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THE EFFECTIVENESS OF THE ECB'S ASSET PURCHASES AT THE LOWER BOUND

by Giuseppe Grande*, Adriana Grasso* and Gabriele Zinna*

Abstract

In this research note, we assess – both theoretically and empirically – whether net asset purchases by the ECB can further reduce term premiums and bond yields in the euro area. Theory says that, at the effective lower bound, the duration extracted by the central bank is no longer sufficient to assess the price impact of the purchases. In fact, we show empirically that their impact is state-contingent, and is smaller the more the shadow rate is below the short-rate lower bound, and the lower the volatility of bond yields. Nevertheless, central bank asset purchases are still effective in reducing long-term term premiums and bond yields. Moreover, in the euro area, there is room to reduce the duration held by the market. Overall, asset purchases remain a viable tool at the disposal of the ECB for exerting downward pressure on yields.

JEL Classification: E43, E52, G12.
Keywords: preferred-habitat theory, term premiums, effective lower bound, quantitative easing, large-scale asset purchases, forward guidance.
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Contents

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1 Introduction[1]

Large-scale asset purchase programmes (APPs) are likely to become a permanent feature of the monetary policy toolkit, especially if advanced economies continue to be prone to low interest rate environments.[2] In this research note, we assess - both theoretically and empirically - whether net asset purchases by the ECB at the effective lower bound (ELB) are able to exert further downward pressure on euro-area term premiums.[3]

We start by reviewing the various theoretical channels through which central banks' asset purchases can exert an impact on asset prices, with a focus on the *duration channel* that emerges in the preferred-habitat (PH) model of Vayanos and Vila (2019)(VV). In the VV model, long-term yields can become arbitrarily low relative to short-term rates, that is, in *theory* the term premium is unbounded from below. However, this is unlikely to happen in *practice*, as central banks do not buy bonds short sold by price-sensitive investors. Put simply, there is - *de facto* - a lower bound on the term premium. The term premium becomes bounded from below also in theory, if one accounts for the nonlinearities associated with the existence of the ELB on very short-term interest rates. In King (2019), the short rate follows a shadow-rate process, and as a result the effects of asset purchases on bond premiums and yields, which arise in a richer PH model set up, become state-contingent.

Inspired by these theoretical studies, we then turn to the empirical analysis. We first present a cross-country comparison of term premiums estimates, which finds that the current level of term premiums in the euro area is not abnormally low compared to the experience of other advanced economies. We then perform event studies on high-frequency euro-area bond yields and stock returns around the main recent monetary policy events. We document that dovish monetary policy announcements led to declines in market yields and increases in share prices.

Subsequently, to sharpen the analysis, we resort to those metrics that, according to King (2019)'s non-linear PH model, should help gauge eventual state-contingent effects of asset

[1]We are indebted to Lorenzo Braccini, Alberto Locarno, Taneli Mäkinen, Stefano Neri, Alessandro Secchi, Stefano Siviero, Marco Taboga and Dimitri Vayanos for comments and suggestions. We are also particularly grateful to Marcello Pericoli and Marco Taboga for providing their estimates of term premiums, and to Fabian Eser, Wolfgang Lemke and Andreea Liliana Vladu for kindly sharing with us their measure of the free float of duration risk, published in the ECB Working Paper, No. 2293. The opinions expressed herein are those of the authors alone and should not be attributed to the Bank of Italy or the Eurosystem. Any remaining errors are the authors' responsibility.

[2]As recently as January 2019, in its "Statement Regarding Monetary Policy Implementation and Balance Sheet Normalization", the Federal Open Market Committee of the Federal Reserve reiterated that "Moreover, the Committee would be prepared to use its full range of tools, including altering the size and composition of its balance sheet, if future economic conditions were to warrant a more accommodative monetary policy than can be achieved solely by reducing the federal funds rate."

[3]Issues related to the feasibility of a new wave of net purchases are not addressed.

purchases. Specifically, the three metrics of interest are: (*i*) the risk-adjusted free float,[4] (*ii*) the shadow rate relative to the ELB, and (*iii*) the volatility of long-term interest rates. In each case, the higher the metric is, the more effective asset purchases should be.

