Bond Convenience Curves and Funding Costs

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Abstract

A convenience yield represents a difference between yield on a safe bond and yield on a synthetic safe bond, constructed by combining a risky bond with a CDS contract. We explain the shapes of eurozone sovereign convenience curves using a model in which arbitrageurs face higher funding costs on bonds with credit risk and bond demand shocks induce funding risk. We provide novel causal evidence for our mechanism using variation in funding costs generated through exogenous haircut category changes. Changes in convenience yields represent a key transmission channel of unconventional monetary policy to bond yields.

Keywords: Sovereign bond convenience yields, money markets, asset pricing with frictions, monetary policy.

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1 Introduction

Consider an investor deciding between two investments with safe cash flows. First, the investor could buy a German government bond, widely considered one of the safest euro denominated assets. Alternatively the investor could buy a synthetic safe bond by combining a same duration Italian bond with the corresponding CDS contract. Because both assets share the same currency, the law of one price predicts that such a synthetic bond trades at the same yield as that of a German bond. Yet in the eurozone such synthetic bonds tend to trade at clearly higher yields than German bonds.

This paper provides a funding cost based explanation for such differences, also called convenience yields (Jiang et al., 2022), CDS-bond bases (Gyntelberg et al., 2013) or segmentation premia (Corradin et al., 2021). In textbook models the investor either does not employ outside financing or can always borrow at the same riskless rate. However, key financial intermediaries in the bond market, such as banks and hedge funds, rely on external financing and the cost of this funding crucially depends on the securities held on the asset side of the balance sheet.

Interest rates applied in repo transactions collateralized with German bonds constitute perhaps the lowest short-term interest rates in the eurozone. If our investor buys German bonds, she can finance the transaction cheaply through the repo market. This implies that she must resort less to costlier financing sources such as unsecured loans, deposits, own equity or fund clients' capital.

The synthetic bond is costlier to finance. Neither major clearinghouses nor the Eurosystem allow the collateralization of CDS contracts. For funding purposes the owner of our synthetic bond is effectively just holding an Italian bond.[1] On the other hand, effective funding costs for Italian bonds are higher for two reasons. First, the corresponding repo rates for Italian bonds are higher than for German bonds. Second, due to greater credit risk, the repo

[1] The CDS contract can have an additional funding cost through margin requirements but this does not change the argument.

haircuts applied to these bonds are larger. This implies that the owner of an Italian bond can obtain less repo funding and must compensate through additional more expensive funding sources.

The higher funding cost of the synthetic safe bond implies that such bonds should indeed trade at higher yields than German bonds. Effectively Italian bond yields are above German yields both due to higher credit risk and lower collateral benefits but the CDS contract only accounts for the credit risk part. But that is not the end of it.

The yield differences between synthetic safe bonds and German bonds are increasing in bond maturity. We do not observe similar stark differences in the relative funding costs of different maturity bonds. However, we argue that this is still consistent with a funding cost based explanation due to *funding risk*.

In a risk neutral world the yield difference between synthetic safe bonds and German bonds would equal the relative expected funding cost over the bonds' maturity. But when investors are risk averse they demand compensation for funding cost shocks that not only alter their financing costs but in equilibrium also lead to fluctions in the prices of synthetic safe bonds. This explains why the term structure of inconvenience yield is upward sloping.

In the empirical part we assess the effects of ECB's unconventional monetary policy operations on bond convenience yields. We find that the convenience yield channel is of similar importance to the standard credit spread channel. Convenience yields are most affected by collateral policies and asset purchases.

Standard policy announcements, however, cannot be directly used to measure the *causal* effect of funding costs on bond yields. This is due to two reasons. First, funding cost changes due to policy shifts, are not necessarily exogenous. Second, they tend to affect all bonds simultaneously, which deters the use of a control group.

Our key empirical contribution is to instead provide novel causal evidence on the effects of haircuts, which are key determinants of effective funding costs, on bond yields. In particular we apply exogenous changes in

Eurosystem haircuts for Italian debt. These haircut changes are due to bond maturity category shifts that are independent of possibly endogenous events such as ECB policy changes or rating downgrades. Moreover, since they always affect only a part of the bonds, unobservables can be controlled using fixed effects. We find that smaller haircuts, which lower effective funding costs, lead to significantly lower convenience yields.

Related Literature

Our paper contributes to the literatures on sovereign bond convenience yields and asset pricing with frictions.

Krishnamurthy and Vissing-Jorgensen (2012) argue that investors value the safety and liquidity benefits of Treasuries beyond their cash flows. These convenience benefits plausibly bear important implications ranging from optimal fiscal and monetary policy (Collard et al., 2020; Calvo and Velasco, 2022) to explaining asset pricing puzzles (Jiang et al., 2021).

Krishnamurthy and Vissing-Jorgensen (2012) model a convenience yield by incorporating Treasury holdings directly to the investor's utility function. Similar reduced form convenience yields appear also in the literature on central bank asset purchases (e.g., Elenev et al., 2021). Our paper is a step closer to building a microfounded theory of convenience yields, at least in the context of a currency union.

Broadly speaking our approach is consistent with such reduced form approaches since, as discussed for example by Chen et al. (2019), pledgeability or collateralizability can be viewed as a type of liquidity benefit. However, note that such collateralizability only has value if the model also features some form of funding friction. Moreover, such reduced form approaches cannot directly explain for example why the shape of the inconvenience curve is upward sloping on average. Why would the liquidity benefit of a German bond relative to an Italian bond be increasing as the maturity of both bonds increase? In our framework this follows directly from the assumption that arbitrageurs are risk averse.

Our empirical approach is related to that in Jiang et al. (2022) who emphasize the effects of convenience yields on government budget constraints. Under further reduced form assumptions on convenience yields, higher fiscal surpluses are associated with decreases in the yields of synthetic safe bonds. While these reduced form assumptions do not hold in our model, this important prediction emerges also in our setting but is not the focus of the paper.[2]Relative to Jiang et al. (2022), our key contribution is to instead delve deeper into the micro level determinants of convenience yields as well as provide novel empirical support for our mechanism.

Eurozone CDS-bond basis has been analyzed in a number of empirical studies. Similar to our paper, Fontana and Scheicher (2016) associate this with funding frictions related to haircuts but do not provide causal evidence for the mechanism. However, as anecdotal evidence they mention how in late 2011 haircut increases by LCH, a major clearinghouse, led to hikes in Italian bond yields. They also discuss some additional factors such as short sale constraints.[3]

Gyntelberg et al. (2017) relate the basis to funding frictions and transaction costs. They indirectly infer the size of these frictions from basis dynamics using a threshold vector error correction model but do not provide direct corroboration for the mechanism. However, Choi et al. (2019) find that dealers trade against widening CDS-bond bases in the US corporate bond market.

A voluminous literature analyzes the effects of financing frictions on asset prices. Duffie (2010), Garleanu and Pedersen (2011) and Bai and Collin-Dufresne (2019) discuss how funding frictions help to explain violations of the CDS-bond basis in the US corporate bond market. Gromb and Vayanos

[2]This prediction holds in our model since we can interpret a fiscal shock as a bond supply shock. Also note that our funding cost can be seen as an Euler equation wedge discussed in Jiang et al. (2022). However, the expectations hypothesis, assumed by Jiang et al. (2022), does not hold in our setting. In particular, due to risk adjustments, longer maturity inconvenience yields are on average higher than short term ones, consistent with our empirical evidence.

[3]Bai and Collin-Dufresne (2019) also discuss the role of additional factors such as market liquidity. However, they focus on the CDS-bond basis in the US corporate bond market.

(2002) associate apparent arbitrage opportunities with funding constraints that require each position to be collateralized separately. Kaldorf (2021) relates eurozone CDS bond bases with repo haircuts but abstracts away from funding risk. Collateral premia affect bond yields also in De Fiore et al. (2018). Augustin et al. (2020) argue that effective funding rates inferred from interest rates swaps go a long way in explaining deviations from covered interest parity measured from cross-currency swaps.

The literature on CDS-bond bases and convenience yields has not focused on the term structure of the basis. Our key theoretical novelty is the argument that funding risk can explain the observed shapes of eurozone convenience curves.

Our key empirical contribution is to provide causal evidence that sovereign bond haircuts affect bond yields. Some papers have provided related evidence in other contexts. Aschcraft et al. (2010) find that rejections from Fed's TALF program had significant effects on the prices of asset backed securities. Chen et al. (2019) use a policy shock and unique features of the Chinese market to identify a significant effect of corporate bond pledgeability on yields. Mésonnier et al. (2022) find that an extension in the Eurosystem's collateral eligibility criteria for corporate bonds lead to a decrease in their yields. Jylhä (2018) argue that Fed's changes in the initial margin requirements for equities between 1934 and 1974 had significant effects on the slope of the security market line.

The financial crisis lead to changes in banks' derivatives pricing frameworks. Segmentation in funding costs spurred banks to modify formulas used for pricing and accounting purposes by so called funding value adjustments (FVA). Many authors have pointed to possible inconsistencies in certain FVA accounting practices (Andersen et al., 2019). For example a bank reporting contract values at market prices modified by FVAs might succumb to double accounting the effects of funding costs. While these debates highlight the importance of funding costs, they are only vaguely related to our paper that is based on the more fundamental economic premise that such costs should affect the pricing of assets.[4]

Finally, our paper relates to a literature on financial market segmentation in the Eurozone, which has also been a major concern among policy makers. Bittner et al. (2022) find that segmentation in bank funding costs between core and periphery banks affects monetary policy transmission in the Eurozone. Martinez et al. (2022) analyze the macroeconomic effects of money market segmentation. They find that reforms that alleviate segmentation in money market rates can lead to substantial welfare gains during a crisis period.

2 Empirical Properties of Inconvenience Yields

2.1 Data

Our main sample is from November 2009 to December 2021. Similarly to Jiang et al. (2022) and Kaldorf (2021) we include 9 eurozone countries: Austria, Belgium, Finland, France, Germany, Italy, Netherlands, Portugal, and Spain. We omit Greece since it was excluded from the sovereign debt market following default.

Our yields are end of day benchmark yields from Datastream complemented with end of day benchmark yields from Bloomberg. In the section on Eurosystem haircuts, we further apply yields of all Italian bonds that are available through Datastream and which ECB lists as eligible collateral assets. We obtain EUR-denomited CDS contracts from Datastream. We use CR contracts before 2014 and CR14 after that. On top of outright default, CR14 contracts pay off in the case of debt redomination without default. CR contracts are triggered also in this case but excluding G7 countries France, Germany and Italy. Hence early parts of our sample are missing redomination risk for three countries.[5]We also omit shorter maturity Finnish and

[4]Moreover, it is not clear if possible inconsistencies in accounting practices would affect the actual pricing of the contracts.

[5]As discussed in Jiang et al. (2022) this is unlikely to have a large impact on the results.

Portuguese CDS quotes due to low market liquidity.

We construct the τ maturity inconvenience yield of country i relative to Germany as

$$icy_t^i(\tau) = y_t^i(\tau) - cds_t^i(\tau) - (y_t^{DE}(\tau) - cds_t^{DE}(\tau)) \tag{1}$$

Here $y_t^i(\tau)$ is the yield of an τ-maturity bond of country i and $cds_t^i(\tau)$ is the premium of the same maturity CDS contract. Note that since we prefer working with positive numbers, our inconvience yield measure is the negative of the convenience yield measure in Jiang et al. (2022).

We approximate repo rates using CME's RepoFunds Rates indices. These represent averages of interest rates applied in centrally cleared repo deals when bonds issued by a specific country are used as collateral. Here a long time series is available only for Germany, France, Italy and Spain.

2.2 Stylized Facts

We first document simple empirical facts concerning inconvenience yields.[6] We start from the following observation concerning the relationship between inconvenience yields and credit risk:

Fact 1: Riskier bonds, as measured by CDS premia, command higher inconvenience yields.

In particular for each country we compute the average inconvenience yield and CDS premium by averaging both over time and across maturities. Figure 1 plots these average inconvenience yields against average CDS premia. Debt issued by riskier countries with higher CDS premia also trade at higher inconvenience yields. The cross-country correlation between the

[6]Facts 1 and 3 are also mentioned by Jiang et al. (2022) though they focus on another fact: the association between fiscal surpluses and convenience yields. As mentioned before this is consistent with our model but is not the focus of the paper.

