

How quantitative easing changes the nature of sovereign risk

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How quantitative easing changes the nature of sovereign risk[☆]

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ABSTRACT

We model the market stabilization function of quantitative easing (QE) programs as a put option written by the central bank to bond holders. This implicit put option protects bond holders against tail risks, in particular sovereign credit risk. The contingent claims model (CCM) that we use to value the implicit put option has not been applied to QE in the literature before. Based on this model, we examine the effect of the European Central Bank's bond purchases by QE on the sovereign credit risk of eight countries of the Economic and Monetary Union (EMU). Model simulations show that in times of market stress investors attached a high value to the implicit put option on sovereign bonds. This indicates that QE lowers investors' perception of sovereign default risk. Understanding this effect of QE is important for addressing tail risks in the euro area via a backstop facility.

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1. Introduction

Since the Global Financial Crisis (GFC) in 2007–2008, central banks have used large-scale asset purchase programs known as quantitative easing (QE) programs. Such programs are primarily aimed at easing the monetary stance by lowering interest rates to prevent downward inflation spirals (see, for instance, [Eser and Schwaab, 2016](#); [Ghyssels et al., 2017](#)). Some QE programs also aim at supporting the monetary transmission process by countering financial market stress (see, for instance, [Acharya et al., 2019](#)).

Compared to the existing literature on the effects of QE on the monetary stance, there is less research of the effectiveness of QE as an instrument to stabilize financial markets, by providing a backstop for some tail risks in sovereign bond markets to support monetary transmission. Our contribution is to study the effectiveness of this backstop. The tail risks covered by the backstop relate to sovereign default risk and associated risk aversion and to disorderly market conditions in public debt markets such as market illiquidity, fire sales, and excessive asset price volatility. In the Economic and Monetary Union (EMU) such risks came to the fore during the sovereign debt crisis in 2010–2012 and at the start of the COVID-19 pandemic in 2020.

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Two related studies about the effects of QE on tail risk in sovereign bond markets are [Hattori et al. \(2016\)](#) and [Cortes et al. \(2022\)](#). Both studies rely on option-implied measures of tail risk of different asset classes and conduct event-study estimations around QE announcements by the US Federal Reserve (Fed). [Hattori et al. \(2016\)](#) measure tail risk in bond markets by the risk neutral densities implied by swaptions, to estimate investors' expectations of large swings in interest rates. They find significant mitigating effects of the announcements of QE and forward guidance on interest rate risks, in particular on volatility expectations and risk premia of long-term interest rates. [Cortes et al. \(2022\)](#) compare the domestic and spillover effects of Fed QE announcements following the subprime and COVID-19 crisis on the tail risks of various assets, including US treasury bonds. They find that announcements of the COVID-19 interventions by the Fed helped to limit tail risk also for mid-maturity government bonds. Our study complements the work of [Hattori et al. \(2016\)](#) and [Cortes et al. \(2022\)](#) by the focus on sovereign risk of EMU countries in relation to the asset purchase programmes of the European Central Bank (ECB). Furthermore, we use a different econometric approach. We derive the option value of the central bank backstop for sovereign bond investors, based on a structural credit-risk model using the contingent claims model (CCM). Instead, the option-implied measures of tail risk used by [Hattori et al. \(2016\)](#) and [Cortes et al. \(2022\)](#) are empirical proxies for sovereign-bond risk that are tested in event studies around daily announcements of QE. Moreover, the empirical application of the CCM model allows us to connect the put option value with macro-economic fundamentals such as governments' finances and the volatility of sovereign bond returns. Furthermore, the CCM model captures the non-linearities between the put-option value and the structural risk parameters.

The CCM has not been applied to central bank bond purchases in the literature before. It is well-known that QE impacts the bond markets via the signaling channel, the duration extraction channel, and the portfolio rebalancing channel. In addition to that, we relate the backstop function of QE to the credit risk extraction channel ([Costain et al., 2021](#)). This backstop can be explicit if asset purchases are conducted to stabilize financial markets. The backstop can however also be implicit if asset purchases are conducted for the purpose of maintaining price stability or supporting monetary transmission. The backstop makes interest payments on sovereign debts more sustainable by lowering sovereign bond yields so that sovereigns can issue new debt at more favorable interest rates, while the interest payments on the bonds held by the central bank will accrue to the treasury in the form of dividends.

A central bank's market stabilization role bolsters the low-risk status of sovereign debt. [Brunnermeier et al. \(2022\)](#) connect this to the central bank's role as market-maker of last resort, which guarantees the possibility of trading sovereign bonds and keeping bid-ask spreads low. In principle, the market stabilization function is only needed in situations where the market itself fails to strike a good equilibrium. Our paper focuses on the more crisis-prone countries in the EMU where it may be extra challenging for the market to coordinate an equilibrium. [De Grauwe and Ji \(2013\)](#) hypothesize that sovereign bond markets in the EMU are more vulnerable to market failure than in stand-alone countries because there is no single national central bank that can act as a monetary back-stop for sovereign default risk. This can lead to a bad equilibrium with rising sovereign spreads, capital outflows, and increasing sovereign default risk. The asset purchases by the ECB therefore have an important signaling function for the low-risk status of EMU sovereign bonds. As a reference point, we also assess the impact of the asset purchase programs in countries that are less prone to crises.

By acting as market-maker of last resort, the central bank changes the nature of sovereign risk. The central bank backstop in particular removes some tail risks from the market, and therefore it shares features with an implicit put option written by the central bank to investors. The literature usually associates a central bank put with the US Federal Reserve responding to stock market downturns (see e.g., [Cieslak and Vissing-Jorgensen, 2021](#)). We add to this concept the option provided by QE, which can be exercised by investors in extreme market conditions by selling the sovereign bonds that they hold in their portfolio to the central bank. These extreme market conditions refer to a common shock that affects all countries in the EMU, such as the COVID-19 pandemic's impact on the financial market. The implicit put option protects investors against some tail losses on their bond holdings. Consequently, the existence of the implicit put option will induce investors to change their expectations about the safety of sovereign bonds, specifically their assessment of sovereign default risk and liquidity risk.

The implicit central bank put option provides a backstop to investors enabling them to sell their bonds to the central bank when the bond value drops below a certain threshold and the sovereign risk spreads increase, indicating dysfunctioning bond markets. We focus on a number of key crisis-prone (periphery) EMU countries, in particular Italy, Ireland, Spain, Greece and Portugal. These countries likely benefit more from the market stabilization effect of QE than the less crisis-prone countries. We test this hypothesis by comparing the put values of three periphery countries with the put values of three core EMU countries (Germany, France and Belgium). Our simulations show that in times of market stress investors attach a high value to the implicit put option on sovereign bonds provided by QE, in particular with regard to the sovereign risk of periphery countries. After the central bank starts buying sovereign bonds, simulations with the CCM show that the value of the put option decreases, reflecting a decline in default risk owing to the central bank backstop. An important parameter that determines this outcome is the volatility of the returns on the underlying bonds. Since the market stabilization function of QE particularly influences bond market volatility, we conduct counterfactual simulations for the option value, based on the estimated volatility parameter excluding the influence of QE. We show that the difference between the actual put value and its counterfactual value tends to be higher in periphery than in core countries. This confirms our hypothesis, implying that QE has additional value for investors in crisis-prone countries.

The remainder of the paper is structured as follows. [Section 2](#) provides the context of the market stabilization function of QE. [Section 3](#) presents the theoretical framework which links the sovereign credit spread to the volatility of sovereign bond

returns. This relationship is applied in Section 4 to the CCM. Section 5 describes the empirical results of the CCM, after which Section 6 concludes.

2. The market stabilization function of QE

The ECB has conducted sovereign bond purchases via several programs since the sovereign debt crisis of 2010–2012 (Fig. 1). We jointly define them as QE programs, while acknowledging that an individual program may have a specific objective. The ECB has increasingly used QE as a market stabilization instrument to successfully reduce the fragility of EMU sovereign bond markets. De Grauwe and Ji (2013), for instance, show that in countries where QE is applied as a market stabilization instrument there is less evidence for overshooting credit spreads.

The ECB activated the Securities Markets Program (SMP) in 2010 to ensure sufficient depth and liquidity in dysfunctioning segments of the sovereign bond markets. This classifies SMP as a market stabilization instrument. Empirical studies show that the SMP indeed had a downward effect on the targeted sovereign bond yields (see, for instance, ECB, 2015).

Similarly, the Outright Monetary Transactions program (OMT) was announced by the ECB in 2012 “to address severe distortions in government bond markets which originate from, in particular, unfounded fears on the part of investors of the reversibility of the euro. Hence, under appropriate conditions, OMTs are an effective backstop to avoid destructive scenarios with potentially severe challenges for price stability in the euro area” (Draghi, 2012). As the purpose of OMT is to avoid bad equilibria, it also classifies as a market stabilization instrument. The mere announcement of the OMT program effectively calmed financial markets and the actual use of this instrument was not needed.

In March 2020, the Pandemic Emergency Purchase Program (PEPP) was introduced as a non-standard monetary policy measure with both a monetary stance and a market stabilization objective (Lane, 2020). The purpose of this program was to provide investors with the reassurance that self-fulfilling market instability risks will be contained by the stabilizing presence of the central bank liquidity provision. The PEPP successfully contributed to stabilizing sovereign bond markets, as the level and volatility of bond yields returned to pre-crisis levels within several months after the start of the pandemic.