Our empirical findings largely support the theoretical predictions of the VV model, and of King's non-linear extension. To start with, reductions in the euro-area risk-adjusted free float are associated with large and economically significant drops in euro-area bond yields; the effect increases as bond maturity lengthens. Meanwhile, we also uncover significant nonlinearities: the effect on bond yields of a unit reduction in the risk-adjusted free float diminishes (*i*) the more the shadow rate is in negative territory relative to the lower bound, and (*ii*) the lower bond yield volatilities are. Based on these multiple pieces of evidence, the ECB's asset purchases appear to exert material effects on bond yields, although being gradually less pronounced than those achieved during the previous rounds of the APP. All in all, the evidence documented in this research note suggests that asset purchases remain a valuable tool at the disposal of the ECB to steer the stance of monetary policy in an ELB environment.

The structure of the note is as follows. In Section 2, we review the main transmission channels of APPs with a focus on the PH theories. In Section 3, we rest on such theories to tackle the theoretical issue of whether there is a lower bound on term premiums connected with APPs. In Section 4, we resort to the empirical evidence to show that there is room to further reduce long-term bond yields in the euro area through additional asset purchases, also when one accounts for their diminishing effects at the ELB.

2 The duration and other trasmission channels

APPs mainly work through two channels. The first channel is the duration channel, whereby central bank's asset purchases of (long-term) government bonds lower the duration risk held by price-sensitive investors, and thus lead to a compression of term premiums and (long-term) bond yields. The duration channel can produce prominent direct effects on the real economy, as long-term yields are central to many investment and consumption choices of agents.[5] The second channel is the signaling channel, which works mainly by lowering the

[4] The risk-adjusted free float is a measure of the riskiness of price-sensitive investors' portfolios. In what follows, we will be more precise about its measurement and effects on rates.

[5] For a recent review of some evidence on the effectiveness of the ECB's large scale APP, including its macroeconomic impact, we refer to Neri and Siviero (2018), among others.

expected component of default-free rates, but it can also contribute to lower term premiums. Forward guidance on asset purchases can also interact with forward guidance on rates.[6]

In what follows, we start by reviewing the duration channel, which is arguably the most effective tool at the disposal of central banks at the ELB to lower term premiums, and consequently induce portfolios balance effects.

Duration channel. The duration channel starts from the premise that government bonds are risky securities, in that they expose investors to duration risk. By activating this channel through bond purchases, central banks aim at lowering the term premium component of yields. This effect finds a theoretical justification in the PH hypothesis originally framed by Modigliani and Sutch (1966, 1967), and recently extended to a no-arbitrage environment by VV.[7] The PH hypothesis rests on the idea that there are investors who have preferences for specific maturities, and as such trade bond of different maturities for reasons other than returns (such as, for example, liability-driven investments of pension funds, reserve accumulation of central banks, or regulatory requirements). In the original models of Modigliani and Sutch, the no arbitrage condition is not enforced. By contrast, in the VV model, no-arbitrage is guaranteed by the trading activity of price-sensitive investors. Therefore, equilibrium interest rates are determined by the interaction of two types of investors: (*i*) the so-called PH investors, who buy long-term bonds for reasons other than returns (e.g., central banks, pension funds, and foreign officials), and (*ii*) the so-called arbitrageurs or price-sensitive investors (such as banks and other types of financial intermediaries), who trade bonds at different maturities for risk-return considerations.

Arbitrageurs (or arbs) are risk-averse investors, and as such balance risk and return. They require a compensation in the form of bond risk premiums (or term premiums), for the risky positions they take on when trading bonds of different maturities. Arbs not only deal with the disconnect between the short rate and longer-maturity bond yields resulting mainly from conventional monetary policy shocks, but also smooth excess supply (or unconventional monetary policy) shocks, thus bringing risk-adjusted yields in line with each other. Arbs' trading activity consists of carry trades (e.g., borrowing short term while lending long term), which are inherently risky, as longer-term bonds have higher duration. By contrast, asset purchases by central banks, i.e. negative excess supply shocks, trigger the unwinding of arbs' carry trades, and thus reduce the riskiness of arbs' portfolios.