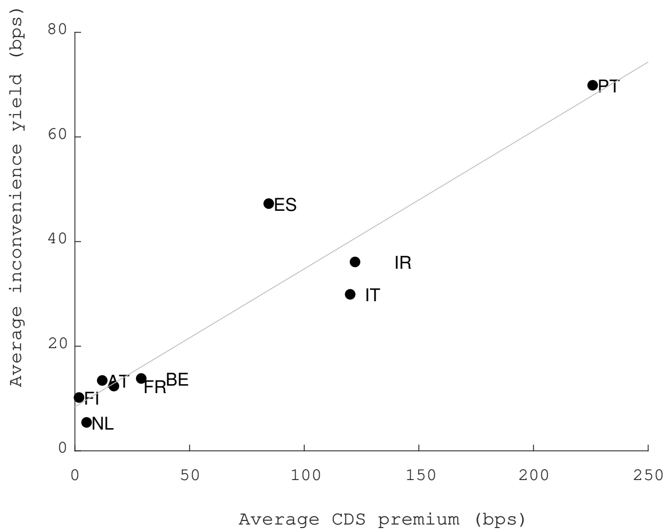

Figure 1: plots the average inconvenience yield for each country against the corresponding average CDS premium.

average inconvenience yield and average CDS premium is more than 0.9. Fact 1 follows.

There is also a positive but weaker time series association between inconvenience yields and CDS premia. Table 1, specification (1) explains daily inconvenience yields by the relative CDS premia. Here both the inconvenience yields and CDS premia are averaged across maturity. The coefficient on the average CDS premium is positive but fairly small and only weakly statistically significant.

Which variables then are good at explaining the time-series evolution of inconvenience yields? We have the following fact:

Fact 2: Inconvenience yields are associated with measures of funding costs and funding risks.

Table 1, specification (2) shows the results when we explain inconvenience yields with relative repo rates. The association is statistically significant and economically large: a one basis point change in the repo rate

	(1) ICY	(2) ICY	(3) ICY Slope	(4) ICY Change
	$(\overline{icy}_t^i)$	$(\overline{icy}_t^i)$	$icy_t^i(10Y) - icy_t^i(1Y)$	$\Delta^{1M} icy_t^i(1Y)$
CDS diff. $(\overline{cds}_t^i - \overline{cds}_t^{DE})$	0.037*			
	(1.79)			
Repo rate diff.		0.80**		
		(2.19)		
Repo rate vol.			3.24***	
			(3.47)	
ICY Slope $icy_t^i(10Y) - icy_t^i(1Y)$				0.106***
				(2.61)
R^2	0.084	0.140	0.050	0.042
Country fixed effects	x	x	x	x
Note:				*p<0.1; **p<0.05; ***p<0.01

Table 1: shows the slope coefficients and R^2 statistics from four regressions. In column (1) inconvenience yields are explained by relative CDS premia (difference w.r.t. Germany). Here inconvenience yields and CDS premia are averaged across maturities. In column (2) inconvenience yields, averaged across maturities, are explained by relative repo rates (difference w.r.t. Germany). In column (3) inconvenience yield slope (10 year minus 1 year inconvenience yield) is explained by monthly volatility of the relative repo rate (volatility of the repo rate difference w.r.t. Germany). In column (4) one month change in one year inconvenience yield is explained by the slope of the inconvenience yield curve (10 year minus 1 year inconvenience yield). All specifications include country fixed effects; standard errors are clustered by country.

difference translates to a 0.8 basis point difference in inconvenience yields.

The repo rate difference is 5 basis points between France and Germany, 11 basis points between Italy and Germany and 14 basis points between Spain and Germany.[7] These repo rate differences are imperfect measures of full funding costs since haircuts applied to riskier bonds are higher. However, the repo rate differences are of similar magnitude than the inconvenience yields of short maturity bonds. For long maturity bonds the inconvenience yields are instead higher than the repo rate differences.

As mentioned by Jiang et al. (2022), inconvenience yields were small before the financial crisis. This is also consistent with a funding cost based narrative since financing conditions tightened following the crisis.

Inconvenience yields depend not only on the direct effect of funding costs, but also on funding risk. Table 1, specification (3) explains the slope of the inconvenience curve for Italy and Spain by the monthly volatility of the repo rate relative to Germany. Higher repo rate volatility translates to a steeper slope of the inconvenience curve. However, repo rate volatility is likely a noisy proxy of true funding risk that depends also on issues such as the perceived probability of tighter future repo haircuts.[8]

More precisely, how does the term structure of inconvenience yields look like? We have the following observation:

Fact 3: The inconvenience curve is upward sloping on average.

Figure 2 shows the term structure of inconvience yields solved by averaging both across time and countries. The term structure exhibits a clear upward sloping pattern. The difference between long and short maturity

[7] For Spain the data begins later in 2014.

[8] High private repo market haircuts during crisis periods might well be the biggest sources of funding risk. An additional complication is that funding risk need not be time-varying in order to affect inconvenience yields. Results are also significant but somewhat weaker if we include France. However, the funding risk for French bonds is plausibly much lower than that for the periphery country bonds. Long time series of repo rates are not available for the other countries.

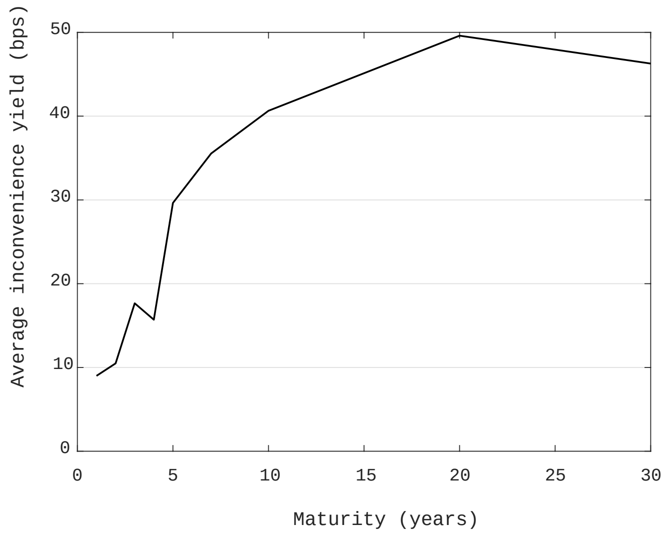

Figure 2: shows the average term structure of inconvenience yields

inconvenience yields is also significantly positive separately for each country;[9]the appendix further shows the average term structures of inconvenience yields for the individual countries.

Our final result concerns the time-series dynamics of the inconvenience curve:

Fact 4: An increase in the spread between long and short maturity inconvenience yields predicts future increases in short term inconvenience yields.

Table 1 column (4) shows a regression of the monthly change of one year inconvenience yields on the difference between 10 year and 1 year inconvenience yields as well as country fixed effects. Higher than average slope of the inconvenience curve is associated with increases in short term inconvenience yields. Our theoretical framework associates this with expectations hypothesis type logic as long maturity inconvenience yields reflect

[9]Here we calculate the standard errors using the method of Newey and West (1987) combined with standard lag selection.

expectations over future funding costs.

3 Model

The model is a two country generalization of Vayanos and Vila (2020) that shares additional elements with Costain et al. (2021) and He et al. (2022).

Model Structure Time is continuous and goes from zero to infinity. There are two countries: Core and Periphery, where the latter variables are denoted by stars. Both countries issue a continuum of zero coupon bonds with maturities between 0 and T. The bonds issued by Core are riskless but those issued by the Periphery are not. As in Costain et al. (2021), in case of a default all periphery bonds lose a fraction δ of their value. This default is given by a Poisson jump process N_t with default intensity ψ.

An arbitrageur trades all bonds. The arbitrageur maximizes a mean-variance objective:

$$\mathbb{E}(dW_t) - \frac{\gamma}{2}\mathbb{V}ar(dW_t). \tag{2}$$

Modelling Funding Costs Vayanos and Vila (2020) effectively assume that all bonds are financed at the same rate.[10] On top of two countries, our second key deviation is the premise that the arbitrageur faces a higher funding cost on Periphery country bonds.

Funding costs tend to reflect two key factors. First, they depend on the overall supply of funding or funding market liquidity, which further reflects issues such as regulatory constraints of dealers as well as central bank actions. Similarly to He et al. (2022), we assume that funding costs are

[10] Costain et al. (2021) also make this assumptions in a two-country model. He et al. (2022) assume differential funding costs for bonds and swaps but abstract away from default risk and assume each bond is financed at the same rate.

increasing in the total amount of bonds to be financed, that is arbitrageurs face an upward sloping supply curve for funding.

Second, funding costs depend on asset risk. Both major clearinghouses and the ECB distinguish between two sources of risk. To compensate for duration risk, haircuts are mildly increasing in bond maturity. However, this increase in haircuts tends to be identical for bonds issued by different countries so it does not create differences in the funding costs for same maturity Core and Periphery bonds. Since inconvenience yields depend on the funding cost difference between same maturity Core and Periphery bonds, we for simplicity normalize the maturity specific component of the funding cost to zero. More importantly, funding costs depend on bond credit risk typically evaluated using internal or external credit ratings.[11]

Let the excess funding cost of a Periphery country bond, relative to a Core bond, be Λ_t. Our key results are based on two empirically motivated facts. First, this excess funding cost is positive $\Lambda_t \geq 0$ with a strict inequality in some states. Second, Λ_t is uncertain so our risk averse arbitrageur demands compensation for funding cost shocks. The specific functional form for Λ_t is therefore not important for the results. However, for the purposes of calibration and illustration, we employ a parametric form for the funding cost. We assumed a constant default probability for Periphery bonds as well a zero probability for Core bonds. Let the excess funding cost then be given by

$$\Lambda_t = \text{Constant} \times \text{Default probability} \times \text{Amount of bonds financed} \equiv \lambda B_t^* \tag{3}$$

Here B_t^* is the total euro amount of bonds held and financed by the arbitrageur and the equivalence follows from the fact that we assumed that the

[11] Haircuts and funding costs can also depend on counterparty risk (Gottardi et al., 2019). As long as this risk is constant similarly to the default probability of the sovereign, it does not affect the argument. Introducing time-varying sovereign or bank default probabilities would not affect our key results though would create an additional channel to model fluctuations in funding costs.

default probability is constant. This constant probability is reasonably realistic for our purposes since we found only a mild correlation between CDS premia and inconvenience yields. Therefore fluctuations in default probabilities do not explain lot of the time-series variation in inconvenience yields even though higher default probability explains the average inconvenience yield of Periphery bonds over Core bonds.

Our form for the excess funding cost is similar to that in He et al. (2022), though here λ reflects both the sensitivity of the funding cost to the funding amount as well as the default probability of the bond.

Model Equations The arbitrageur's wealth dynamics $dW_t - W_t r_t dt$ are given by:

$$\int_0^T X_t(\tau)\left(\frac{dP_t(\tau)}{P_t(\tau)} - r_t\right)d\tau + \int_0^T X_t^*(\tau)\left(\frac{dP_t^*(\tau)}{P_t^*(\tau)} - r_t - \Lambda_t\right)d\tau - \delta B_t^* dN_t \tag{4}$$

Here $P_t(\tau)$ and $P_t^*(\tau)$ are the prices of τ-maturity Core and Periphery bonds respectively and $X_t(\tau)$ and $X_t^*(\tau)$ are the corresponding bond holdings in euros. Moreover, $B_t^* = \int_0^T X_t^*(\tau)d\tau$ and the excess funding cost of Periphery bonds is $\Lambda_t = \lambda B_t^*$, as discussed above. The short rate r_t[12] follows an Ornstein-Uhlenbeck process:

$$dr_t = \kappa(\bar{r} - r_t) + \sigma dz_t. \tag{5}$$

Here $\{z_t : 0 \leq t < \infty\}$ is a Wiener process. The model also features preferred habitat investors. Their demands for Core and Periphery bonds are given by

$$Z_t(\tau) = -\theta(\tau)\beta_t, \quad Z_t^*(\tau) = -\theta^*(\tau)\beta_t \tag{6}$$

Here β_t is a demand shock. We assume β_t follows a Markov chain with jump intensities ϕ_l and ϕ_h.