The ECB's prime QE program to ease monetary and financial conditions is the Public Sector Purchase Program (PSPP), which it activated in 2015. The PSPP's purpose is to address the risk of a prolonged period of low inflation. Lowering long-term bond yields by sovereign bond purchases can contribute to raise inflation, since lower bond yields loosen financial conditions for firms and households and so support spending and GDP growth. While it also supports the fiscal position of EMU governments, the PSPP is not a market stabilization instrument. Nonetheless, the PSPP also has changed the character of the sovereign bond market, since the ECB holds a significant amount of sovereign debt of EMU countries. The PSPP is the largest program in terms of assets purchased (Fig. 1). The bonds purchased under the PSPP are guided by the Eurosystem's national central banks' capital key, subject to issue share and issuer limits. These rules aim to preserve market functioning and price discovery and to ensure that the purchases would not be perceived as circumventing the euro area's monetary financing prohibition. While the PSPP was not introduced as a market stabilization instrument, it contributed to reducing sovereign bond yields by about 30–50 basis points at announcement (Altavilla et al., 2015). The long-term stock effects of the PSPP on euro area bond yields are estimated to range from 50 to 100 basis points (Eser et al., 2019). To formally analyze the QE programs, we now introduce a structural model for sovereign credit risk.

3. Theoretical framework and concepts

In this section we first discuss a theoretical framework for sovereign credit risk, which determines the relationship between the credit spread on sovereign bonds and bond return volatility. Second, we review the concepts of credit risk and volatility and discuss the application of the framework to sovereign risk of EMU countries.

3.1. Theoretical framework

Our theoretical framework for sovereign credit risk follows the approach in Jeanneret (2015) and Gómez-Puig et al. (2018).¹ For ease of exposition, we assume that the government issues an infinite maturity debt contract that gives creditors a claim on the sovereign's assets A through a constant debt service that is initially set at C . The level of the sovereign's assets evolves over time according to the following stochastic process:

$$dA_t = \mu A_t dt + \sigma A_t dZ_t \quad (1)$$

where σ represents the constant volatility of the asset growth rate μ and Z is a Brownian motion. We assume that the government defaults on its debt (D) if the asset value falls below the exogenously defined threshold B . This default occurs at time:

$$T^D = \inf \{t > 0 | A_t < B\} \quad (2)$$

¹ For an elaborate derivation of the theoretical framework we refer to the online appendix.

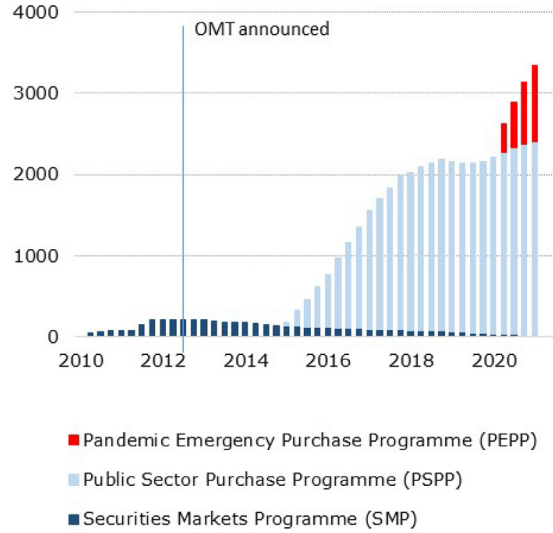


Fig. 1. ECB sovereign bond purchase programs (EUR billions).

In the event of default at time T^D , the government and creditors restructure the debt contract and agree to reduce the amount of debt service by a fraction ϕ , with $\phi \in [0, 1]$.

Sovereign bonds do not offer explicit and contractual seniority to particular groups of creditors. Around a sovereign default some creditors however may get a preferential status in practice. [Steinkamp and Westermann \(2014\)](#) for instance show that market participants expect that at least some multilateral creditors will be senior to private investors in case of a sovereign default in the euro area. The debt service C that the sovereign has to pay is therefore a weighted average of what it has to pay to senior creditors B and junior creditors J to be willing to invest in the debt contract:

$$C = \alpha C_B + (1 - \alpha) C_J$$

where α is the fraction of sovereign debt held by senior creditors.² We define $C_J = C_B + \lambda$ to reflect that junior creditors implicitly demand a higher reward λ than senior creditors to compensate for the risk of being subordinated to senior debt holders. In case of a default the reduction in the debt service will be different across creditors. For senior creditors, the fraction ϕ_B may be negligible, while for junior creditors the fraction ϕ_J may be substantial. Again, the overall fraction ϕ is a weighted average across senior and junior creditors:

$$\phi = \alpha \phi_B + (1 - \alpha) \phi_J.$$

Under the assumptions above, the value of sovereign debt is given by the sum of the present discounted value of coupons C until default plus the present discounted value of coupons after default:

$$D(A_t) = \mathbb{E}^Q \left[\int_0^{T^D} C e^{-rt} dt \right] + \mathbb{E}^Q \left[\int_{T^D}^{\infty} (1 - \phi) C e^{-rt} dt \right]. \quad (3)$$

With r being the risk-free interest rate for all maturities. In the euro area, r would be best approximated by the Overnight Indexed Swap (OIS) rate. The closed form solution to this pricing equation, which gives the price of debt as a function of the asset value, reads as follows:

$$D(A_t) = \frac{C}{r} \left[1 - \phi \left(\frac{A_t}{B} \right)^\beta \right] \quad (4)$$

with $\beta = \frac{1}{2} - \frac{\mu}{\sigma^2} - \sqrt{\left(\frac{1}{2} - \frac{\mu}{\sigma^2} \right)^2 + \frac{2r}{\sigma^2}} < 0$ see, for instance, [Dixit and Pindyck \(1994\)](#).

By definition the credit spread (s) is given by the difference between the sovereign bond's coupon yield and the risk-free rate:

$$s(A_t) = \frac{C}{D(A_t)} - r \quad (5)$$

or

² One can think of C and α as the parameters that clear the market.

$$s(A_t) = \frac{r\phi\left(\frac{A_t}{A}\right)^\beta}{1 - \phi\left(\frac{A_t}{A}\right)^\beta}. \quad (6)$$

Further, if we apply Itô's lemma to the pricing equation we find that the volatility of the sovereign bond returns (σ_D) and the volatility of sovereign assets returns are connected in the following way (see the online appendix for the derivation):

$$\sigma_D = \sigma A_t \frac{D_A}{D(A_t)} \quad (7)$$

where D_A is the derivative of the sovereign debt value ($D(A)$) with respect to the sovereign asset value (A). This further simplifies to:

$$\sigma_D = -\frac{\beta\phi\sigma\left(\frac{A_t}{A}\right)^\beta}{1 - \phi\left(\frac{A_t}{A}\right)^\beta} \quad (8)$$

Using the equations for the credit spread and volatility of the sovereign bond returns, we can derive the following mechanical relation between the sovereign bond's credit spread and the volatility of the sovereign bond returns:

$$s(A_t) = -\frac{r}{\beta\sigma} \sigma_D. \quad (9)$$

Because $\beta < 0$ this relation implies that a higher sovereign bond return volatility goes hand in hand with a higher credit spread. The relation between both variables is affected by the risk-free rate, the expected return on sovereign assets, and the volatility of sovereign assets returns.

3.2. Credit risk and tail risks

Credit risk reflects the probability and size of economic losses resulting from a borrower defaulting on its contractual obligations towards a debtor. From an ex ante perspective there are several degrees of a loss that can be treated as separate credit risk components. First, investors require a compensation for the expected loss. This measure is forward-looking and conditional on, for instance, the debtor's current value, leverage, volatility, debt structure, and the risk-free interest rate. The compensation for expected loss differs between senior and junior debt holders, as derived in the previous section. Second, risk-averse investors will also require compensation for the unexpected loss. Third, when risk aversion is very high, investors also want to be compensated for a loss that even goes beyond the unexpected loss. This is the stress loss embedded in the tail of a loss distribution (see Fig. 2).

Measures of credit risk therefore take into account tail risks, which are associated with default risk, which in turn interacts with liquidity or exchange rate risk. Such tail risks will show up in extreme values of bond returns volatility. In credit risk models, tail risk is usually expressed in terms of a number of standard deviations of a certain loss amount (Chatterjee, 2015). Tail risk expresses the likelihood and size that a credit related loss will exceed the expected loss, measured by the number of standard deviations by which the actual loss deviates from the expected loss at a certain confidence level.

Empirical literature finds that the compensation and risk premiums required for the three credit risk components is time-varying (Heynderickx et al., 2016). Investors find it difficult to diversify tail risk due to the high correlation between defaults in stressed market conditions. Correlated defaults are indeed associated with systemic risk and financial instability (Ibragimov et al., 2011; Patro et al., 2013). Central banks try to mitigate this risk of correlated defaults by providing a backstop to financial markets, e.g., by extending liquidity provision to counterparties, and through asset purchase programs.