[6]According to Vissing Jorgensen and Krishnamurthy (2011), the duration channel and the signaling channel can be both seen as special cases of a more general portfolio-balance channel, which includes also the potential impact of large-scale asset purchases on risk factors other than duration, such as illiquidity, default and lack of safety.

[7]For an insightful description of Modigliani and Sutch's PH hypothesis, see Cozzi (2005).

By deploying large scale bond purchase programmes, the central bank "extracts duration" from the market and, by doing this, lowers the aggregate duration risk held by price-sensitive investors, relieving their risk-bearing capacity. Consequently, price-sensitive investors require a lower compensation per unit of exposure to duration risk, i.e., the price of duration risk drops. This, in turn, lowers term premiums along the entire curve, thus producing *global* effects across the yield curve. The higher the duration of the bond is, the larger the fall in the corresponding term premium is.

In the VV model, arbs' portfolios risk is central to determining the effects of asset purchases on the prices of risk. Indeed, the stochastic discount factor, or marginal utility, depends on the wealth of arbs, which consists of their cash holdings plus their bond holdings. Thus, the bond portfolio of arbs is the key object to look at to predict the evolution of term premiums, and hence yields. Put simply, what ultimately determines the time variation in the prices of risk, which are common to all bonds, is the arbs' portfolio on a risk-adjusted basis, whereby each bond holdings is weighted by its duration risk. By contrast, in the VV model, the quantity of risk, i.e. each bond's sensitivity to the risk factors, is constant over time, and maps variation in the prices of risk onto the cross section of bond yields. All in all, in VV model, time variation in bond premiums is solely driven by that in the prices of risk, which is in turn due to that in the duration risk of arbs' portfolios.[8]

The original VV model, however, does not account for the ELB on the short rate and therefore neglects the nonlinearity that can stem from modeling the short rate with a shadow-rate process. King (2019) makes this important extension to the VV model, and a number of novel insights emerge. Interestingly, bond risk exposures – i.e. the quantities of risk – are no longer constant and, together with the prices of risk, contribute to determine variation in bond risk premiums. Intuitively, the longer the shadow rate is expected to remain below the ELB between periods t and $t + x$, the lower the duration-risk exposure of the x-year bond will be. This is so because, when the shadow rate is below the ELB, the policy rate will be at the ELB for a while; as a result, the variance of the x-period-ahead short rate is lower in the non-linear model than in the linear model. However, not only the volatilities of yields but also their covariances, and hence the riskiness of the arbs' bond portfolio, are reduced near the ELB, so that the link between changes in duration risk and bond risk premiums

[8]Direct estimates of the structural two-factor VV model are provided by Zinna (2016) and by Kaminska and Zinna (2019) for UK and US real rates, respectively. An indirect calibration of the VV model focusing on supply effects, rather than on asset purchases, can be found in Greenwood and Vayanos (2014). Moreover, in the VV model, when additional supply/demand maturity-specific factors are considered (instead of considering a unique global supply/demand factor), the effects of bond supply and asset purchases become more localized, i.e. the price impact is mostly felt by the rate on the bond actually bought/sold. The reduced-form empirical analysis of local asset purchases' effects on U.S. nominal interest rates can be found, for example, in D'Amico and King (2013).

weakens. That is, the effects of additional bond purchases become less effective as the short rate moves close to the ELB, and the more the shadow rate moves in negative territory.

The effects of bond purchases are not confined to the government bond market, as reductions in the returns on safer assets can trigger portfolio effects across asset classes of different risk profiles, so that risk premiums on other assets can also drop. Indeed, the imperfect substitutability between cash and bond holdings induces price-sensitive investors to rebalance their portfolios into riskier assets – both domestic and foreign – in their quest for returns; when they buy foreign currency assets, the domestic currency eventually depreciates, thus also inducing an exchange-rate effect.

Signaling channel. The announcements of future purchases can exert a price impact on their own right. The effects of such announcements, typically made well in advance of their implementation, are inherently more difficult to assess.