[12]We can view this as the funding cost of Core bonds.

The demand shocks of Periphery bonds imply that their future excess funding costs are uncertain. Demand shocks for Core bonds are largely irrelevant for our results. For simplicity we assumed that Core bonds are subject to the same demand shock, though we could also set excess supply of these bonds to a constant.

We normalize excess bond supply to zero, that is market clearing requires:

$$Z_t(\tau) + X_t(\tau) = 0, \quad Z_t^*(\tau) + X_t^*(\tau) = 0. \tag{7}$$

If we define $\Theta^* = \int_0^T \theta^*(\tau)d\tau$, the size of Periphery bond balance sheet of arbitrageurs is now $B_t^* = \Theta^* \beta_t$.

The model yields a simple solution for the prices of Core, Periphery and synthetic risk-free bonds that is characterized in the following proposition. Here the prices depend on maturity, the interest rate as well as the state of the supply shock. The synthetic safe bond is defined as a bond with no default risk but the same funding cost than a Periphery bond. Here we assume the CDS contracts and therefore synthetic bonds are in zero supply.[13]

Proposition 1. *The prices of Core, Periphery and synthetic risk-free bonds are given by:*

$$P_{it}(\tau) = \exp(-C_i(\tau) - A(\tau)r_t), \quad i = l, h$$

$$P_{it}^*(\tau) = \exp(-C_i^*(\tau) - A(\tau)r_t), \quad i = l, h$$

$$\hat{P}_{it}(\tau) = \exp(-\hat{C}_i(\tau) - A(\tau)r_t), \quad i = l, h$$

Here

$$A(\tau) = \frac{1 - e^{-\kappa\tau}}{\kappa}$$

[13]CDS contracts are naturally in zero net supply but preferred habitat demands for the contracts might imply some excess demand to be absorbed. We abstract away from such effects since the eurozone sovereign CDS market is fairly small relative to the cash bond market. It would also not be clear how to separately model preferred habitat demands for Periphery bonds and CDS contracts.

and $C_i(\tau)$, $C_i^*(\tau)$ and $\hat{C}_i(\tau)$ are given in the appendix.

Proof: see appendix.

Here the inconvenience yield curve is then given by

$$icy_t(\tau) = \frac{\hat{C}_i(\tau) - C_i(\tau)}{\tau}$$

and the CDS curve is

$$\frac{C_i^*(\tau) - \hat{C}_i(\tau)}{\tau}$$

As in He et al. (2022), we effectively assume that the excess bond supply to be held by our arbitrageur is always at least zero. This rules out negative inconvenience yields for Periphery country bonds, consistently with our data. It also avoids dealing with short sales that could be subject to certain additional frictions and costs other than the (reverse) repo rate.

The following proposition helps to understand the determination of the term structure of inconvenience yields:

Proposition 2. *We can decompose a τ-maturity inconvenience yield to an expected funding cost component and a funding risk component:*

$$icy_t(\tau) \approx \frac{1}{\tau}\mathbb{E}_t \int_t^{t+\tau} \Lambda_s ds + Funding\ risk_t$$

Here $icy_t(\tau) \to \Lambda_t$ as $\tau \to 0$. The short end of the inconvenience yield curve is determined by the current funding cost. The long end also reflects expected future funding costs and a funding risk premium.

Proof: see appendix.

If agents were risk neutral, inconvenience yields would merely reflect the excess funding cost of a bond during the bonds' maturity, implying that synthetic risk free bonds would have the same expected returns as

Core bonds. Here the inconvenience yield curve would fluctuate in time as expected future costs change but the term structure would be flat on average. Therefore the funding risk premium must instead explain the average slope of the inconvenience curve.

The proposition implies the following further remarks:

Remark 1. *Assume no excess funding costs $\Lambda_t = 0$ for $t \in [0, \infty)$. Then inconvenience yields are zero.*

However, note that funding costs can be zero today yet bonds trade at an inconvenience yield. Here the mere expectation of future funding cost induces inconvenience yields both through expectations and funding risk channels. A second simple remark is the following:

Remark 2. *Assume no demand shocks / funding cost risk. Then the inconvenience curve is constant:*

$$icy_t(\tau) = \Lambda$$

That is if the funding cost is constant, the inconvenience yield curve is always at the constant funding cost. This holds even when the agents are risk averse.

3.1 Inconvenience Yields: a Calibration Exercise

The original model of Vayanos and Vila (2020) is characterized by an integral equation that must be solved numerically. The above model is somewhat more complicated. The full model is characterized through a 4 equation system of integral equations. The synthetic risk free curve is then further represented by a 2 equation system of integral equations.

We focus on the model implications for inconvenience yields. Interest rate risk does not directly affect inconvenience yields. However, due to convexity adjustments, this effect is not exactly zero. But because this effect is very small, we for simplicity set interest rate volatility to zero. As explained in the appendix, this simplifies the solution to solving a two equation system of integral equations, which can be solved quickly and accurately using finite elements.[14]

Similarly, to He et al. (2022) we normalize $\beta_l = 0$. We consider maturities from zero to 10 years and set $\theta(\tau) = \theta^*(\tau) = \frac{1}{10}$ for $\tau \leq 10$ and, $\theta(\tau) = \theta^*(\tau) = 0$ for $\tau > 10$. Then $\Theta = \Theta^* = 1$.

We calibrate the model to the average inconvenience curve for Italy and Spain[15]. Similarly to interest rate risk, credit risk has minor direct effects on inconvenience yields but the effect is not exactly zero. As in Costain et al. (2021) we set the default loss parameter to $\delta = 0.25$ and the default intensity to 3bps per annum. Note, however, while credit risk has more important indirect effects on inconvenience yields through funding costs.

The stationary distribution of a Markov chain depends only on the ratio of the transition intensities $\frac{\phi_l}{\phi_h}$. We approximate funding costs using one year inconvenience yields. Because we normalized $\beta_l = 0$, the funding cost will be zero in the low state [16]. We also normalize $\beta_h = 1$. We can then replicate the mean and volatility of funding costs by setting $\frac{\phi_l}{\phi_h} \approx 0.38$, $\lambda = 0.006$, that is in the high state the funding cost is 60bps. Given the parametric form for the funding cost in Equation 3, λ could further be split to the default probability of 3bps per annum and a sensitivity constant of 20. However, this distinction is not important for the results.

The longer maturity inconvenience yields depend also on risk aversion and the level of the transition intensities. For example setting $\gamma = 112$[17], $\phi_l = 0.18$ and $\phi_h = 0.49$ produces a good fit to the average term structure of inconvenience yields for Italy and Spain, as illustrated in Figure 3. The model also predicts that an increase in the slope of inconvenience yield curve

[14] We have also solved the full model. Here the choice of initial conditions is more important to guarantee that a standard solver finds a solution.

[15] This averaging is done to reduce possible measurement error.

[16] In the data short maturity inconvenience yields are indeed often fairly close to zero.

[17] As in Vayanos and Vila (2020) risk aversion cannot be calibrated separately from bond supply which we normalized to be one in the high state.

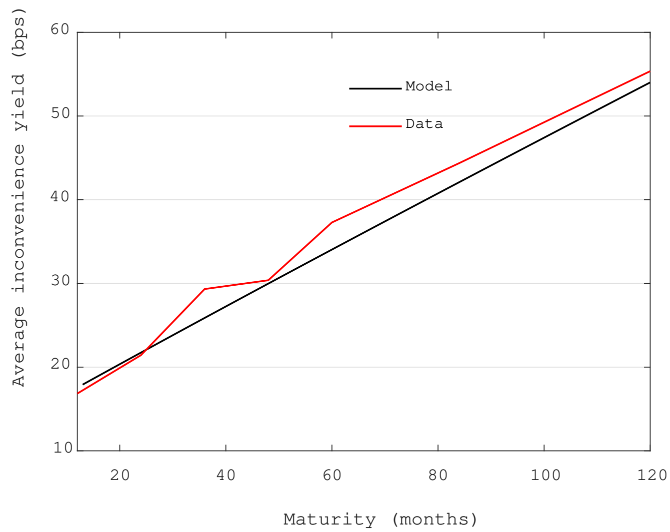

Figure 3: shows the average term structure of inconvenience yields for Italy and Spain as well as that implied by the calibrated model.

predicts increases in short maturity inconvenience yields.

For example through modifying the bond supply functions, which we simply normalized, we could fit additional data moments such as the average term premium. However, these are not the focus of our paper.

The empirically motivated assumption that excess funding costs are independent of bond maturity implies that the average inconvenience curve would be flat if our arbitrageur were risk neutral. Explaining the shape of the inconvenience curve in a risk-neutral model would require setting the excess funding cost of long maturity Periphery bonds, relative to that of short maturity bonds, to implausibly high levels. In our framework the arbitrageur's risk aversion instead explains the upward sloping shape of the curve.

Finally, anticipating our empirical section concerning Eurosystem operations we now discuss the effects of monetary policy on inconvenience yields. As in Vayanos and Vila (2020) a central bank asset purchase is effectively equivalent to a bond supply shock. Figure 4 shows the effects of an asset purchase on the average inconvenience yield curve modelled as a permanent

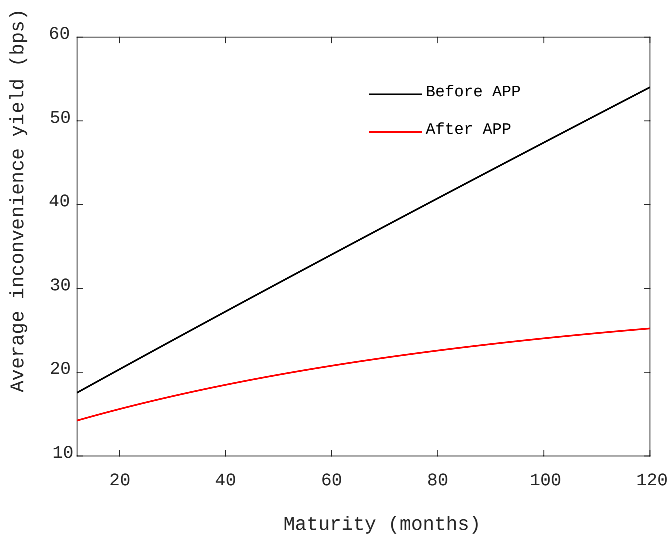

Figure 4: shows the effects of a central bank asset purchase on the average inconvenience curve. The purchase corresponds to a permanent 10% reduction in bond supply.

unexpected 10% reduction in effective bond supply.

In the model, these purchases affect inconvenience yields in two ways. First, they lower funding costs as the amount of bonds that arbitrageurs need to finance is lower. Second, they lower funding risk premia as the amount of risk that arbitrageurs need to bear is smaller. Because long maturity inconvenience yields are affected by both channels but short maturity inconvenience yields primarily by the first, the effects are larger for the longer maturities. Note that in the model, these purchases depress bond yields also by lowering duration and credit risk premia but these effects do not affect inconvenience yields.

The second way for the central bank to affect inconvenience yields is to directly alter the funding cost parameter λ. This can be achieved either through collateral policy or liquidity support. Lowering bond haircuts would directly reduce effective funding costs and also the amount of funding risk borne by arbitrageurs. Similar effects could be obtained by cheaper collateralized funding through liquidity support programs such as LTRO/TLTRO.

4 Funding Costs and Inconvenience Yields: Causal Evidence

In this section we provide causal evidence that bond haircuts affect bond inconvenience yields. However, we first discuss the structure of the eurozone funding market, which helps to understand the coming results.

4.1 On the Market for Collateralized Funding

It is difficult to directly measure bond funding costs. In principle the costs depend on three variables: interest rate on collateralized funding, costs of other sources of funding such as rate on uncollateralized loans and the share of collateralized funding. The share of cheap collateralized funding is constrained by bond haircuts, which are therefore important determinants of effective funding costs.