3.3. Volatility

Based on the relation between the sovereign bond's credit spread and the volatility of the sovereign bond returns derived in the previous subsection, we use the realized volatility of sovereign bond price returns (σ_D) as an indicator for sovereign default risk. An alternative approach would be to derive the implied volatility from the market prices of interest rate derivatives, based on the evolution of the entire term structure. In theory, historical volatility is closely correlated to implied volatility, since the latter is derived from an option series on a future and the future itself is related to individual bonds, of which one is cheapest to deliver. There are also valid reasons from an empirical perspective to believe that the historical volatility of sovereign bond price returns is a reasonable approach for our analysis. First, given that bond returns along the entire term structure are correlated, the observed volatility of the most liquid bond is in general a reasonable proxy for the volatility of the entire term structure. If the liquid bond is consistently priced, the observed volatility of the term structure will move in line with the volatility of the return of the most liquid bond. Second, central banks that implement QE, in principle buy sovereign bonds over the entire term structure according to the outstanding amounts, in order to be market neutral. Third, in CCM models applied to sovereign risk, it is common to use historical volatility instead of implied volatility, see for instance Gray et al. (2007b) and Gómez-Puig et al. (2018). Finally, there is not a liquid market for interest rate derivatives

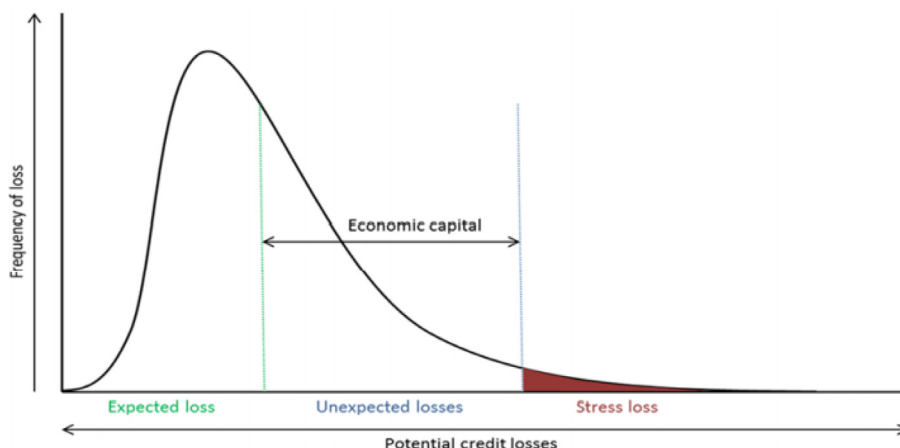


Fig. 2. Credit loss distribution. Source: Chatterjee, 2015

for the countries in our sample, which makes it impossible to use implied volatility in the CCM model later on. Moreover, implied volatility also has its own challenges, as it is model-dependent and difficult to interpret, as Fabozzi (2009) points out.

Fig. 3 shows the realized volatility of 10-year sovereign bond price returns of several EMU countries in our sample. Volatility is measured as the annualized standard deviation of daily bond returns calculated over a rolling 45-day horizon. Volatility was low until the Global Financial Crisis in 2008, which was a wake-up call for investors that sovereign bonds of EMU countries are risky. Volatility has peaked occasionally since then, most strongly during the European sovereign debt crises of 2010–2012. It was in this period that the ECB introduced QE. At the start of the COVID-19 pandemic in March 2020, volatility peaked again and the ECB implemented additional monetary policy measures. We now turn to the CCM as an application of the theoretical framework to analyze sovereign credit risk with a structural model.

4. Contingent claims model

In this section we first discuss the CCM that we use as the structural model in this paper. Second, we present the model set-up and the empirical application. Third we introduce the data.

4.1. Application of the CCM

A contingent claim is a derivative contract whose future payoff depends on the value of another asset. The CCM deals with the valuation of these derivative contracts and is a generalization of the option pricing theory founded by Black and Scholes (1973) and Merton (1973). The CCM has been applied to a wide variety of settings, ranging from corporate default risk (Merton, 1974, and Leland, 1994) to financial stability (Gray et al., 2010).

In structural credit risk models such as the CCM, the credit or default risk is driven by uncertainty in the assets value of a debtor relative to its debt obligations, i.e. the default barrier. The CCM is useful for deriving risk-neutral default measure estimates. We apply the CCM to sovereign credit risk. The CCM is usually called the “Merton model” when it is applied to measure credit risk (Merton, 1974). The Merton model takes a balance sheet perspective and is based on the following three guiding principles: (i) the value of liabilities is derived from the values of assets; (ii) asset values follow a stochastic process similar to Eq. (1), and (iii) different types of liabilities have different priority, i.e., senior and junior claims on the assets. These principles also apply when analyzing sovereign credit risk. Gray et al. (2007b) introduce the CCM to sovereign credit risk assessment. Gapen et al. (2007), Briere and Ferrarini (2016), and Gómez-Puig et al. (2018) follow similar approaches to derive forward-looking indicators of sovereign risk. Following Gray et al. (2007b) we assume that all sovereign assets and liabilities are measured at their current market values. This means that random changes in financial inflows, outflows, and fluctuations in market prices cause uncertainty in the values of the sovereign assets and liabilities. As a consequence, the total value of all sovereign assets could decline below the level of promised payments on the debt, causing distress or even default.

Comparable to the theoretical framework in Section 3.1, the CCM relates a measure of credit risk to sovereign bond return volatility. The measure of credit risk in this case is the price of a put option. Key features of this model are its structural specification and the independence of economic agents’ preferences or return expectations. In a situation without QE, an investor is fully exposed to the default risk of a sovereign bond. In this case the observed spread of a bond is a compensation for the expected loss on the bond plus the risk premium that risk-averse investors require to hold the bonds. The required compensation differs between senior and junior debt holders. This risk premium is a compensation for the unexpected loss. In

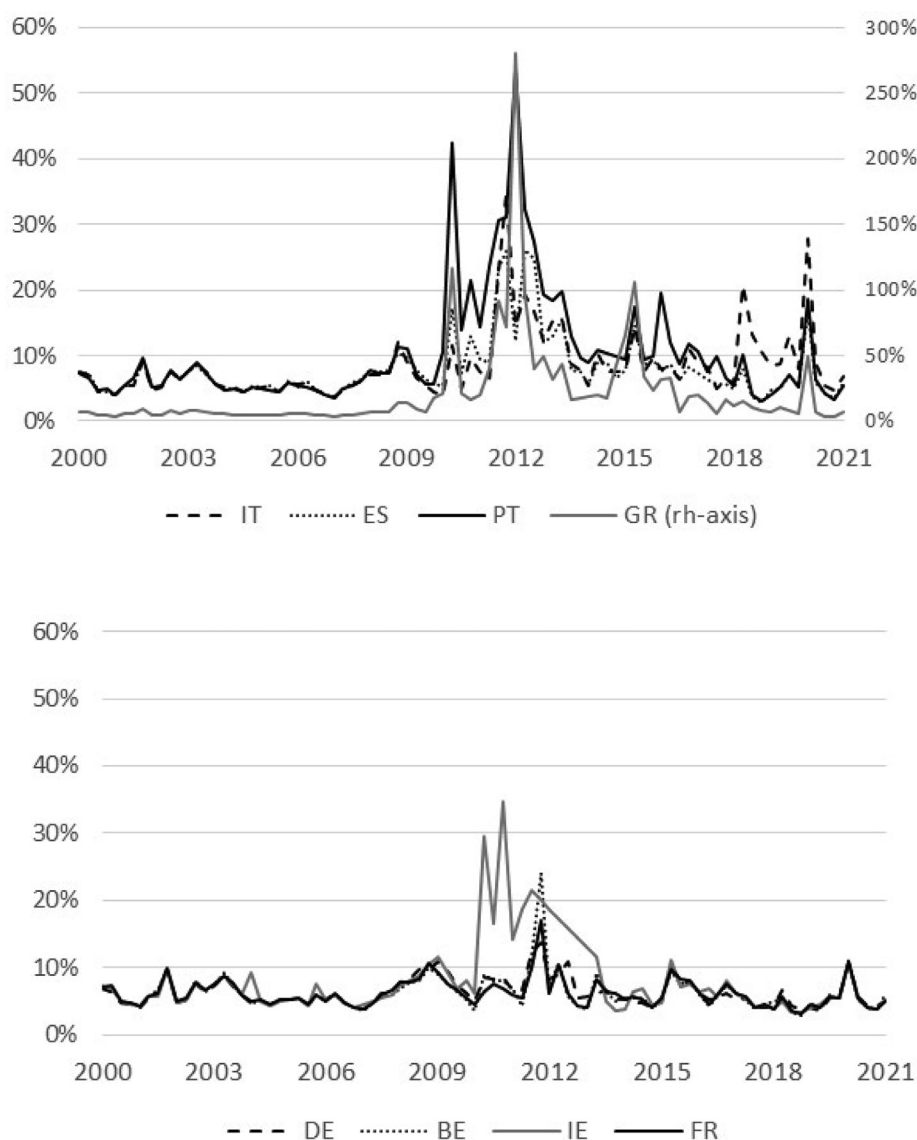


Fig. 3. Bond return volatility (end-of quarter annualized standard deviation of daily bond returns, calculated over 45-day horizon; percentage).

stressed market conditions, the risk premium may overshoot due to high risk aversion among investors who also require a compensation for a possible stress loss (see also Fig. 1).

