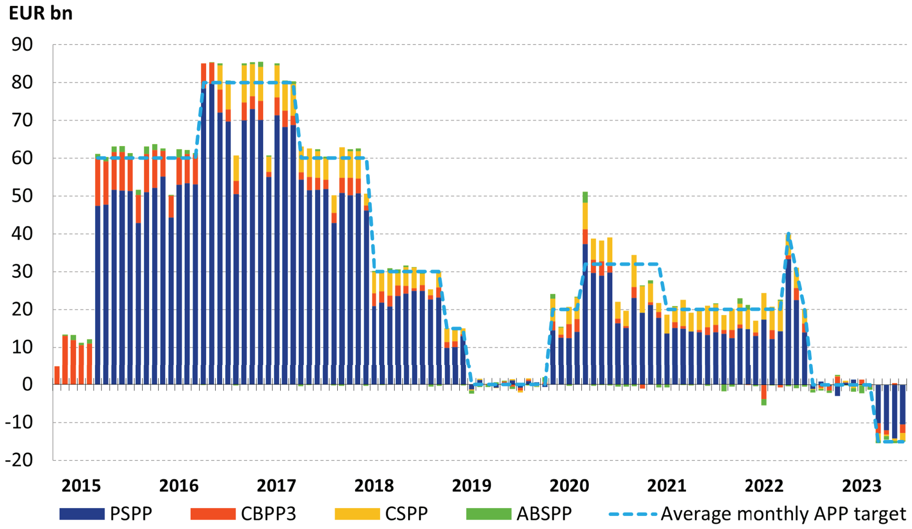

Figure B.3: **The ECB Asset Purchase Programs: Net Asset Purchases**
Illustration of the net asset purchases by different programmes under the asset purchase programmes. All numbers are in billions of euros. Source: the ECB official statistics.

been shown to have direct impacts on financial markets, for examples see De Santis (2020); Koijen et al. (2021); Arrata et al. (2020); and to have substantial impacts on macroeconomic variables, see Gambetti and Musso (2020) and Hohberger et al. (2019), amongst many others.

After June 2022, ECB started to only partially reinvest principal payments from maturing securities in its portfolio of purchases assets. On March 1, 2023, the ECB switched to full-blown quantitative tightening (QT) after eight years of balance sheet expansion by committing to reducing its public sector bond holdings by €15 billion per month. This process of normalizing the ECB's balance sheet is anticipated to be very gradual and presumably will follow the Eurosystem capital key as well.

C Appendix: Additional Regression Results

	1	2	3	4
α	87.150***	51.064	61.555**	53.602*
	(1.069)	(29.499)	(10.722)	(18.343)
δ_{pspp}	-0.371***	-0.316**	-0.362***	-0.388***
	(0.018)	(0.069)	(0.057)	(0.064)
controls	NO	YES	YES(Δ)	YES(6 lags)
Country FE	YES	YES	YES	YES
No of obs	328	328	328	304
Adj. R^2	0.801	0.881	0.848	0.955
Std. Err.	Country	Country	Country	Country

Table A1: **Average Treatment Effects of ECB Asset Purchases: Clustered SE**
The table reports the coefficient estimates from regression (7) together with their respective clustered standard errors. The first column reports the regression without controls, the second column reports the estimates with the set of control variables, the third column contains the results including controls in first differences, and the last column contains controls with L set to six lags. The last three rows report the use of country fixed effects, the number of observations, and the adjusted R^2. The underlying safety premium sample starts in January 1995 for Denmark, in January 1999 for both Germany and Sweden, and in January 1993 for Switzerland. In all four cases, the samples end in December 2021. Note that we only run the regression for the period since January 2015 after the ECB had launched its first QE program. Asterisks *, ** and *** indicate significance at the 10 percent, 5 percent and 1 percent levels, respectively.

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Sveriges Riksbank
Visiting address: Brunkebergs torg 11
Mail address: se-103 37 Stockholm

Website: www.riksbank.se
Telephone: +46 8 787 00 00, Fax: +46 8 21 05 31
E-mail: registratorn@riksbank.se