The second complication is that the market for collateralized funding is scattered. Loosely speaking, such financing can be obtained either from the private repo market or from the Eurosystem. The 2021 ICMA survey estimates the size of the private European repo market at EUR 8 trillion and that roughly half of these contracts are collateralized with sovereign bonds. In recent years, the repo market has grown both in absolute terms and in importance relative to the market for unsecured funding.

Contracts in the private market can be split to general and special collateral repos. In a general collateral (GC) repo, the lender may choose a collateral asset from a basket of similar bonds. The financial crisis, which erupted in 2007, fragmented the European general collateral repo market. Subsequently there is no longer a eurozone GC repo market but rather separate GC repo segments for bonds issued by different eurozone countries each with a separate repo rate (ICMA, 2019). Special collateral repos further specify the bond, as characterized by an ISIN code, to be used as collateral.

Eurosystem funding comes in several flavors. Initially the bulk of funding was provided in main refinancing operations (MRO) through lending arrangements that mirror those in the private repo market. More recently funding has also been provided through liquidity support programs such as LTRO, TLTRO and PELTRO. The ECB sets the funding terms in the Eurosystem but most of the actual funding is provided by the national central banks.

In liquidity support operations the Eurosystem provides funding over a longer, possibly several year period. The rates applied tend to be below the MRO rate, but the programs are subject to special requirements related to fostering bank lending. These liquidity support programs were introduced amid the eurozone crisis but their relative importance grew again during the later parts of our sample. Despite the restrictions, these programs can serve as a de facto funding channel for sovereign bond investments (Carpinelli and Crosignani, 2021).

Private repo rates tend to be lower than the ECB:s MRO rate. For example the repo rates measured by the Repofunds indices tend to hover below the MRO rate, roughly consistently with the logic that the central bank acts as a lender of last resort in the market. However, rates on LTRO/TLTRO operations can be more competitive with the private repo market. Unlike rates in the private repo market, Eurosystem rates do not depend on the type of collateral posted.[18]

Private clearinghouses set haircuts separately for debt issued by each country. They adjust the haircuts dynamically whenever the perceived riskiness of the sovereign changes.[19] Eurosystem initially applied haircuts similar to those in the private market but altered the system in September 2008 amid financial stability concerns. The ECB divides the sovereigns into two

[18]Small differences in the private repo rates for different type of collateral reflect additional compensation for collateral and counterparty risk as well as certain additional benefits of holding high quality bonds. For example the ability to reuse the collateral obtained through a repo transaction in a secondary repo subject to a low haircut can lower overall funding costs.

[19]Not all repos are centrally cleared. In this case the haircuts are set by the credit department of the bank (Julliard et al., 2019).

categories based on perceived riskiness. It sees the haircuts not only as a risk management device but also as a policy tool. It is therefore reluctant to procyclically increase haircuts following negative news or rating downgrades. To alleviate funding market stress it actually temporarily slammed all haircuts by 20% following the outbrake of the COVID-19 pandemic.

This tends to imply that for lower quality sovereign debt the Eurosystem haircuts are below those in the private repo market. These differences are strongest during crisis periods. In 2011 haircuts set on Italian 10 year bonds by LCH, a major clearinghouse, reached 30%. At the same time the Eurosystem applied a haircut of merely 10%. Later in 2013, the private repo market haircuts for Portuguese bonds touched 80%, while Eurosystem haircuts remained close to 10%. Similar stark increases in private market haircuts were not seen for bonds issued by safer eurozone countries such as Germany. The difference between private and Eurosystem haircuts for riskier assets is sometimes called a haircut subsidy (Drechsler et al., 2016).

Low repo rates and haircuts imply that the private market tends to provide cheaper funding for debt issued by safer eurozone countries. However, Eurosystem funding can be more competitive for riskier sovereign bonds, for which the private market haircuts tend to be higher.[20]

Our identification focuses on Eurosystem haircuts for Italian debt. We use Eurosystem haircuts since they are available daily for all bonds and follow simple mechanical rules based on maturity and credit risk categories. We focus on Italy for two reasons. First, as mentioned highest quality bonds tend to be funded through the private repo market rather than the Eurosystem. Italian debt has been viewed consistently as risky, for example it did not

[20] Drechsler et al. (2016) find evidence that banks holding riskier collateral assets were more likely to borrow from the ECB between 2008 and 2011. However, similar detailed data for the private repo market is hard to obtain. Still, the lower repo rates for e.g. German bonds combined with haircuts similar to those at the Eurosystem indirectly suggest that German bonds are rather financed through the private repo market. Especially the MRO rate tends to be higher than the rates in the private repo market. While the LTRO/TLTRO rates are lower than the MRO, the ECB's haircut policies still incentive participants to provide weaker collateral (Nyborg, 2017)

experience the rating upgrades seen for Spanish debt during later parts of our sample. Second, since Italy is a large country with a high debt to GDP ratio, there are plenty of bonds available for identification.

4.2 The effect of funding costs on bond yields

We now provide causal evidence that bond haircuts, a key component of funding costs, affect bond inconvenience yields. As discussed above, we focus on the effects of Eurosystem haircuts on Italian bond yields. We initially present results for changes in plain bond yields, since the matching of Italian and German yields as well as CDS quotes is not perfect and may introduce noise to the estimation. However, we then show that this change is driven by the change in the inconvenience portion of the yield.

ECB maintains a daily list of bonds eligible as collateral for Eurosystem operations and the haircut applied to each eligible bond. We map bond yields to haircuts directly through ISIN codes and using the historical haircut listings that are downloadable from the ECB homepage. ECB also publishes the specific rules that govern the assignment of the haircuts through tables such as those depicted in Table 2. This illustrative table shows the haircuts applied to debt issued by central governments in late 2012.

After a bond is issued its haircut can, in principle, change for three reasons. First, ECB might decide to alter the haircut values in the table. An example of this would be the collateral easing measures introduced following the break of the pandemic. Second, the haircut would change if a credit rating switch moves the bond to another credit risk category.[21]

Third, the haircut changes whenever the bond moves to another maturity category. In particular, the haircuts change in a stepwise fashion when predetermined thresholds for different maturity buckets are crossed. For

[21]This effect is nuanced since as mentioned the ECB is reluctant to increase haircuts during crisis periods due to financial stability concerns. For example during the eurozone crisis it announced exemptions according to which downgrades of central government debt below investment grade would not affect their haircuts.

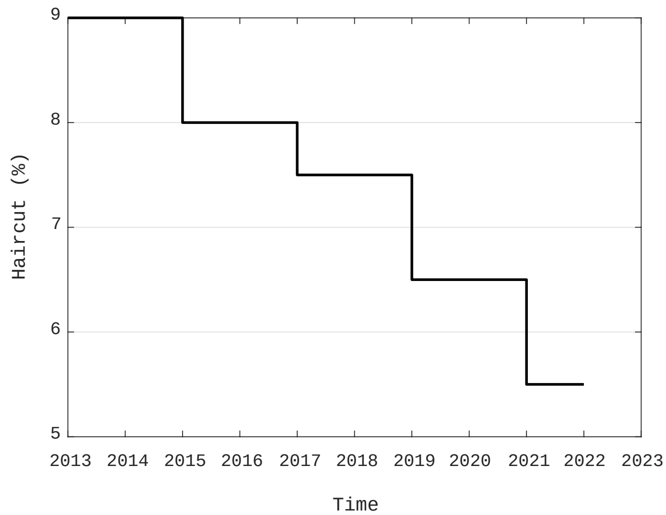

Figure 5: shows the haircut schedule for a bond in the 2nd credit rating category with a tenor of 10 years in November 2012.

example according to Table 2, the haircut of a fixed coupon bond in the second credit rating group would fall by 1.5 percentage points if the bond's tenor falls from 10 years and 1 day to exactly 10 years. To further illustrate the determination of haircuts, Figure 5 shows the planned haircut schedule for a bond with a tenor of 10 years in late 2012. Note that the actual haircuts can change from this schedule due to changes in collateral policies. However, ECB has not changed the definitions of maturity categories so the dates of haircut changes are determined by the bond's issuance date and maturity[22].

Haircut changes induced by the first two reasons are not necessarily exogenous. In the first case an additional problem is that ECB collateral policy changes can coincide with other ECB policies such as asset purchases. However, maturity category changes depend only on the issue date of the bond and the maturity category thresholds, which are essentially arbitrary. Haircut changes due to maturity category shifts are thus plausibly exogenous. Moreover, since each day the maturity bucket changes for at most a fraction

[22]Government Treasuries tend to issue bonds on a fairly continuous basis throughout the year according to an auction schedule determined each year.

AAA to A-			BBB+ to BBB-		
Residual Mat	Fixed coupon	Zero coupon	Residual Mat	Fixed coupon	Zero coupon
0-1	0.5	0.5	0-1	5.5	5.5
1-3	1.5	1.5	1-3	6.5	6.5
3-5	2.5	3	3-5	7.5	8
5-7	3	3.5	5-7	8	8.5
7-10	4	4.5	7-10	9	9.5
> 10	5.5	8.5	>10	10.5	13.5

Table 2: Eurosystem haircuts for Category I assets (debt issued by central governments) in 2012

of the bonds, possible unobservables can be controlled using bond and time fixed effects. Therefore, we exclude haircut changes due to changes in either haircut parameters or issuer credit rating, and only include maturity category induced haircut changes.

Table 3 shows the effects of haircut changes on Italian bond yields. We explain the daily yield change (Δy^{IT}) with indicator variables that get value of one or zero depending on the date of the maturity category change. First, indicator variable HCI obtains a value of one on the day that ECB changes the haircuts due to a maturity category change. We also report results for indicator variables $HCI1$ and $HCI2$, which get a value of one if the haircut changed one or two days ago, respectively, and are zero otherwise. We have two reasons to report the results for multiple days. First, ECB reports haircuts in the evening (at 18.15 CET) so that they become effective the next day, and second, e.g. as the repo maturities vary, not all bonds are necessarily refinanced on each day. Finally, the aggregate variable $HCIALL$ obtains a value of one, if any of $HCI, HCI1$ or $HCI2$ has a value of one. We also show $HCIALL$ interacted with indicator variables $< 1, 1-3, 3-5, 5-7$ and $7-10$ for the maturity category.

Table 3 shows that all variables related to maturity category changes obtain a negative coefficient. A reduced bond haircut due to a maturity category change leads to a lower yield. As specification (3) shows, the impact is strongest on the first day after the announcement that is the first day the new lower haircut is in effect, but statistical significance increases if we take the aggregate measure for all 3 days in specification (4). In specification (5), instead of bond fixed effects, we use fixed effects per maturity bucket. Specification (6) shows that the effect is broadly distributed between the maturity buckets, i.e. the impact is not driven by a single maturity category. Δy^{IT} is measured in basis points, so the cumulative impact for the three days is around 1 basis point lower inconvenience yield. This is small in economic terms, but so are the changes in haircuts due to maturity buckets. In our sample, the average change in haircut is just under 1 percentage point, which translates to a small increase in funding costs, depending on the relevant interest rates.

We also analyze the impact a change in the integer part of a bond's maturity has on the yield changes Δy^{IT}. A natural alternative explanation for the results is that there is something special around the date in which the integer part of the maturity measured in years changes. To rule this out, Table 4 shows analysis similar to that in Table 3 but so that the indicator variables are based on all dates when the full year part of maturity changes.[23]

Table 4 shows that there is no effect when the year part of the maturity changes once we include fixed effects for both bonds and dates. Many of the corresponding coefficients are also positive rather than negative.

Table 5 replicates the results in Table 3 for German bonds. We see that a change in Eurosystem haircut has no effect on German bond pricing. These bonds are funded on the private market with better terms, so it is natural that Eurosystem haircuts do not have significant effects on their yields.

Table 6 shows regressions similar to those in Table 3, except that the dependent variable is the change in the inconvenience yield of an Italian bond instead of the plain yield change. We match each Italian bond with the nearest maturity Italian CDS contract, German CDS contract and German bond and solve for bond specific inconvenience yields using Equation (1).

[23] For example, a maturity change from 4.0 to 3.98 years would be included in Table 4 but excluded from 3, as both four and three years belong to the same maturity category. See Table 2 for categories.