In a situation with QE as a market stabilization instrument, the bondholder is protected from negative tail outcomes by the central bank put. Note that the investor does not directly pay a premium for this protection, because the central bank considers market stability to be a public good. The central bank finances the central bank put by creating money in the form of central bank reserves when buying bonds. The put premium is implicit and actually accrues to the sovereign which issues the bond that is eligible for QE, since the put option for tail risk reduces the risk premium component in the bond spread. This is the case for newly issued bonds. With regards to existing bonds that become eligible for QE, the windfall of the put option accrues to the bondholder (investor) to the extent that the put premium (which does not have to be paid) is larger than the reduction in the bond spread at the moment the put is written.³ In that case existing bond holders earn a windfall due to the central bank put option.

³ Note that the sovereign is typically the single shareholder of the central bank. So the sovereign also benefits from the profits that the central bank makes on its QE program. The expected profit is a function of the bond yield relative to the funding costs of creating central bank reserves. The profits are distributed over time to the sovereign in the form of dividends. Similarly, the sovereign may receive less benefits if the QE program is loss-making.

Our motivation to use the CCM as a structural model to assess the effect of the central bank backstop on sovereign risk is the important role of volatility in the model. By including realized bond return volatility in the CCM, this market stabilizing effect of QE is then taken into account in the valuation of the put option. The option value is proxied by performing counterfactual simulations from 2015 onwards. Moreover, since realized volatility is time-varying and driven by risk aversion, it also addresses some of the limitations of the CCM. One limitation is that the CCM assumes Gaussian distributed probability distributions with constant volatility, while risky-asset returns have empirical distributions with fat tails and volatility clusters and actual default probability distributions are fat tailed. In the literature various methods are proposed to remedy the assumption of a Gaussian distribution for the underlying asset returns, such as alternative volatility models or adjustments of the default probability (see [Aboura et al., 2014](#) for an overview). We apply the latter method by mapping the risk-neutral default probabilities onto actual sovereign default data. The mapping is based on data of sovereign default rates per credit rating bucket, as collected by Moody's for the 1983–2020 period. We use those actual default rates to adjust the risk-neutral default probability. This adjustment ensures that the default probability used in the CCM exhibits the fat tail characteristics of real world sovereign default risk. Another limitation of the CCM is that it assumes the market for sovereign assets to be frictionless, competitive and arbitrage-free in order to have a self-financing trading strategy. More complicated approaches to correct for this are beyond the scope of our paper and in general will lead to higher values for the implicit put option due to the higher uncertainty involved ([Cochrane and Saá-Requejo, 2000](#)). Also note that to the extent the CCM leads to estimation errors, these are likely of the same sign and order of magnitude and therefore will cancel out in the counterfactual analysis that we perform.

The starting point for the CCM is a sovereign's balance sheet, where both assets and liabilities are marked-to-market. Whereas the outstanding amounts of sovereign debt, both in local and in foreign currencies, can be easily observed, this is not the case for the market value and the volatility of sovereign assets. The CCM is nevertheless effective in getting an "implied" estimate of both variables using the observable market price dynamics of sovereign liabilities.

Here an assumption is necessary to distinguish between junior and senior sovereign debt. [Gray et al. \(2007b\)](#) define local currency sovereign debt and base money to be junior and foreign currency debt to be senior. The main argument is that sovereign local-currency liabilities have "equity-like features" because governments can easily issue local-currency debt and base money in large amounts even if this causes a dilution in their value.

However, individual EMU countries have no control over the currency in which their debt is denominated, since the ECB controls the monetary base in the euro area. As part of a monetary union, individual EMU countries cannot inflate or dilute local currency debt in a crisis situation before defaulting on foreign currency debt. In this case foreign currency debt can therefore not be assumed to be senior to local currency debt. Therefore an alternative approach is required. [Gómez-Puig et al. \(2018\)](#) deal with this by classifying creditors according to their residency and institutional characteristics. This classification is based on sovereign debt restructurings in the past. Most sovereign debt contracts offer no explicit seniority to a particular group of creditors, however in practice some creditors may have a preferred status. [Gómez-Puig et al. \(2018\)](#) argue that multilateral organizations such as the IMF are the most senior lenders. Domestic banks also have a senior status as they typically have substantial investments in domestic government bonds. The government's creditworthiness depends heavily on the creditworthiness of its domestic banks and the government therefore has an incentive to treat domestic banks as senior lenders, to not undermine its own creditworthiness. Bonds held by the ECB and other national central banks in the euro area are also senior claims. Bonds however held by the domestic central bank and private investors are junior claims according to [Gómez-Puig et al. \(2018\)](#). We follow their approach, except for their treatment of domestic central bank debt as junior claims, taking into account that the ECB and all national central banks in the euro area have one common credit status. In the next subsection we explain how we apply their approach.

4.2. Model set-up

Similar to [Gómez-Puig et al. \(2018\)](#), we define junior sovereign debt (J) to be equal to the value of total sovereign debt held by domestic investors excluding domestic banks.⁴ This assumes that, although the government may default on its debt held by domestic investors, it will try to avoid defaulting on the part held by domestic banks to prevent the collapse of the banking sector as a consequence. This argument is particularly relevant for the vulnerable countries because commercial banks in these countries typically hold significant amounts of local government debt. We define senior sovereign debt (B) to be equal to the total default-free value of sovereign debt held by preferred creditors (e.g. multilateral organizations) plus the interest payments (being part of C in [Section 3.1](#)) minus sovereign debt held by junior debt holders (J). We assume that the bonds purchased under QE programs are part of the sovereign debt held by senior creditors and the strike price of the put option is equal to the default-free value of debt (B). The interest payments are a composite of interest rate payments on the debt held by senior and junior creditors and so implicitly differences in credit spreads on debt held by senior and junior bond holders are taken into account.

⁴ In the context of a country, the residual claim on the country's assets belongs to junior bondholders since countries do not have shareholders. In other words, the role of junior bondholders in a structural credit-risk model of a country akin to [Merton \(1974\)](#), is equivalent to the role of shareholders in a structural credit-risk model for a firm.

Both junior and senior debtholders have a claim on the sovereign's assets. The value of the claim that junior creditors have in the CCM is given by

$$J_t = A_t N(d_1) - B_t e^{-rT} N(d_2) \quad (10)$$

where A is the unobserved market value of sovereign assets, r the long-term risk-free market interest rate, T the duration of the sovereign debt, $d_1 = \frac{\ln\left(\frac{A_t}{B_t}\right) + (r + \frac{1}{2}\sigma^2)T}{\sigma_A \sqrt{T}}$, $d_2 = d_1 - \sigma_A \sqrt{T}$, σ is the unobserved volatility of the return on sovereign assets, and $N(\cdot)$ the cumulative standard normal distribution function. $N(d_1)$ is the risk-neutral probability of the value of the assets at maturity exceeding the default-free value of debt. Variable d_2 is the distance to distress and $N(-d_2)$ reflects the risk-neutral probability of default. We take a long-term, risk-free market interest rate because the average duration of the outstanding debt is also long-term. We derive the risk-free interest rate from collateralized interest rate swaps (OIS rate). From the CCM we moreover know that the value of the claim that junior creditors have is also equal to

$$J_t = A_t \frac{\sigma}{\sigma_D} N(d_1) \quad (11)$$

Where σ_D is the volatility of the sovereign bond returns as observed in financial markets. Because sovereign debt contracts in the euro area offer no explicit seniority to a particular group of creditors the observed sovereign bond price and volatility reflect the preferences of senior and junior creditors.⁵ The historical volatility is time-varying and driven by investors' risk aversion and thereby addresses one of the limitation of the CCM in assuming Gaussian distributed probability distributions with fixed parameters.

Eqs. (10) and (11) together can now be used to numerically solve for the two unknowns: sovereign asset value (A) and sovereign asset volatility (σ).⁶ The numerical procedure involves an iterative procedure where σ_D is taken as the initial value for σ while the initial value of A is guessed. Using these initial values, σ and A are calculated for each quarter. The procedure repeats until the values of both σ and A converge to values that simultaneously solve from equations (8) and (9) in the successive iterations. The tolerance level for the convergence is set at 10^{-9} (for the procedure see Tabbae and Van den End, 2005).

Based on this we can determine the value of the implicit put option,

$$P_t = B_t e^{-rT} N(-d_2) - A_t N(-d_1) \quad (12)$$

The value of put option P reflects the expected loss (related to the risk-neutral default probability), which is covered by the debt guarantee (Gray et al., 2007a).⁷ B is the value of debt held by senior bond holders and B determines the strike price of the put option since the seller of the option (or guarantor) provides protection against default on the debt. Applying this concept to QE as a market stabilization instrument, the strike price of the put option on sovereign bonds is implicit as its level is not communicated by the central bank to the market.

The value of the risky debt D equals the value of a default-free bond with similar duration minus the value of the put option:

$$D_t = B_t e^{-rT} - P_t \quad (13)$$

Gray et al. (2007a) relate the yield to maturity (y) of risky debt (D) to the credit spread (s), which is defined as the compensation for the risk-neutral default probability,

$$\exp(-y_t) = \frac{D_t}{B_t} = \frac{B_t e^{-rT} - P_t}{B_t} \quad (14)$$

which can be rewritten to get the spread s written in terms of P ,

$$s_t = y_t - r_t = -\frac{1}{t} \ln \left(1 - \frac{P_t}{B_t e^{-rT}} \right) \quad (15)$$

The strike price in terms of the sovereign debt level is related to a reference level of the credit spread at which the central bank will intervene with asset purchases to prevent disorderly market conditions.⁸

By extending QE programs over time, the ECB has (implicitly) shown an increased willingness to provide protection against tail risk in sovereign bond markets. In the CCM model this implies that the strike price of the central bank put option is reduced, or in other words, the central bank is prepared to intervene at an increasingly lower level of sovereign debt and

⁵ Note that the sovereign could default on the bonds held by the central bank without directly affecting the price of the bonds held by external investors.