In King's extension of the VV model to an ELB environment, shocks to the shadow rate may be interpreted as forward guidance either on yields or on asset purchases. This is coherent with the fact that, in practice, the two types of forward guidance are strongly connected, and their separate effects can be hardly identified. Besides, in King's model, forward guidance can affect not only expected rates, but also term premiums.[9] Therefore, his model suggests that, in normal times, forward guidance exerts a stronger price impact than previously uncovered by studies that neglected its effect on term premiums, which was instead attributed solely to asset purchases, coherently with the linear PH model of VV. That said, at the ELB, asset purchases represent the most effective tool at the disposal of central banks to deliver additional monetary stimulus.

Other channels. While the duration and signaling channels, with the associated portfolio effects, are arguably the two main transmission mechanisms affecting interest rates and the exchange rate, the effects of the APPs are magnified by their impact on the balance sheets of banks, firms, households and the public sector.[10] The decline in the returns on safer assets made possible by central banks' net purchases reduces banks' cost of funding on wholesale markets, strengthening their ability to lend (bank-lending channel). Reductions in government bond yields, and the related improvement of the economic outlook, increase the net worth and creditworthiness of firms and households; moreover, they strengthen the fiscal position of sovereign borrowers (balance-sheet channel), making their recourse to external financing both easier and cheaper.[11]

[9] Unlike Greenwood et al. (2015), in which forward guidance on rates only operates through changes in expected rates.

[10] For an account of these other mechanisms see, e.g., Cova and Ferrero (2015).

[11] Besides, by raising banking system's excess liquidity for an extended period of time, net purchases may contribute to push and keep money-market rates at the lower limit of the "corridor" of official interest rates

Purchases of private-debt securities. APPs may also involve purchases of corporate bonds, which are less liquid than government bonds. For the bonds that are regularly traded on the secondary market, APPs could alter their actual or expected liquidity, and thus lower liquidity risk premiums, which may be sizable.[12] For bonds that are rarely traded and mainly rely on over-the-counter trades, the APP may impact on the ease of finding a counterparty (Duffie et al., 2005). Besides, even if central banks were not to buy directly the most illiquid bonds, as the premiums on the safest bonds drop, investors can rebalance their holdings into riskier bonds, including the most illiquid ones. Central bank purchases of private debt securities may thus be regarded as a way of overcoming market fragmentation and ensuring a smoother transmission of the monetary policy impulse.

3 Are term premiums bounded in the preferred-habitat theory?

Given the low level reached by interest rates around the globe, it is natural to wonder whether there is still room for term premiums to drop even further in response to additional asset purchases. Put differently, is there a lower bound on term premiums in PH models? To try to answer this key question, the PH theory provides some useful guidance. In what follows, we discuss the main insights one can get from the linear model of VV and the non-linear extension of King (2019).

In the VV model, the only risk factor driving time variation in term premiums is the size and maturity composition of the bond portfolio of the price-sensitive investors. Indeed, bond purchases by central banks are effective because they "extract duration" from the market, and thus reduce the riskiness of arbitrageurs' portfolios, driving term premiums down. Long-term rates – *in theory* – can become arbitrarily low relative to short-term rates, that is, the term premium is unbounded from below. This is due to the fact that the model is linear and there is an infinite supply of bonds, as price-sensitive investors could in principle short sell bonds to PH investors. However, central banks cannot buy bonds "manufactured" by price-sensitive investors; as a result, the free-float is bounded at zero.[13] This in turn

(excess-liquidity channel). While this channel is likely to be already fully active in fiscally stronger euro-area countries, additional liquidity could be warranted in other countries.

[12] According to Dick-Nielsen et al. (2012), liquidity premiums of BBB US corporate bonds lie in the range of 4-93 basis points.