	Yield Change $\Delta y_t^{IT}(\tau)$					
	(1)	(2)	(3)	(4)	(5)	(6)
HCI	-0.41	-0.19	-0.18		-0.17	
	(-0.82)	(-0.72)	(-0.67)		(-0.65)	
$HCI1$	-1.62***	-0.62**	-0.60**		-0.59**	
	(-3.16)	(-2.56)	(-2.51)		(-2.45)	
$HCI2$	-0.65	-0.32	-0.30		-0.29	
	(-1.26)	(-1.64)	(-1.54)		(-1.49)	
$HCIALL$				-0.36***		
				(-3.06)		
< 1					-0.33***	
					(-3.48)	
$1-3$					-0.26***	
					(-4.71)	
$3-5$					-0.26***	
					(-5.81)	
$5-7$					-0.29***	
					(-8.81)	
$7-10$					-0.27***	
					(-9.76)	
> 10					-0.23***	
					(-8.00)	
$< 1XHCIALL$						-0.49
						(-1.50)
$1-3XHCIALL$						-0.69**
						(-2.37)
$3-5XHCIALL$						-0.35**
						(-2.08)
$5-7XHCIALL$						-0.51***
						(-3.15)
$7-10XHCIALL$						0.24
						(1.53)
# of Obs.	667107	667107	667107	667107	667107	667107
R^2	0.00008	0.00003	0.00003	0.00002	0.00009	0.00004
Bond fixed effects			x	x		x
Time fixed effects		x	x	x	x	x
Note:				*p<0.1; **p<0.05; ***p<0.01		

Table 3: shows the impact of Eurosystem haircuts on Italian bond yields. Dependent variable Δy^{IT} is the daily change in bond yield measured in basis points. Indicator variable HCI gets a value of one, if during that day ECB reports a change in bond haircut due to maturity category change and value of 0 otherwise. We include also the lagged values of the indicator. $HCI1$ has value of one, if ECB reported a haircut change the previous day and $HCI2$ gets value of one if haircut changed 2 days since. Aggregate variable $HCIALL$ gets value of one, if any of $HCI, HCI1$ or $HCI2$ has value of one. $< 1, 1-3, 3-5, 5-7$ and $7-10$ are dummies for the bonds' the maturity category. We also show $HCIALL$ interacted with indicator variables $< 1, 1-3, 3-5, 5-7$ and $7-10$ for the maturity category. The sample is from April 2010 until end of 2021. Standard errors are clustered by bond and date.

	Yield Change Δy^{IT}			
	(1)	(2)	(3)	(4)
TI	-1.21***	-0.08	-0.09	
	(-2.87)	(-0.67)	(-0.72)	
$TI1$	-1.14*	0.11	0.10	
	(-1.90)	(0.79)	(0.75)	
$TI2$	-0.14	0.20	0.20	
	(-0.29)	(1.53)	(1.48)	
$TIALL$				0.07
				(0.91)
# of Obs.	667107	667107	667107	667107
R^2	0.00026	0.00001	0.00001	0.00000
Bond fixed effects			x	x
Time fixed effects		x	x	x
Note:	*p<0.1; **p<0.05; ***p<0.01			

Table 4: shows the impact of changes in the integer part of an Italian bond's maturity on bond yields. Dependent variable Δy^{IT} is the daily change in bond yield measured in basis points. Indicator variable TI gets a value of one, if during that day the integer part of a bond's maturity changes and value of 0 otherwise. We include also the lagged values of the indicator. $TI1$ has value of one, if the year of the tenor changed the previous day and $TI2$ gets value of one if the tenor changed 2 days since. Aggregate variable $TIALL$ gets value of one, if any of $TI, TI1$ or $TI2$ has value of one. Standard errors are clustered by bond and date.

	Yield Change Δy^{DE}					
	(1)	(2)	(3)	(4)	(5)	(6)
HCI	-0.62**	-0.08	-0.10		-0.10	
	(-2.53)	(-0.70)	(-0.87)		(-0.90)	
$HCI1$	0.08	0.15	0.13		0.12	
	(0.30)	(1.44)	(1.25)		(1.11)	
$HCI2$	-0.20	0.08	0.06		0.04	
	(-0.75)	(0.70)	(0.52)		(0.39)	
$HCIALL$				0.03		
				(0.55)		
< 1					-0.04	
					(-0.95)	
$1-3$					-0.08***	
					(-2.78)	
$3-5$					-0.13***	
					(-6.79)	
$5-7$					-0.16***	
					(-9.86)	
$7-10$					-0.16***	
					(-11.65)	
> 10					-0.17***	
					(-8.08)	
$< 1XHCIALL$						0.18
						(1.31)
$1-3XHCIALL$						0.09
						(0.74)
$3-5XHCIALL$						-0.15
						(-1.21)
$5-7XHCIALL$						0.03
						(0.23)
$7-10XHCIALL$						-0.07
						(-0.76)
# of Obs.	403603	403603	403603	403603	403603	403603
R^2	0.00006	0.00001	0.00001	0.00000	0.00057	0.00002
Bond fixed effects			x	x		x
Time fixed effects		x	x	x	x	x
Note:						*p<0.1; **p<0.05; ***p<0.01

Table 5: shows the impact of Eurosystem haircuts on German bond yields. Dependent variable $\Delta y^D E$ is the daily change in bond yield measured in basis points. Indicator variable HCI gets a value of one, if during that day ECB reports a change in bond haircut due to maturity category change and value of 0 otherwise. We include also the lagged values of the indicator. $HCI1$ has value of one, if ECB reported a haircut change the previous day and $HCI2$ gets value of one if haircut changed 2 days since. Aggregate variable $HCIALL$ gets value of one, if any of $HCI, HCI1$ or $HCI2$ has value of one. $< 1, 1-3, 3-5, 5-7$ and $7-10$ are dummies for the bonds' the maturity category. We also show $HCIALL$ interacted with indicator variables $< 1, 1-3, 3-5, 5-7$ and $7-10$ for the maturity category. The sample is from April 2010 until end of 2021. Standard errors are clustered by bond and date.

	Inconvenience Yield Change Δicy^{IT}					
	(1)	(2)	(3)	(4)	(5)	(6)
HCI	-0.18	-0.24	-0.21		-0.20	
	(-0.26)	(-0.73)	(-0.66)		(-0.63)	
$HCI1$	-1.92***	-0.60**	-0.57**		-0.54**	
	(-2.74)	(-2.21)	(-2.15)		(-2.06)	
$HCI2$	0.22	-0.22	-0.19		-0.16	
	(0.20)	(-1.10)	(-0.95)		(-0.83)	
$HCIALL$				-0.32**		
				(-2.40)		
<1					-0.41***	
					(-3.40)	
$1-3$					-0.30***	
					(-4.65)	
$3-5$					-0.29***	
					(-5.81)	
$5-7$					-0.31***	
					(-7.98)	
$7-10$					-0.28***	
					(-9.03)	
>10					-0.23***	
					(-7.05)	
$<1XHCIALL$						-0.40
						(-1.09)
$1-3XHCIALL$						-0.53
						(-1.33)
$3-5XHCIALL$						-0.33*
						(-1.66)
$5-7XHCIALL$						-0.49***
						(-2.69)
$7-10XHCIALL$						0.09
						(0.48)
# of Obs.	667107	667107	667107	667107	667107	667107
R^2	0.0000	0.0000	0.0000	0.0000	0.0002	0.0000
Bond fixed effects			x	x		x
Time fixed effects		x	x	x	x	x
Note:						*p<0.1; **p<0.05; ***p<0.01

Table 6: shows the impact of Eurosystem haircuts on Italian bond inconvenience yields. Dependent variable Δicy^{IT} is the daily change in bond inconvenience yield measured in basis points and given by $icy_t^{IT}(\tau) = y_t^{IT}(\tau) - cds_t^i(\tau) - (y_t^{DE}(\tau) - cds_t^{DE}(\tau))$ where $y_t^{IT}(\tau)$ is the yield of an τ-maturity Italian bond, $y_t^{DE}(\tau)$ is the yield of the closest maturity German bond and $cds_t^i(\tau)$ is the premium of the closest maturity CDS contract. Indicator variable HCI gets a value of one, if during that day ECB reports a change in bond haircut due to maturity category change and value of 0 otherwise. We include also the lagged values of the indicator. $HCI1$ has value of one, if ECB reported a haircut change the previous day and $HCI2$ gets value of one if haircut changed 2 days since. Aggregate variable $HCIALL$ gets value of one, if any of $HCI, HCI1$ or $HCI2$ has value of one. $<1, 1-3, 3-5, 5-7$ and $7-10$ are dummies for the bonds' the maturity category. We also show $HCIALL$ interacted with indicator variables $<1, 1-3, 3-5, 5-7$ and $7-10$ for the maturity category. The sample is from April 2010 until end of 2021. Standard errors are clustered by bond and date.

The results are very similar to Table 3. Hence the effects in Table 3 are driven by the changes in the inconvenience yield portion of the yield.

Note that if the maturities of an Italian and German bond matched exactly, both bonds would switch maturity buckets on exactly the same days. Then the haircut changes on the bonds would also coincide. However, note that since German bonds tend to be funded in the private repo market on better terms, we found no significant effects on ECB haircuts on German bond yields. Moreover, there is some inaccuracy in matching since for each Italian bond, there is not necessarily a German bond with exactly the same tenor. Hence the haircut on a German bond matched to an Italian bond can change on slightly different days.

We found very similar results for the effects of haircut changes on inconvenience yields and plain yields. This suggests that haircuts do not have effects on changes in CDS premia. Table 7 confirms this by showing regressions similar to those in Table 6, except now the dependent variable is the premium on the Italian CDS matched to an Italian bond. We find no statistically significant effect. Together, these additional tests suggest that the yield changes documented in Table 3 are driven by the funding costs and not changes in Italian creditworthiness or the market premium of Italian CDS.

	CDS Premium Change Δcds^{IT}			
	(1)	(2)	(3)	(4)
HCI	-0.21	0.11	0.10	
	(-0.49)	(1.09)	(1.08)	
$HCI1$	0.61	0.04	0.04	
	(1.24)	(0.77)	(0.73)	
$HCI2$	-0.94	-0.06	-0.06	
	(-1.20)	(-1.16)	(-1.22)	
$HCIALL$				0.03
				(0.69)
# of Obs.	667107	667107	667107	667107
R^2	0.0000	0.0000	0.0000	0.0000
Bond fixed effects			x	x
Time fixed effects		x	x	x
Note:		*p<0.1; **p<0.05; ***p<0.01		

Table 7: shows the impact of Eurosystem haircuts on Italian CDS premia. Dependent variable Δcds^{IT} is the daily change in an Italian CDS premium matched to an Italian bond. The change is measured in basis points. Each Italian bond in our sample is matched to an Italian CDS contract based on maturity. Indicator variable HCI obtains a value of one, if during that day ECB reports a change in the bond's haircut due to maturity category change and value of zero otherwise. We also include the lagged values of the indicator. $HCI1$ obtains a value of one, if ECB reported a haircut change the previous day and $HCI2$ gets value of one if haircut changed 2 days since. Aggregate variable $HCIALL$ gets value of one, if any of $HCI, HCI1$ or $HCI2$ has value of one. The sample is from April 2010 until end of 2021. Standard errors are clustered by bond and date.

We next discuss why we find certain alternative interpretations for our results implausible. First, maturity category changes can coincide with bond coupon dates. However, these coupon effects on bond yields tend to be small and rather lead to an increase in bond yields. The coupon dates also do not always concur with haircut change dates and we find no significant effects for changes in the integer part of maturity. A second alternative would be that the results are related to index inclusion effects. However, the fact that we do not find significant results for plain changes in the integer part of bond maturity and also no effects for German bonds suggest otherwise. The key Italian bond indices tracked by ETF:s such as Bloomberg Italy Treasury Bond Index are also not based on maturity categories. Moreover, the sign of this channel would be ambiguous as moving between categories might increase or decrease bond yields depending on the relevant importance of the categories.