⁶ A theoretical proxy for the value of A is the present discounted value of the net fiscal surpluses (see for instance Gapen et al., 2007). However, calculating this proxy is problematic as it requires estimating future economic performance, the political commitment to a variety of programs including social security and other entitlement programs, and the use of an appropriate discount rate.

⁷ We follow the approach taken by other papers in this field and use the pricing formula in Eq. (12) which is applicable to European options on non-dividend paying assets and which can only be exercised at expiration. Pricing formulas that do take into account early exercise make the valuation procedure more complicated without materially changing the outcomes.

⁸ The reference level of the spread is inversely related to the bond price, as central bank interventions at a lower spread level mean that the central bank is prepared to buy at a higher bond price level and vice versa.

associated spread level. A reason for this might be that the central bank finds that the monetary transmission process is distorted at a lower level of spreads than it was before.

To reflect this time-varying nature of the strike price, we extend the CCM model by adding to the option equation for the strike price S_t , which is the time-varying level at which the central bank activates the option,

$$P_t = (B_t + (B_0 - S_t))e^{-rT}N(-d_2) - A_tN(-d_1) \quad (16)$$

In the steady state at $t = 0$ it holds that $B_0 = S_0$, with P_t being equal to the put option value in Eq. (12). In Eq. (16), however, the value of the option increases if the default-free debt B_t increases relative to a constant strike price ($S_t = S_0$). A higher sovereign debt level implies higher sovereign default risk, making the put option written by the central bank increasingly valuable for investors.

The option value also rises if the debt level B_t remains constant ($B_t = B_0$), while the central bank lowers the strike price S_t . A lower strike price implies that the central bank is prepared to purchase sovereign bonds for market stabilization purposes at lower levels of sovereign debt, which is associated with a lower reference level of the bond spread. This would raise the value of the put option for investors if the actual debt level B_t remains constant or increases.

The put option value and the credit spread on sovereign bonds are both related to the default risk of sovereign bonds. The main difference is that the put option value measures the implicit protection of investors in sovereign bonds and the aggregate value of this protection by central bank QE programs at each point in time. While the credit spread is only a function of the probability and size of economic losses resulting from a borrower defaulting. Furthermore, the intervention by the central bank via QE programs is less directly linked to the default risk of individual countries, as QE programs are implemented in all EMU countries (countries with high or low default risk), in relation to the shares of national central banks in the capital of the ECB (capital key).

4.3. Data

For the CCM we use quarterly data on sovereign debt taken from the ECB's Statistical Data Warehouse (see Appendix 1), for the period 2000Q1 – 2021Q1. This data source provides data on total government debt, interest payments, domestic government debt, short term debt and government debt securities held by domestic banks. Data on the duration of government debt and the risk-free interest rate is taken from Bloomberg. Total government debt, or public debt, includes the debt of the central, local, and government sub-sectors. While actually only central government debt is sovereign debt, we use this broader concept of public debt since this debt is eligible for the ECB's public sector purchase programs.

5. Outcomes

In this section we first show the empirical results for the put option values based on the CCM. Second we perform a counterfactual analysis. Third we do a scenario analysis with higher interest rates. Fourth, we provide a discussion and an interpretation of the numerical results.

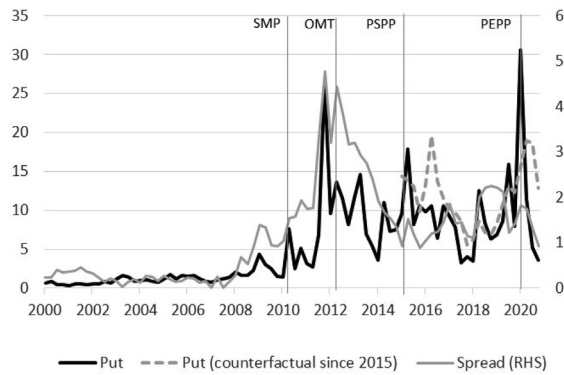
5.1. Put values

We conjecture that the central bank effectively provides investors with a put option on sovereign bonds via QE. The central bank backstop will lower the option value if it reduces the default risk on debt. A likely channel for this is the downward effect of asset purchases on bond return volatility, which is a driving factor of $A, N(-d_1)$ and of the put option value P in Eq. (12) and bearing in mind that σ drives A and d_1 . We apply the numerical procedure from the previous section to derive the put option values for eight countries: Germany, France, Belgium, Italy, Spain, Ireland, Greece and Portugal, see Box 1 for a numerical example. Based on the put values of the individual countries, we also construct an aggregate put value for a group of periphery and core EMU countries and for the full sample of countries, as proxy for the put value in the EMU as a whole. These eight countries together represent 60% of the euro area based on their capital keys. Using the put values of the periphery and core EMU country groups we test the hypothesis that investors attach a higher value to the put option written on crisis-prone countries.

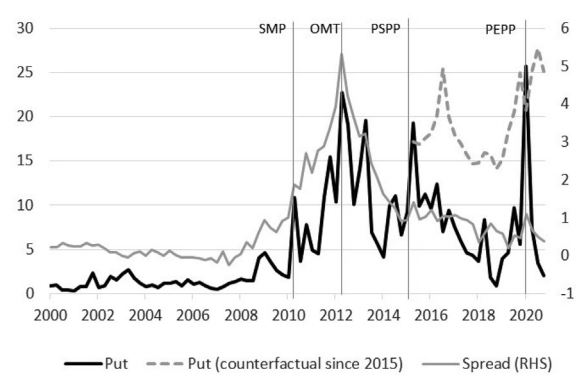
Fig. 4 shows the evolution of the put option value (in billions of euros) over time for the different countries and the full sample aggregate.⁹ The option value is based on the time-varying realized bond return volatility σ , which is derived from volatility of the sovereign bond returns σ_D , among other things. The option values increased sharply following the EMU sovereign debt crisis and decreased after mid-2012, in tandem with the decline of volatility in sovereign bond markets (see Fig. 2). At

⁹ For calculating the put option's value we first calculate $d_1 = \frac{\ln\left(\frac{B_t}{S_t}\right) + (r + \frac{1}{2}\sigma^2)T}{\sigma_A\sqrt{T}}$ and $d_2 = d_1 - \sigma_A\sqrt{T}$. Next, we transform these variables in the following way $d'_1 = \ln(1.7d_1 + 1)$ and $d'_2 = \ln(1.1d_2 + 0.9)$. Note that $N(-d_2)$ represents the risk-neutral default probability which overstates the actual default probability (Gray et al., 2007a). In the application to corporate credit risk, the standard adjustment mechanism for this is to map firm risk-neutral default probabilities against a database of actual corporate defaults (Moody's KMV). Similarly we map the rating based sovereign default probabilities of Moody's on the distance to distress. The parameters α and β in $\ln(\alpha d_1 + \beta)$ are calibrated by minimizing the difference between the actual default probabilities and $1 - \ln(\alpha d_1 + \beta)$. The outcomes are sensitive to calibration of the mapping.

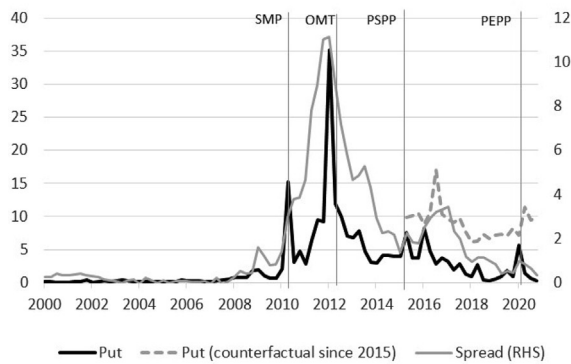
Italy



Spain



Portugal



Ireland

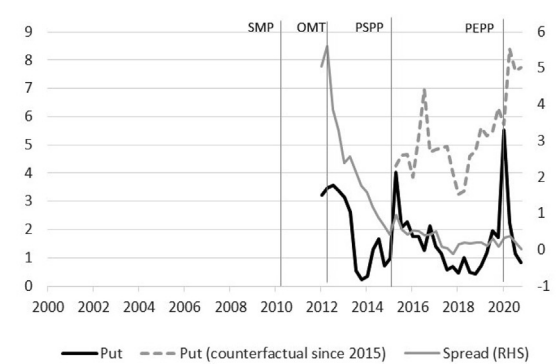
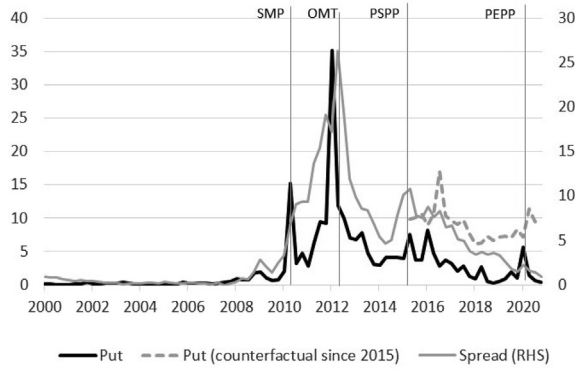


Fig. 4. Put option value (left-hand axis in EUR bn) and credit spread (right-hand axis in percentage points).