An effect we have not been able to rule out concerns haircut changes in the private repo market. The ECB category changes might coincide with those in the private market, which might contribute to our findings. However, for example LCH SA tends to apply categories based on bond durations rather than bond maturities. These effects are hard to measure especially due to the opaque nature of the bilateral portion of the repo market. Still such effects would be consistent with the broader message of this section that bond haircuts affect bond yields.

Finally, interpreting the size of the effect of haircuts on yields is subject to two caveats. First, we have only focused on the effects of Eurosystem haircuts. However, if the ECB would start increasing haircuts, the private market might at some point become more competitive for Italian bonds. After this point, these bonds would be financed through the private repo market and further increases in Eurosystem haircuts would no longer affect yields on Italian bonds similarly to what we observed for German bonds. Second, the maturity category induced haircut changes do not constitute unexpected haircut shocks and such unexpected changes might have larger effects. However, note that these haircut changes and respective yield effects are both small in absolute terms. Therefore transaction costs and other frictions would likely eat the profits from strategies attempting to trade bonds around category changes.

5 Monetary Policy Transmission

Yield spreads can change either because of changes in CDS spreads or changes in inconvenience yields. Using a variance decomposition Jiang et al. (2022) find that changes in inconvenience yields explain a large fraction of yield spread movements. As discussed, a central bank can affect inconvenience yields both by lowering funding costs and by removing funding risk from arbitrageurs' balance sheets. But how important is this channel for understanding the effects of monetary policy on yield spreads?

Analyzing the effects of monetary policy on bond yields is complicated. Our approach is similar to Bauer and Neely (2014). They focus on simple announcement effects, but rather than attempting to measure the full effect on bond yields, concentrate on the relative contributions of different channels.

We use information on the ECB webpage to create a series of announcement dates for key monetary policy decisions. We classify the policies into categories similarly to Kilponen et al. (2015). We exclude policies that primarily affected a single country. We also omit changes to the collateral framework that did not involve sovereign bonds. The full list of included policy announcements is given in the appendix.

We decompose changes in bond yield spreads relative to Germany into changes in inconvenience yields and changes in CDS spreads:

$$\Delta y_t^{i,r}(\tau) = \Delta icy_t^i(\tau) + \Delta cds_t^{i,r}(\tau) \tag{8}$$

Here $y_t^{i,r}(\tau) = y_t^i(\tau) - y_t^{DE}(\tau)$ and $cds_t^{i,r}(\tau) = cds_t^i(\tau) - cds_t^{DE}(\tau)$. Taking squares and then averaging over announcement events, we obtain

Policy	ICY Share
Collateral Policy Changes	66 %
Securities Market Program	39 %
Outright Monetary Transactions Program	9 %
Draghi “Whatever-It-Takes” Speech	15 %
Extended APP	36 %
PEPP	54 %
Liquidity Support	38 %
Average	48 %

Table 8: shows the share of yield spread changes around monetary policy announcements that are due to changes in inconvenience yields.

$$\begin{gathered}\frac{1}{N}\sum_{i=1}^{N}(\Delta y_t^{i,r}(\tau))^2 = \\ \frac{1}{N}\sum_{i=1}^{N}(\Delta icy_t^{i}(\tau))^2 + \frac{1}{N}\sum_{i=1}^{N}(\Delta cds_t^{i,r}(\tau))^2 + \frac{1}{N}\sum_{i=1}^{N}2\Delta y_t^{i,r}(\tau)\Delta cds_t^{i,r}(\tau)\end{gathered} \tag{9}$$

We then compute the contribution of changes in inconvenience yields as

$$\frac{\frac{1}{N}\sum_{i=1}^{N}(\Delta icy_t^{i}(\tau))^2}{\frac{1}{N}\sum_{i=1}^{N}(\Delta y_t^{i,r}(\tau))^2} \tag{10}$$

To allow for some time for the CDS quotes to adjust, we compute the changes over a two day window around the announcement. We focus on the most liquid 5 year maturity and compute the average inconvenience relative to Germany. The results are given in Table 8.

On average, the inconvenience yield share is close to half. The cross component is small so that changes in inconvenience yields and CDS spreads are roughly equally important in explaining yield spread changes. The inconvenience yield share is highest for collateral policies followed by the recent Pandemic Emergency Purchase Program (PEPP). The high share for collateral policies seems natural since haircut changes directly affect funding costs but might not have large effects on credit risk per se.

Note that our classification of yield changes to those caused by different policies is naturally imperfect. For example, the most important change in the collateral framework was the 20% temporary reduction in all haircuts that was officially announced and implemented in April 2020. However, loosening of bond haircuts was already discussed in March 2020, when PEPP was announced so that this annoucement effect might be partly attributed to changes in collateral policy.

Our model predicted that asset purchases would lead to a more substantial fall in longer maturity inconvenience yields. To gauge this prediction, we focus on Italy and Spain for which both short and longer maturity CDS contracts are reasonably liquid. We also concentrate only on the announcement effects of the Public Sector Purchase Program (PSPP) in 2015 and that for the PEPP. This is because the earlier programs concentrated on longer maturity debt, which might more mechanically imply greater falls in longer maturity inconvenience yields.

We find that 10 year inconvenience yields fell on average by 27 basis points around the announcements but one year inconvenience yields merely 0.3 basis points. This is consistent with our prediction that longer maturity inconvenience yields should fall more. However, note that this is based on merely two events and fully identifying the effects of unconventional monetary policy is difficult. For example, the announcement of the PSPP initially led to a fairly small decline in yields. However, subsequent falls followed in the next months, possibly in relation to the implementation of these purchases.

The above results bear important policy implications. First, a central bank interested in controlling spread differences should choose the optimal policy tool depending the source of these spreads. Collateral policies appear particularly effective against rising inconvenience yields. Second, any realistic model capturing the effects of monetary policy on yield spreads should account for both sovereign risk and inconvenience yield channels.

6 Conclusion

Two assumptions rationalize the term structure of eurozone inconvenience yields. First, arbitrageurs face higher funding costs on periphery country debt with greater credit risk. Second, future funding costs are uncertain and arbitrageurs are risk averse. Using exogenous variation in ECB haircuts induced by maturity category changes, we document causal evidence that funding costs affect bond yields. Changes in inconvenience yields explain a large fraction of yield spread variation around monetary policy announcements.

7 Appendix

7.1 Included ECB Policy Announcements

7.2 On the OIS-Germany Basis

Rates on overnight indexed swaps (OIS) tend to trade above yields on German bonds. Providing a comprehensive analysis of this difference is beyond the scope of this paper. However, here we note that this OIS Germany spread is consistent with a funding cost based explanation.

First, observe that swaps are zero net supply securities that could easily be priced using our framework. Here the swap spread emerges from higher funding costs of swaps relative to safe bonds. Compare two investments. First, an investor could buy a German bond using cheap repo financing by pledging the bond as collateral. Here the investor would receive the bond return and pay the German repo rate. An alternative would be to buy an OIS swap and hence receive the OIS rate and pay the OIS reference rate called EONIA[24].

[24]At the beginning of 2022, the EONIA rate was replaced with the €STR rate but our sample ends just before this. This replacement was preceded by a several year transition period during which EONIA was quoted simply as a constant spread over the €STR rate. Most swaps still used EONIA as the reference rate. Note that while EONIA was unsecured

Collateral Policies	
Apr. 8, 2010	graduated valuation haircuts for lower-rated assets
20 Feb 2015	haircut changes
7 April 2020	all haircuts reduced by 20% till September 2021
Securities Market Program	
May 10, 2010	announced (initially Greek, Irish and Portuguese debt)
August 7, 2011	extension announced (Italian and Spanish debt included)
Outright Monetary Transactions Program	
Sep. 6, 2012	
Draghi "Whatever-It-Takes" Speech	
Jul. 26, 2012	
Extended APP	
Jan. 22, 2015	APP announced
Nov. 9, 2015	Amends PSPP issue share limit
Mar. 10, 2016	APP extended, also new corp bond purchases
Apr. 21, 2016	APP extended
Oct 26, 2017	APP scale down announced
March 12, 2020	Temporary APP envelope announced
PEPP	
Mar 18, 2020	750 billion PEPP package announced
Jun 4, 2020	PEPP size increased
Dec 10, 2020	PEPP size increased
Sep 19, 2021	purchase pace reduced
Dec 16, 2021	PEPP reductions discussed
Liquidity Support	
May 7, 2009	New LTRO announced
Aug. 4, 2011	New LTRO announced
Oct. 6, 2011	New LTRO announced
Dec. 8, 2011	New LTRO announced
Nov. 20, 2013	suspends early repayment LTRO
Jun. 5, 2014	New TLTRO:s announced, also cut rates on the same day
Jul. 3, 2014	Details of TLTRO:s announced
18 Sep, 2014	TLTRO allotment published
7 Nov, 2014	suspends early repayment TLTRO
22 Jan 2015	modification to TLTRO rates
10 March 2016	new TLTRO:s announced
May 3 2016	TLTRO legal acts published
Jun 2 2016	TLTRO dates announced
March 17, 2019	new TLTRO:s announced
Jun 6, 2019	TLTRO details announced
Jul 29, 2019	TLTRO details announced
Sep 12, 2019	TLTRO changes announced, changes to renumeration of bank excess liquidity reserves
March 12, 2020	New TLTROs and changes to previous, also bank capital reliefs
April 30, 2020	PELTRO announced, TLTRO interest rates reduced
Dec 10, 2020	New PELTROs

Table 9: shows the policy announcements considered for studying the effects of unconventional monetary policy.

Since EONIA rates were unsecured, they used to trade above German repo rates. This higher effective funding cost of swaps implied that OIS rates should also have traded above German bond yields. If the OIS German basis had been lower than the EONIA repo basis, one could have attempted to profit by buying a German bond using repo financing and selling an OIS swap. Here the investor would have received the difference between the return on a German bond and the OIS rate and paid the difference between the repo rate and EONIA. This suggests that the OIS German basis should indeed have been greater than or equal to the EONIA repo basis.

For longer maturity bonds the OIS-German basis was somewhat higher than the EONIA-repo-basis. In particular, in our sample, the difference between yields of ten year German bonds and rates on ten year OIS swaps is 37bps. On the other hand, based on the repo indices the German repo-EONIA basis is around 17bps. The unexplained portion is, therefore, 20bps.

What explains the remaining part? In our framework fluctuations between unsecured funding and repo rates imply funding risk associated with swap investments. This implies that longer horizon OIS-German basis should remain above the corresponding funding cost difference.

There can also be some inaccuracy in measuring the basis. This is because bond coupons imply that the duration of a bond and a swap can be slightly different. Here we are also approximating the repo rate of a 10 year bond with an index that represents an average of the repo rates on different maturity German bonds. Note that shorting German cash bonds can also be subject to additional frictions.

7.3 On Model Interpretation

We next discuss some issues related to interpreting our theoretical pricing model. First, our arbitrageur plausibly represents both banks and hedge funds. He et al. (2022) derive a similar model with both banks and hedge

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since it was overnight the credit risk was still smaller than that related to many other forms of unsecured borrowing.

funds, where the former also provide financing to the latter. However, due to perfect risk sharing, they show that the model is effectively homeomorphic to a model with a single arbitrageur.

However, He et al. (2022) motivate the funding cost of Treasuries by the SLR ratio, the US implementation of the Basel III Tier 1 capital ratio. However, since EU regulation treats bonds issued by different countries equally, bank regulation cannot directly explain relative inconvenience yields in the eurozone. Moreover, all of these bonds have zero risk weight when measuring capital adequacy. As explained before, in the eurozone differences in funding costs instead emanate from the fact that the bonds are treated distinctly in money markets. However, regulatory constraints can have effects on the overall level of liquidity in money markets.

Note that our approach would also be consistent from the viewpoint of a CDS dealer.[25] Since short sales tend to be conducted via reverse repo transactions and the relevant repo rates are higher, short sale costs of Periphery country bonds tend to be lower than those of Core bonds. When a dealer must absorb CDS demand by selling protection, a natural hedge is to sell a Periphery bond and possibly also buy an OIS swap. The lower short sale cost of Periphery bonds implied by higher repo rates would push down CDS premia of lower quality bonds relative to those of high quality bonds, consistently with the corresponding cash bonds trading at an inconvenience yield.