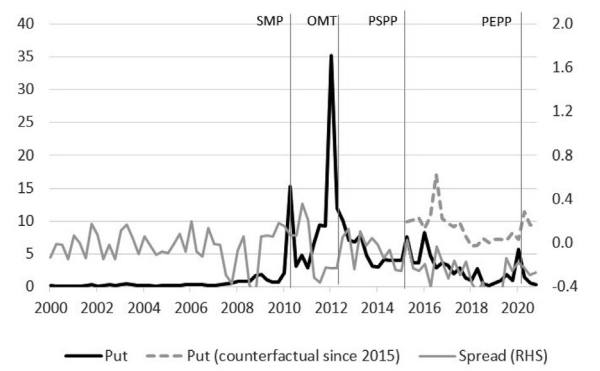
that time the ECB announced the OMT program, which mitigated sovereign risk, by putting a backstop facility in place for crisis-prone countries. In 2015 the volatility in the bond market spiked again, which comes to the fore in the spike of the aggregate put value. The background of this spike was the default of Greece on its IMF loan. In 2020, the put value surged as a reflection of the impact of the pandemic on fiscal finances and sovereign risk. For instance, the option value embedded in the debt increased to EUR 30 bn for Italy and EUR 25 bn for Spain. After the start of the PEPP, the put option value decreased again sharply and reverted back to pre-crisis levels in a few months. At the start of the pandemic (March 2020) the actual bond market volatility increased sharply again and only declined after the PEPP program was introduced. It suggests that the PSPP program alone did not provide investors sufficient protection against tail risk in sovereign bonds for otherwise volatility would not have increased that much. The PEPP program however seemed to offer such protection, as reflected in the decline of the put values in the course of 2020. This indicates that the market stabilization function of PEPP was valuable for investors in sovereign bonds. Note that the development of the put option closely follows the credit spread on long-term government bonds, in line with Eq. (15). This indicates that the option value is influenced by the volatility reducing effect of QE, which hides the underlying effect of QE on sovereign default risk.

The CCM model also provides an indication of the probability of central bank intervention. This likelihood can be proxied by the probability of default $N(-d_2)$, with d_2 the distance to distress, as explained in Section 4.2. The likelihood of central bank intervention will increase if a country moves closer to the default point, as measured by d_2 . The reason for this is that a sovereign default of an EMU country could put the whole euro area at stake, through spill-over and contagion effects to other countries and increasing redenomination risk. Hence the probability of intervening can be proxied by the likelihood of sovereign default $N(-d_2)$. This proxy of probability of central bank intervention is plotted in Fig. 5, for the eight EMU countries in the sample. As expected, the probability is much higher for peripheral countries (Greece in particular), compared to core euro area countries.

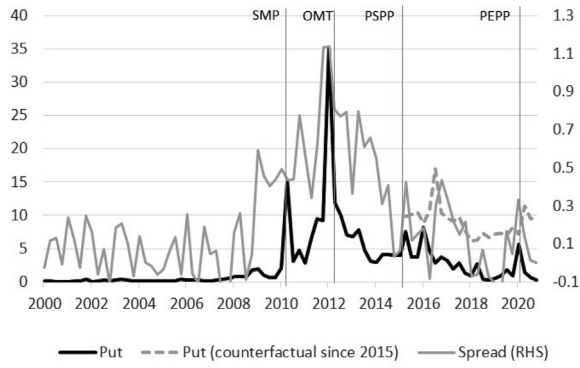
Greece



Germany



France



Belgium

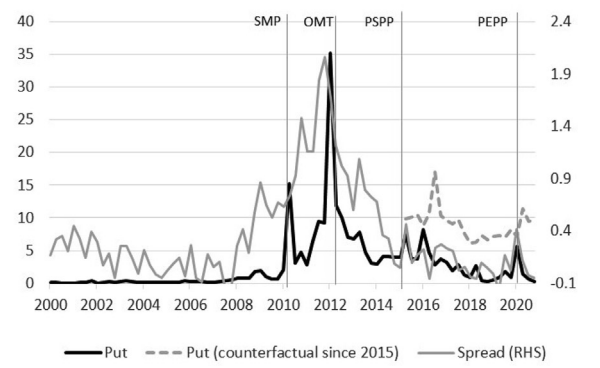


Fig. 4 (continued)

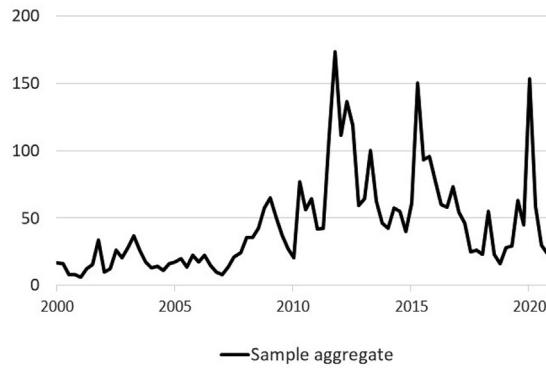


Fig. 4 (continued)

5.2. Counterfactual analysis

To gauge the underlying effect of QE on default risk and hence on the value of the put option, we perform a counterfactual simulation from 2015 onwards. To construct the counterfactual put value we estimate the following equation for the bond return volatility of each country i ,

$$\sigma_{D,t} = \alpha + \beta_1 QE_{dum,t} + \beta_2 debt_t + \beta_3 EPU_t + \varepsilon_t \quad (17)$$

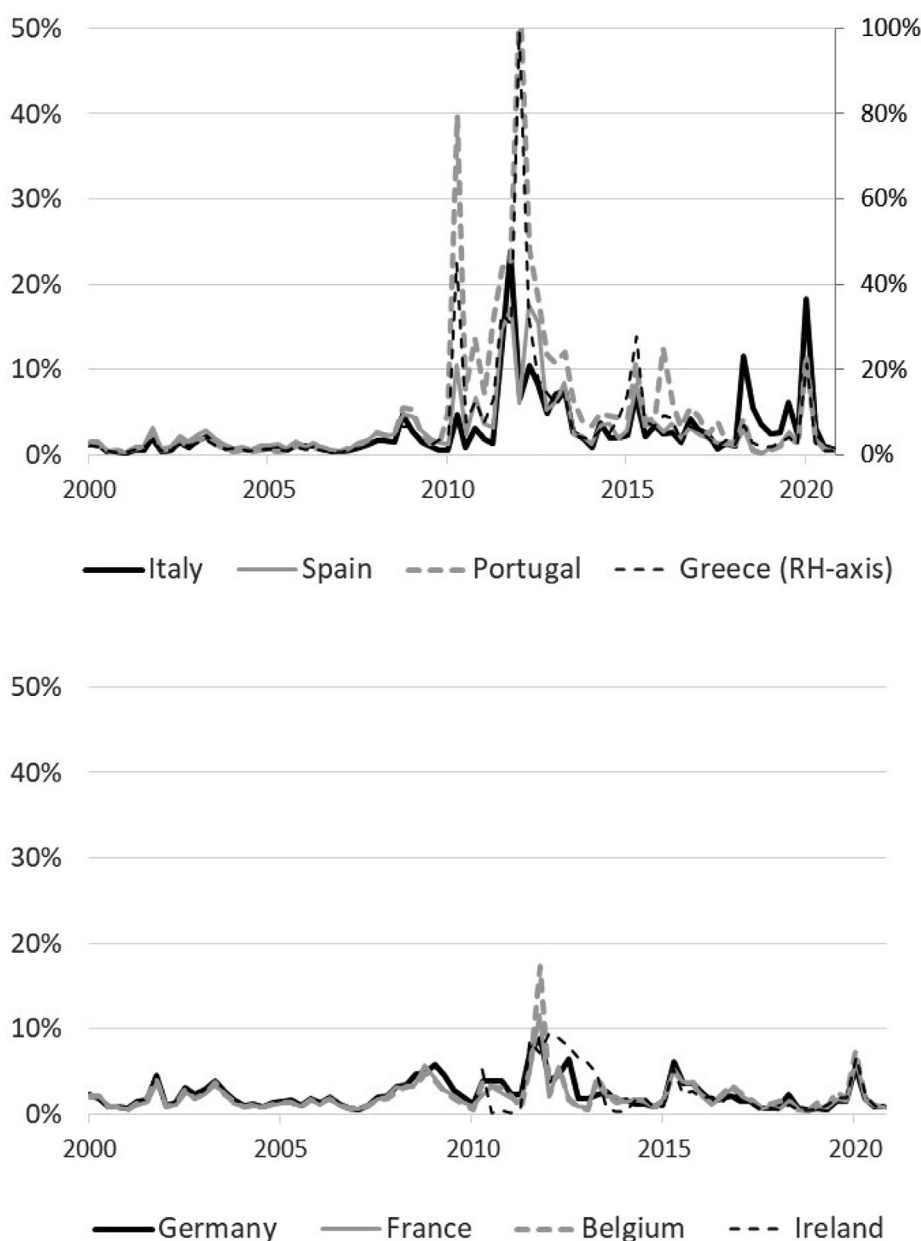


Fig. 5. Probability of central bank intervention (percentage).

With variable $debt_t$ the public debt ratio, EPU_t the Economic Policy Uncertainty index (policyuncertainty.com) and QE_{dummyt} a dummy variable which is 1 from 2015 onward (when ECB started the PSPP) and 0 otherwise. QE_{dummyt} captures the effect of the ECB sovereign bond purchases on bond return volatility. Variable $debt_t$ captures the channel through which changes in the fiscal deficit affect volatility (in an alternative specification of Eq. (17) we included the fiscal deficit instead of debt, but the deficit has low explanatory power for $\sigma_{D,t}$ than debt). Such channels for instance run through implicit guarantees and fiscal multipliers (Silva, 2021). Variable EPU_t captures the effect of policy uncertainty on bond return volatility. This relates to literature which associates policy uncertainty to all kind of externalities for financial markets and the economy (Bloom, 2009). For instance, the elevated political uncertainty related to the sovereign default of Greece in 2015 spilled-over into financial market turbulence.

The estimation results in Appendix 2 show that coefficient QE_{dummyt} is significantly negative for all countries, confirming that QE lowered bond return volatility. Coefficient $debt_t$ is significantly positive in five out of the eight countries in the sample and EPU_t is positively significant for all countries. The signs of these coefficients are in line with the postulation that an increase of public debt and policy uncertainty raises bond return volatility.

Based on the estimated Eq. (17) we compute the counterfactual bond return volatility by predicting $\sigma_{D,t}$ from 2015q1 onward, with the fitted coefficients α , β_2 and β_3 , and the restriction $\beta_1 = 0$. The predicted counterfactual $\sigma_{D,t}$ is then included in Eq. (12) to determine the value of the counterfactual put option. This is the value of the put option as if QE had not taken place, assuming that volatility was not lowered by the ECB bond purchases. The difference between this counterfactual and actual put value indicates the value of the central banks' commitment to support market stability, assuming that QE has reduced bond return volatility from 2015 onward.

The dashed lines in Fig. 4 show the counterfactual values of the put option, assuming the counterfactual bond return volatility from 2015 onward. The value added of the QE programs that reflects the protection of bond investors against tail risk is measured by the difference between the bold lines (actual put value) and the dashed lines (counterfactual put value) in Fig. 6. Concerning the periphery countries this difference is highest for Greece and Spain. During the pandemic, the difference increased strongly for Italy, reflecting the increased Italian sovereign risk related to the (expected) fiscal and economic impact of the pandemic. The difference between the actual and counterfactual put values of Germany and France are high relative to periphery countries, but this reflects the larger size of their economies. In percentages of GDP, the difference of the put values is relatively low in core countries (e.g. in 2016q2, when the difference peaked, it was 3.9% GDP for Germany and 6.7% GDP for Spain) The overall positive difference between the counterfactual and actual put value indicates that QE was valuable to investors.

To provide an indication of the additional value of the put option (i.e. the QE backstop) for crisis-prone countries, the total put value of a group of core and periphery countries is computed. We created a group of periphery countries (Italy, Spain, Portugal) by aggregating the put values of these countries and a group of core EMU countries (Germany, France, Belgium). Since the sovereign risk in periphery countries is generally higher, the put option value is expected to be higher as a consequence. This hypothesis is tested by comparing the difference between the actual put value and its counterfactual (as if no QE was in place) for both country groups, expressed as percentage of aggregate GDP of each group. In line with the expectation, QE turns out to be more valuable for investors in periphery countries than in core countries. Fig. 7 shows that the difference between the actual put value and its counterfactual tends to be higher in periphery than in core countries. This confirms the hypothesis, implying that QE has additional value for investors in crisis-prone countries.

5.3. Scenario with higher interest rate

The CCM model is useful to gauge the likelihood of a central bank intervention in a situation of rising interest rates. Such a scenario affects the sovereign risk in the model through two channels: the discount rate channel (via variable r) and the interest payment channel (part of variable B). Both channels have a different effect on sovereign risk and hence on the put value. A rising interest rate lowers the present value of the sovereign debt via Eq. (12), in particular via $B_t e^{-rt}$ and via the distance to distress d_1 . On the other hand, a rising interest rate increases sovereign risk via higher interest payments of the government, which are part of the debt level B . It depends on the maturity structure (parameter T in the model) of the sovereign debt to what extent a rising interest rate affects the put value via both channels. A higher average debt maturity lowers the sensitivity of the put value to a rise in the interest rate.

To illustrate the impact of the discount rate channel (via variable r) and the interest payment channel (via B of which C is a component) we simulated for Italy as an example a scenario with an increase in the interest rate of 100 basis points ($r + 100$ bp) and a scenario with a tripling of the government interest rate payments. The model outcomes of both scenarios, as well of the benchmark outcome, are presented in Appendix 3 for the main variables in the model using values per the end of 2020. The scenario of a 100 bp increase in the risk free rate (r) lowers A , owing to the reduction of the present value of the debt. This leads to a higher distance to default (d_1) and hence lower sovereign risk, as reflected in a lower put value. The outcomes further show that a tripling of the government interest payments raises B and thereby A , compared to the benchmark outcome. This increases sovereign risk, as reflected in the rise of the put value.

In July 2022, the ECB announced the Transmission Protection Instrument (TPI). The TPI has been established to counteract the fall-out of rising interest rates on the EMU sovereign bond market. This instrument should counteract a deterioration in financing conditions that is not warranted by country-specific fundamentals, to safeguard the transmission mechanism in particular EMU countries. A deterioration in financing conditions could follow from a rising policy interest rate. The TPI was announced at the start of the hiking cycle of the ECB. This shows the relationship between rising interest rates, the potential impact on sovereign risk and the backstop facility of the central bank which aims at counteracting an unwarranted increase in sovereign risk.

5.4. Discussion and interpretation of the results

The assumed central bank put differs from a regular put option since the central bank put is not traded as a separate instrument in financial markets; it is therefore an implicit option. Hence, the central bank does not communicate the reference levels (strike price) to the market in advance. The conditions of the central bank put are therefore not fully clear to investors. Nevertheless, CCM can be used to analyze central bank interventions in bond markets that aim at resolving market instability and preventing bad equilibria. The put option can be useful for investors and policy makers for monitoring and measuring the tail risk associated with default risk. The tail risk will show up in extreme values of bond returns volatility

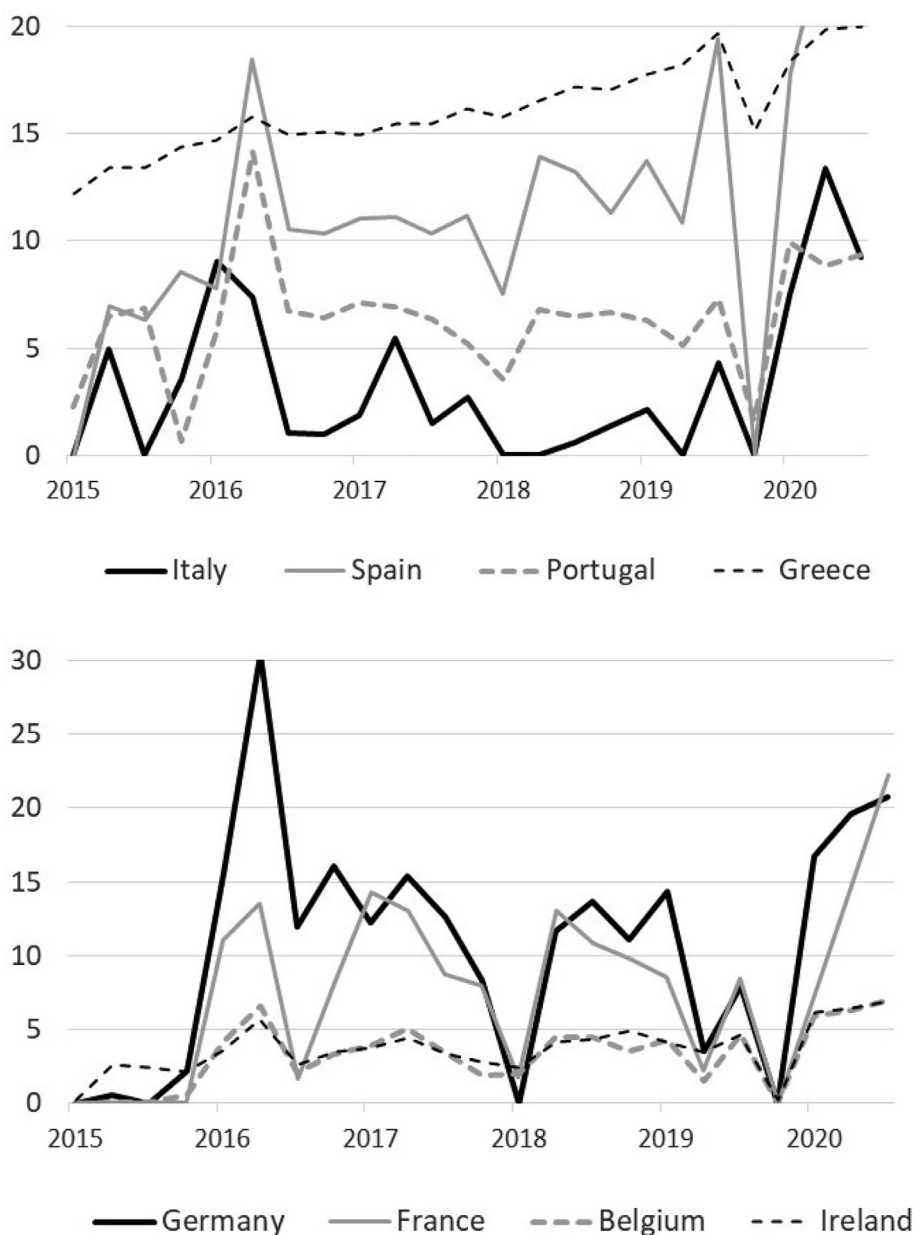


Fig. 6. Underlying value of QE reflected in put option value. (difference between counterfactual put value and actual put value, EUR bn).

and this factor determines the put option value. That makes the put option a useful concept for central banks to assess financial instability related to sovereign risk of EMU countries. Different than the credit spread on sovereign bonds, the put option value measures the implicit protection of investors in sovereign bonds and the aggregate value of this protection by central bank QE programs at each point in time. Moreover, the empirical application of the CCM model allows us to connect the put option value with macro-economic fundamentals (like governments' finances and the volatility of sovereign bonds).