Alternatively, when a dealer acts as a net protection buyer, a natural hedge is to buy a Periphery bond and, perhaps, also sell an OIS swap. Here the higher funding cost of periphery country bonds would again lower the equilibrium CDS premium and be concordant with an inconvenience yield for the periphery cash bonds.

In our model an arbitrageur effectively funds bond investments through

[25]We thank George Pennacchi for making this point. As mentioned our key framework abstracts away from such effects since we do not consider separate preferred habitat demands for CDS contracts and to avoid dealing with certain additional complications with short sales of cash bonds.

(partly) collateralized borrowing. But who provides this financing? Questions related to microfoundations of financial intermediation are naturally beyond the scope of this paper. However, we could justify our setting in a general equilibrium framework, e.g., by assuming the existence of more risk averse agents that endogenously choose to fund intermediaries as in Drechsler et al. (2018).

Our framework equates a bond inconvenience benefit with a collateral benefit that effectively implies lower funding costs. Could safe assets offer other convenience benefits? First, note that in a reverse repo transaction, some benefits might accrue also to the lender who could use the collateral in a secondary repo deal (rehypothecation). The lender might also be able to use the bond in other transactions such as short sales. Note that such possible additional benefits would flow to the lender rather than the borrower and would still affect our arbitrageur through funding costs. While such additional benefits might therefore, e.g., affect the determination of the funding cost parameter λ, they would not affect our key results.

7.4 Discussion on Model Mechanism

We next discuss the intuition behind our key pricing mechanisms. The pricing of safe bonds works similarly to that in the classic model of Vasicek (1977). In a risk-neutral world, the price of a safe bond would be $\mathbb{E}_t \exp\left(-\int_t^T r_s ds\right)$. High expected future interest rates lower the price and increase the yield of a safe bond today. Moreover, interest rate shocks have stronger relative effects on the prices of long maturity safe bonds.

However, since our arbitrageur is risk averse, she demands to be compensated for interest rate shocks that lead to fluctuations in the prices of safe bonds, especially those of longer maturity ones. This mechanism explains the average term structure of core country yields in the model. The amount of compensation depends on the risk aversion parameter and bond supplies.

In a risk neutral world the price of a synthetic safe bond would instead be $\mathbb{E}_t \exp\left(-\int_t^T (r_s + \Lambda_s) ds\right)$. Here the safe instantaneous short rate is modified by the funding cost so that the effective interest rate in the pricing formula is now $r_s + \Lambda_s$. Because of higher funding costs the bond is now valued using a higher discount rate and hence trades at a lower price and higher yield. Moreover, fluctuations in funding costs have stronger effects on the prices of long maturity synthetic safe bonds. Here funding costs increase the volatility of effective short rate changes.

When our arbitrageur is risk averse, uncertain funding costs add an extra element of risk. This explains the average term structure of synthetic safe yields and why inconvenience yields tend to be increasing in bond maturity. The pricing of funding cost shocks work similarly to those of standard interest rate shocks with one key exception. As in Vayanos and Vila (2020) and He et al. (2022), short rate shocks are uncorrelated with bond supply shocks. However, in the model funding costs increase when the demand from preferred habitat investors is low since this implies that arbitrageurs must hold and therefore finance more bonds. This mechanism further increases the compensation required for funding cost fluctuations, i.e. the funding risk premium.

7.5 Descriptive Statistics

Table 10 shows key descriptive statistics for different tenor bond yields, CDS premia and inconvenience yields averaged over countries. Table 11 displays the same statistics for different countries but focuses on the 5 year tenor. Figure 6 shows the average term structures of inconvenience yields separately for each country. Some of the term structures for the smaller countries like Portugal show some irregularities, possibly due to low market liquidity of certain maturities.

7.6 Proof of Proposition 1

Conjecture:

$$P_{it}(\tau) = \exp(-C_i(\tau) - A(\tau) r_t), \quad i = l, h$$

Yields, $\bar{y}_t(\tau)$, (bps)									
Mat.	6m	1Y	2Y	3Y	4Y	5Y	7Y	10Y	30Y
Mean	-18.28	14.92	51.92	72.06	56.85	120.82	149.63	192.64	153.44
Volatility	51.56	96.49	136.90	149.71	107.24	168.97	158.68	166.56	62.11
Skewness	1.56	1.73	1.50	1.32	0.79	1.05	0.75	0.60	-0.33
Ex. Kurtosis	2.88	2.17	1.58	0.87	-0.73	-0.01	-0.71	-0.98	-1.41
CDS Premia, $\overline{cds}_t(\tau)$, (bps)									
Mat.	6m	1Y	2Y	3Y	4Y	5Y	7Y	10Y	30Y
Mean	23.20	45.63	64.75	71.92	50.15	87.80	89.35	93.00	103.03
Volatility	41.89	67.59	90.07	88.51	43.29	88.98	70.06	68.57	62.52
Skewness	2.06	2.24	2.21	2.07	1.92	1.79	1.64	1.53	1.44
Ex. Kurtosis	4.09	4.41	3.96	3.36	3.19	2.37	2.20	1.78	1.76
Inconvenience Yields, $\overline{icy}_t(\tau)$, (bps)									
Mat.	6m	1Y	2Y	3Y	4Y	5Y	7Y	10Y	30Y
Mean	2.34	9.00	10.49	17.66	15.70	29.64	35.54	40.64	46.27
Volatility	18.96	16.63	25.96	27.13	17.38	34.37	34.76	27.92	13.44
Skewness	-2.38	-0.00	1.69	2.58	1.56	1.78	1.40	1.18	-0.34
Ex. Kurtosis	8.47	7.02	7.37	8.89	3.89	3.28	2.10	0.78	-0.19

Table 10: shows descriptive statistics for different tenor bond yields, CDS premia and inconvenience yields, averaged over countries.

Yields, $y_t^i(5Y)$, (5Y, bps)										
	AU	BE	DE	ES	FI	FR	IR	IT	NL	PT
Mean	48.27	65.66	22.48	159.22	15.52	50.88	186.22	184.79	34.59	335.27
Volatility	106.46	128.37	89.49	188.22	81.98	99.01	315.27	159.86	95.97	440.60
Skewness	1.00	1.05	1.07	0.80	1.09	0.82	1.83	0.92	0.95	1.77
Ex. Kurtosis	-0.24	-0.08	0.27	-0.71	0.12	-0.55	3.15	0.11	-0.18	2.49

CDS Premia, $cds_t^i(5Y)$, (5Y, bps)										
	AU	BE	DE	ES	FI	FR	IR	IT	NL	PT
Mean	27.76	47.64	15.78	107.12	15.85	33.75	140.99	148.93	20.13	248.01
Volatility	30.93	58.44	14.14	103.16	13.32	32.48	211.20	86.98	19.73	291.64
Skewness	1.91	2.10	1.77	1.38	2.39	1.78	1.93	1.82	2.10	1.95
Ex. Kurtosis	2.95	4.00	2.65	1.13	5.21	2.88	2.73	3.25	4.70	3.22

Inconvenience Yield, $icy_t^i(5Y)$, (5Y, bps)									
	AU	BE	ES	FI	FR	IR	IT	NL	PT
Mean	13.82	11.32	45.41	6.44	10.43	38.54	29.16	7.76	80.57
Volatility	15.25	20.28	44.52	12.18	13.07	72.24	44.14	10.56	120.23
Skewness	2.05	1.28	1.76	1.60	0.57	3.10	1.27	1.03	2.51
Ex. Kurtosis	8.15	4.59	3.26	3.82	2.69	11.91	2.70	1.24	6.55

Table 11: shows descriptive statistics for yields, CDS premia and inconvenience yields for different countries for the 5 year tenor.

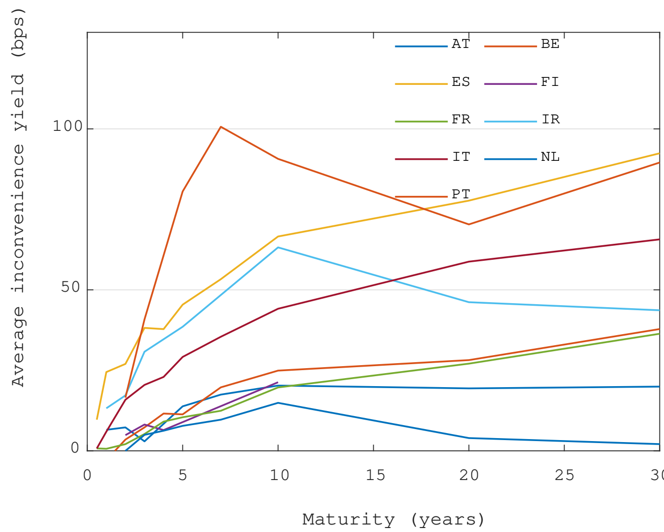

Figure 6: shows the average term structure of inconvenience yields separately for each individual country.

$$P^*_{it}(\tau) = \exp(-C^*_i(\tau) - A^*(\tau)r_t), \;\; i = l, h$$

Using Ito's lemma:

$$\frac{dP_{it}(\tau)}{P_{it}(\tau)} = C'_i(\tau) + A'(\tau)r_t + A(\tau)\kappa(r_t - \bar{r}) + \frac{1}{2}\sigma^2 A(\tau)^2 + (e^{C_i(\tau) - C_{-i}(\tau)} - 1)dJ_t - A(\tau)\sigma dZ_t, \;\; i = l, h$$

$$\frac{dP^*_{it}(\tau)}{P^*_{it}(\tau)} = C^{*\prime}_i(\tau) + A^{*\prime}(\tau)r_t + A^*(\tau)\kappa(r_t - \bar{r}) + \frac{1}{2}\sigma^2 A^*(\tau)^2 + (e^{C^*_i(\tau) - C^*_{-i}(\tau)} - 1)dJ_t - A^*(\tau)\sigma dZ_t, \;\; i = l, h$$

Expected price changes are

$$\mu_{it} = C'_i(\tau) + A'(\tau)r_t + A(\tau)\kappa(r_t - \bar{r}) + \frac{1}{2}\sigma^2 A(\tau)^2 + \phi_i(e^{C_i(\tau) - C_{-i}(\tau)} - 1), \;\; i = l, h$$

$$\mu^*_{it} = C^{*\prime}_i(\tau) + A^{*\prime}(\tau)r_t + A^*(\tau)\kappa(r_t - \bar{r}) + \frac{1}{2}\sigma^2 A^*(\tau)^2 + \phi_i(e^{C^*_i(\tau) - C^*_{-i}(\tau)} - 1), \;\; i = l, h$$

The variance term satisfies

$$\mathbb{V}ar(dW_{it}) =$$
$$(\int_0^T X_{it}(\tau)A(\tau)d\tau)^2\sigma^2 + (\int_0^T X^*_{it}(\tau)A^*(\tau)d\tau)^2\sigma^2 + 2(\int_0^T X_{it}(\tau)A(\tau)d\tau)(\int_0^T X^*_{it}(\tau)A^*(\tau)d\tau)\sigma^2 +$$
$$(\int_0^T X_{it}(\tau)(e^{C_i(\tau)-C_{-i}(\tau)}-1)d\tau)^2\phi_i + (\int_0^T X^*_{it}(\tau)(e^{C^*_i(\tau)-C^*_{-i}(\tau)}-1)d\tau)^2\phi_i +$$
$$2(\int_0^T X_{it}(\tau)(e^{C_i(\tau)-C_{-i}(\tau)}-1)d\tau)(\int_0^T X^*_{it}(\tau)(e^{C^*_i(\tau)-C^*_{-i}(\tau)}-1)d\tau)\phi_i + \delta^2\psi(\int_0^T X^*_{it}(\tau))d\tau)^2$$