Central banks and regulators are considering liquidity backstop facilities to support the functioning of the sovereign bond markets in stress conditions (Group of Thirty, 2021). Such interventions can, similar to QE as a market stabilization instrument, promote overall welfare if they result in financial markets responding more rationally to macro-fundamentals and contribute to lower sovereign spreads by reducing bond market volatility. However, if financial markets become normalized again while the central bank continues to purchase assets, the risk of unintended side effects and moral hazard increases. If sovereign debt levels remain high or other macroeconomic imbalances persist, the related risks shift from investors to the central bank, which offers an implicit put option against tail risk through QE. This also reduces incentives for governments to pursue structural reforms to improve the economy. These risks can be avoided by relating the strike price of the central bank

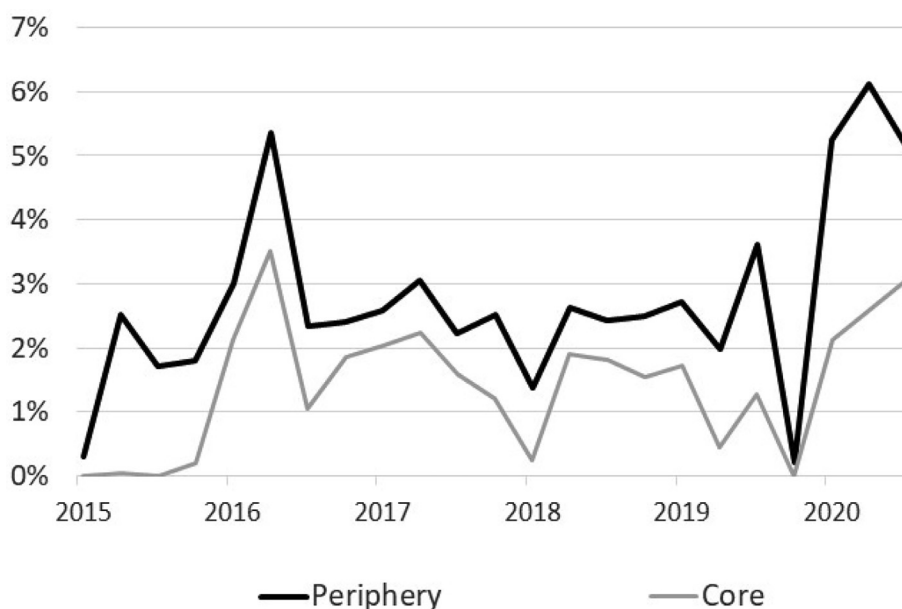


Fig. 7. Underlying value of QE reflected in put option value. (difference between counterfactual put value and actual put value, percentage GDP). Note: Group of core countries consists of Germany, France, Belgium. Group of periphery group consists of Italy, Spain and Portugal.

Box 1 Numerical example. As an example, we apply the CCM model to sovereign risk data for Italy as of December 2011. Sovereign debt held by junior creditors at that time amounted to EUR 1,038 bn (EUR 1,283 bn local sovereign debt minus EUR 245 bn local sovereign debt held by local banks). Sovereign debt held by senior creditors amounted to EUR 957 bn (EUR 1,973 bn total sovereign debt plus EUR 22 bn interest payments minus EUR 1,038 bn held by junior creditors). Furthermore, the 10-year Overnight Index Swaps rate (r) was at 2.05%, the duration (T) of the government debt 8.44 years, and the sovereign debt volatility (σ_D) 34.74%. Based on this input we use the iterative process to numerically determine the sovereign asset value (A) to be EUR 1,813 bn and sovereign asset volatility (σ) to be 20.9%. Based on this we can determine the value of the put option ($P_t = B_t e^{-rT} N(-d_2) - A_t N(-d_1)$) embedded in sovereign debt that reflects the default risk to be equal to EUR 30 bn. Note that total assets equal total liabilities in the following standard way,

$$A_t = E_t + B_t e^{-rT} - P_t \text{ or } 1,813 = 1,038 + 957e^{-0.0205 \cdot 8.44} - 30.$$

put option more closely to the risk of disorderly market conditions. For a QE market stabilization program this means that the reference level of credit spreads, which determines or triggers the sovereign bond purchases, is increased if the risk of a bad equilibrium diminishes (and vice versa). This calls for a time-varying strike price of the central bank put, which is countercyclical to spread developments in financial markets.

6. Conclusions

Over the last decade, the ECB has increasingly used QE as a market stabilization instrument. In principle, the market stabilization function is only needed in situations where the market fails to strike a good equilibrium. However, by acting as market-maker of last resort, the central bank also changes the nature of sovereign risk. The central bank backstop in fact removes tail risks from the market.

Based on the CCM model we postulate that QE features as a put option written by the central bank to bond holders which protects them against tail risk. It resembles the market stabilization function of QE, through which the central bank purchases bonds from investors in stressed market conditions. The implicit central bank put option provides investors with a backstop to sell their bonds to the central bank when the bond value drops and sovereign risk spreads increase.

The central bank will step up its purchases at spread levels that are associated with dysfunctioning bond markets. In such conditions, the value of the put option will increase as simulated with the CCM. Hence, the CCM provides a framework to quantify the value of the market stabilization function of QE. An important parameter that determines this value is the volatility of the returns on the underlying bond. Since the market stabilization function of QE particularly influences bond market volatility, we conduct counterfactual simulations for the option value based on the volatility parameter. The simulations show that the ECB's market stabilization policy was valuable to investors in the sovereign bonds of the eight countries in our sample.

Understanding the impact of central bank bond purchases is important for effectively addressing tail risks in the euro area. Our results can guide policymakers on the use of backstop facilities for sovereign bond markets. This will be welfare improving, provided that unintended side effects such as moral hazard risk and reduced fiscal discipline are mitigated by the design of the program.

CRedit authorship contribution statement

Dirk Broeders: Methodology, Formal analysis, Writing – original draft. **Jan Willem van den End:** Conceptualization, Investigation, Resources, Writing – original draft, Supervision. **Leo de Haan:** Software, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix 1. Data definitions and sources

Variable name	Description	Definition	Source
<i>B</i>	Total sovereign debt	Quarterly, end of period	ECB
<i>J</i>	Total sovereign debt held by domestic investors excluding domestic banks	Quarterly, end of period	ECB
<i>interest payments</i>	Interest expenses of government	Quarterly, end of period	ECB
<i>T</i>	Duration government debt	Quarterly, end of period	Bloomberg
<i>r</i>	Risk-free long-term interest rate (10 years Overnight Index Swap (OIS) rate)	Quarterly, end of period	Bloomberg

Appendix 2. Estimation outcomes.

Variables	QE_dum	Debt	EPU	Adj R ²
<i>Country</i>				
Germany	−0.02***	0.06***	0.00***	0.24
France	−0.01***	−0.02	0.00***	0.12
Belgium	−0.03***	0.00	0.00***	0.17
Italy	−0.02**	0.11***	0.00***	0.26
Spain	−0.07***	0.10***	0.00***	0.24
Ireland	−0.07***	0.07***	0.00***	0.24
Greece	−0.27***	0.19	0.00*	0.06
Portugal	−0.16***	0.19***	0.00***	0.40

Note: Estimation results of Eq. (17). Coefficients of constant term not reported.

***, **, * denote significance on 1%, 5%, 10% level. Based on 254 monthly observations.

Appendix 3. Impact of scenario with higher interest rate (outcomes for Italy, 2020q1).

	<i>r</i>	<i>J</i>	<i>DB</i>	<i>A</i>	σ_J	σ	<i>d</i> ₁	Put value
<i>Benchmark outcomes</i>	−0.3	1386	1202	2624	0.048	0.025	9.627	3.6
<i>Interest payments*3</i>	−0.3	1386	1231	2655	0.048	0.025	9.572	3.8
<i>r + 100 bp</i>	0.7	1386	1202	2512	0.048	0.027	9.845	2.9

Appendix. Supplementary material

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jimonfin.2023.102881>.

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