FOCs are

$$\mu^\tau_{it} - r_t = A(\tau)\gamma\sigma^2\left(\int_0^T X_{it}(\tau)A(\tau)d\tau + \int_0^T X^*_{it}(\tau)A^*(\tau)d\tau\right) +$$
$$\gamma(e^{C_i(\tau)-C_{-i}(\tau)}-1)\phi_i\left(\int_0^T X_{it}(\tau)(e^{C_i(\tau)-C_{-i}(\tau)}-1)d\tau + \int_0^T X^*_{it}(\tau)(e^{C^*_i(\tau)-C^*_{-i}(\tau)}-1)d\tau\right)$$

$$\mu^*_{it}(\tau) - r_t - \underbrace{\delta\psi}_{\text{default compensation}} - \underbrace{\lambda B^*_{ti}}_{\text{funding cost}} = \underbrace{A^*(\tau)\gamma\sigma^2\left(\int_0^T X_{it}(\tau)A(\tau)d\tau + \int_0^T X^*_{it}(\tau)A^*(\tau)d\tau\right)}_{\text{Interest rate shock premium}} +$$
$$\underbrace{\gamma(e^{C^*_i(\tau)-C^*_{-i}(\tau)}-1)\phi_i\left(\int_0^T X_{it}(\tau)(e^{C_i(\tau)-C_{-i}(\tau)}-1)d\tau + \int_0^T X^*_{it}(\tau)(e^{C^*_i(\tau)-C^*_{-i}(\tau)}-1)d\tau\right)}_{\text{Supply shock risk premium}} +$$
$$\underbrace{\gamma B^*_t\delta^2\psi}_{\text{Credit risk premium}}$$

Now plug in

$$X_{ti}(\tau) = \theta(\tau)\beta_i$$

$$X^*_{ti}(\tau) = \theta^*(\tau)\beta_i$$

We obtain

$$\mu_{it}(\tau) - r_t = A(\tau)\gamma\beta_i\sigma^2\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right) +$$
$$(e^{C_i(\tau)-C_{-i}(\tau)} - 1)\phi_i\beta_i\gamma\left(\int_0^T \theta(\tau)(e^{C_i(\tau)-C_{-i}(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_i^*(\tau)-C_{-i}^*(\tau)} - 1)d\tau\right)$$

$$\mu_{it}^*(\tau) - r_t - \delta\psi - \lambda\Theta_i^*\beta_i = A^*(\tau)\gamma\beta_i\sigma^2\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right) +$$
$$(e^{C_i^*(\tau)-C_{-i}^*(\tau)} - 1)\beta_i\phi_i\gamma\left(\int_0^T \theta(\tau)(e^{C_i(\tau)-C_{-i}(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_i^*(\tau)-C_{-i}^*(\tau)} - 1)d\tau\right) +$$
$$\gamma\Theta_i^*\beta_i\delta^2\psi$$

We can solve:

$$A'(\tau) = -A(\tau)\kappa - 1$$

$$A^{*\prime}(\tau) = -A^*(\tau)\kappa - 1$$

The solution is simply

$$A(\tau) = A^*(\tau) = \frac{1 - e^{-\kappa\tau}}{\kappa}$$

For the rest of the coefficients we obtain the system:

$$C_l'(\tau) - A(\tau)\kappa\bar{r} + \frac{1}{2}\sigma^2 A(\tau)^2 + \phi_l(e^{C_l(\tau)-C_h(\tau)} - 1) =$$
$$A(\tau)\gamma\beta_l\sigma^2\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right) +$$
$$(e^{C_l(\tau)-C_h(\tau)} - 1)\phi_l\beta_l\gamma\left(\int_0^T \theta(\tau)(e^{C_l(\tau)-C_h(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_l^*(\tau)-C_h^*(\tau)} - 1)d\tau\right)$$

and

$$C_h'(\tau) - A(\tau)\kappa\bar{r} + \frac{1}{2}\sigma^2 A(\tau)^2 + \phi_h(e^{C_h(\tau)-C_l(\tau)} - 1) =$$
$$A(\tau)\gamma\beta_h\sigma^2\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right) +$$
$$(e^{C_h(\tau)-C_j(\tau)} - 1)\phi_h\beta_h\gamma\left(\int_0^T \theta(\tau)(e^{C_h(\tau)-C_l(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_h^*(\tau)-C_l^*(\tau)} - 1)d\tau\right)$$

$$C_l^{*\prime}(\tau) - A^*(\tau)\kappa\bar{r} + \frac{1}{2}\sigma^2 A^*(\tau)^2 + \phi_i(e^{C_l^*(\tau)-C_h^*(\tau)} - 1) - \delta\psi - \lambda\Theta_i^*\beta_l =$$
$$A^*(\tau)\gamma\beta_i\sigma^2\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right) +$$
$$(e^{C_l^*(\tau)-C_h^*(\tau)} - 1)\beta_l\phi_l\gamma\left(\int_0^T \theta(\tau)(e^{C_l(\tau)-C_h(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_l^*(\tau)-C_h^*(\tau)} - 1)d\tau\right) +$$
$$\gamma\Theta^*\beta_i\delta^2\psi$$

$$C_h^{*\prime}(\tau) - A^*(\tau)\kappa\bar{r} + \frac{1}{2}\sigma^2 A^*(\tau)^2 + \phi_i(e^{C_h^*(\tau)-C_l^*(\tau)} - 1) - \delta\psi - \lambda\Theta_h^*\beta_h =$$
$$A^*(\tau)\gamma\beta_h\sigma^2\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right) +$$
$$(e^{C_h^*(\tau)-C_l^*(\tau)} - 1)\beta_h\phi_h\gamma\left(\int_0^T \theta(\tau)(e^{C_h(\tau)-C_l(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_h^*(\tau)-C_l^*(\tau)} - 1)d\tau\right) +$$
$$\gamma\Theta_h^*\beta_h\delta^2\psi$$

Define

$$D_i(\tau) = A(\tau)\kappa\bar{r} - \frac{1}{2}\sigma^2 A(\tau)^2 + A(\tau)\gamma\sigma^2\beta_i\left(\int_0^T \theta(\tau)A(\tau)d\tau + \int_0^T \theta^*(\tau)A^*(\tau)d\tau\right)$$

and

$$D_i^*(\tau) = D_i(\tau) + \delta\psi + \lambda\Theta^*\beta_i + \gamma\Theta^*\beta_i\delta^2\psi$$

Then we can write the system as

$$C_l'(\tau)+\phi_l(e^{C_l(\tau)-C_h(\tau)}-1)=D_l(\tau)+$$
$$(e^{C_l(\tau)-C_h(\tau)}-1)\phi_l\beta_l\gamma\left(\int_0^T\theta(\tau)(e^{C_l(\tau)-C_h(\tau)}-1)d\tau+\int_0^T\theta^*(\tau)(e^{C_l^*(\tau)-C_h^*(\tau)}-1)d\tau\right)$$

and

$$C_h'(\tau)+\phi_h(e^{C_h(\tau)-C_l(\tau)}-1)=D_h(\tau)+$$
$$(e^{C_h(\tau)-C_l(\tau)}-1)\phi_h\beta_h\gamma\left(\int_0^T\theta(\tau)(e^{C_h(\tau)-C_l(\tau)}-1)d\tau+\int_0^T\theta^*(\tau)(e^{C_h^*(\tau)-C_l^*(\tau)}-1)d\tau\right)$$

$$C_l^{*\prime}(\tau)+\phi_l(e^{C_l^*(\tau)-C_h^*(\tau)}-1)=D_l^*$$
$$(e^{C_l^*(\tau)-C_h^*(\tau)}-1)\beta_l\phi_l\gamma\left(\int_0^T\theta(\tau)(e^{C_l(\tau)-C_h(\tau)}-1)d\tau+\int_0^T\theta^*(\tau)(e^{C_l^*(\tau)-C_h^*(\tau)}-1)d\tau\right)$$

$$C_h^{*\prime}(\tau)+\phi_h(e^{C_h^*(\tau)-C_l^*(\tau)}-1)=D_h^*$$
$$(e^{C_h^*(\tau)-C_l^*(\tau)}-1)\beta_h\phi_h\gamma\left(\int_0^T\theta(\tau)(e^{C_h(\tau)-C_l(\tau)}-1)d\tau+\int_0^T\theta^*(\tau)(e^{C_h^*(\tau)-C_l^*(\tau)}-1)d\tau\right)$$

The synthetic risk-free curve is obtained by combining a periphery bond with a CDS contract or alternatively pricing periphery bonds absent default risk with the model implied stochastic discount factor. Conjecture that the synthetic curve is given by $\hat{P}=\exp\left(-\hat{C}_i(\tau)-A(\tau)r_t\right)$. Define

$$\hat{D}_i(\tau)=D(\tau)+\lambda\Theta^*\beta_i$$

We have

$$\hat{C}_l'(\tau)+\phi_l(e^{\hat{C}_l(\tau)-\hat{C}_h(\tau)}-1)=\hat{D}_l(\tau)+$$
$$(e^{\hat{C}_l(\tau)-\hat{C}_h(\tau)}-1)\phi_l\beta_l\gamma\left(\int_0^T\theta(\tau)(e^{C_l(\tau)-C_h(\tau)}-1)d\tau+\int_0^T\theta^*(\tau)(e^{C_l^*(\tau)-C_h^*(\tau)}-1)d\tau\right)$$

and

$$\hat{C}_h'(\tau) + \phi_h(e^{\hat{C}_h(\tau)-\hat{C}_l(\tau)} - 1) = \hat{D}_h(\tau) +$$
$$(e^{\hat{C}_h(\tau)-\hat{C}_l(\tau)} - 1)\phi_h\beta_h\gamma\left(\int_0^T \theta(\tau)(e^{C_h(\tau)-C_l(\tau)} - 1)d\tau + \int_0^T \theta^*(\tau)(e^{C_h^*(\tau)-C_l^*(\tau)} - 1)d\tau\right)$$

Special Case Set $\beta_l = 0$ and $\sigma = 0$. We obtain

$$C_l(\tau) = C_h(\tau) = 0$$

and

$$D_i^*(\tau) = D_i(\tau) + \delta\psi + \lambda\Theta^*\beta_i + \gamma\Theta^*\beta_i\delta^2\psi\lambda$$

$$C_l^{*\prime}(\tau) + \phi_l(e^{C_l^*(\tau)-C_h^*(\tau)} - 1) = D_l^*$$

$$C_h'(\tau) + \phi_h(e^{C_h^*(\tau)-C_l^*(\tau)} - 1) = D_h^*$$
$$(e^{C_h^*(\tau)-C_l^*(\tau)} - 1)\beta_h\phi_h\gamma\int_0^T \theta^*(\tau)(e^{C_h^*(\tau)-C_l^*(\tau)} - 1)d\tau$$

7.7 Proof of Proposition 2

To see that inconvenience yields approach funding costs, note that we have, $C_i(0) = \hat{C}_i(0) = 0$, $C_i'(0) = 0$ as well as $\hat{C}_i'(0) = \Lambda_t$. L'Hôpital gives

$$\frac{\hat{C}_i(\tau) - C_i(\tau)}{\tau} \to \Lambda_t.$$

Consider the risk-neutral case. The pricing conditions for a riskless and synthetically riskless bond are:

$$\mu_{it}(\tau) = r_t, \quad \mu_{it}^*(\tau) = r_t + \Lambda_t$$

Here the solution is

$$P_{it}(\tau) = \mathbb{E}_t \exp\left(-\int_t^T r_s ds\right)$$

$$\hat{P}_{it}(\tau) = \mathbb{E}_t \exp\left(-\int_t^T (r_s + \Lambda_s) ds\right)$$

A first order approximation of exp implies that the inconvenience yield is

$$icy_t(\tau) = -\frac{1}{\tau}\log \hat{P}_{it}(\tau) + \frac{1}{\tau}\log P_{it}(\tau) \approx \mathbb{E}_t \frac{1}{\tau}\int_t^{t+\tau} (r_s + \Lambda_s) ds + \mathbb{E}_t \frac{1}{\tau}\int_t^{\tau} r_s ds = \frac{1}{\tau}\int_t^{\tau} \Lambda_s ds$$

More accurately, we would have

$$icy_t(\tau) = \frac{1}{\tau}\int_t^{\tau} \Lambda_s ds + \text{convexity adjustment}$$

We define the funding risk premium as the residual part from this expectation. It is time-varying.

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