[13] In principle, the free float can turn negative if other PH investors, such as pension funds, buy the bonds manufactured by the arbitrageurs.

implies – *de facto* – a lower bound on the term premium, resulting from central banks' asset purchases.[14]

The recent work by King (2019) shows that the term premium is bounded from below also in theory, if one accounts for the nonlinearities associated with the existence of the ELB. This is because unconventional monetary policies (UMPs) alter not only the duration held by arbitrageurs but also yield volatilities and covariances, which in turn help determine both bonds' sensitivities, i.e. the "quantity" of duration risk, and the price of duration risk. Thus, both components of bond risk premiums depend on yield volatilities. But volatilities are endogenous in the model: they fall with the amount of duration risk extracted, as well as with the intensity of forward guidance already in place. As a result, additional asset purchases are still effective, but one needs to extract increasingly more duration to produce similar impact on yields, especially when the shadow rate is far in negative territory and bond volatilities are low.

To sum up, in the non-linear PH model, the effects of asset purchases, as well as those of forward guidance (i.e., shocks to the shadow rate), become state-contingent. Consequently, the free-float (i.e. the duration held by price-sensitive investors) no longer suffices to properly evaluate the effects of APPs on risk premiums and yields. Specifically, King shows that key metrics to determine the effectiveness of net purchases are: (*i*) the risk-adjusted free float, (*ii*) the shadow rate relative to the ELB, and (*iii*) the volatility of long-term interest rates; in each case, the higher the metric is, the more effective bond purchases are. Finally, albeit in the model the risk aversion of price-sensitive investors is constant, asset purchases are more effective, all else equal, when investors' risk aversion is high.

4 Asset purchases, term premiums and interest rates in the euro area

In this section, we argue that net asset purchases still represent an effective tool at the disposal of the ECB. This conclusion is based on multiple pieces of evidence. We first compare current levels of term premiums in the euro area with their historical levels, as well as with available estimates for other countries. We then turn to assess market participants' expectations about the effects of the ECB's recent monetary policy decisions, as can be gauged by the reaction of asset prices to policy announcements. Finally, we delve into the state-contingent effects of asset purchases by focusing on the metrics described before and suggested by economic theory.

[14] It is important to stress that in this note we only consider theoretical or de facto bounds to the term premiums, but not the constraints imposed by the current operational framework imposed by the current design of the APP. Some of these constraints are discussed, for instance, by Claeys et al. (2019).

4.1 Term premium estimates

In all the major safe-haven countries, term premiums are currently low, but the historical and cross-country comparison can be informative on how further down euro-area term premiums could go.

For advanced economies, the evidence of recent decades suggests that term premiums can turn substantially negative, and they can remain so for a prolonged period of time. Wright (2011) and Bauer et al. (2014) provide estimates of term premiums implied in the 5-year 5-year forward interest rates for several advanced economies in 1990-2009. Over that period, term premiums were negative for most of the time in the United Kingdom, Australia and New Zealand and occasionally in other countries.[15]

In recent years, term premiums turned negative also in the United States and Germany (Figure 1, Panels I and II). In the US, term premiums have been negative almost uninterruptedly since late 2014, regardless of the maturity considered. In Germany, they have been negative in the short-term segment of the yield curve ($<$ 3 years) since early 2015, at the 4-year maturity since mid-2017, and for most of the longer-term maturities since early 2019. In particular, the 10-year term premium implied in German Bunds has been negative since mid-May 2019 (Figure 1, Panel III).

Based on a non-linear term structure model that accounts for a time-varying effective nominal lower bound estimated on euro-area quarterly OIS interest rates, the 10-year term premium for the euro area as a whole is currently about half a percentage point above the minimum reached at the start of the ECB's APP in early 2015 (Figure 1, Panel IV).

Based on this evidence, long-term euro-area term premiums turned negative only recently and are still considerably higher than the US ones. Moreover, the current level of term premiums in the euro area does not appear extraordinarily low by international comparison and historical standards.

4.2 Asset prices around ECB's monetary policy decisions

The real-time impact of monetary policy decisions on asset prices provides valuable information on whether additional accommodation by the ECB can further exert beneficial effects

[15]It is important to observe that the results hold under different estimation approaches. term premiums are given by the difference between long-term interest rates and the corresponding expected rates, which are forecasts of (average) future short-term interest rates. Their computation is thus model dependent, as it relies upon the forecasting model used to predict future short-term interest rates.

on financial markets. The analysis consists of an event study analysis of high-frequency asset prices, sampled at one-minute intervals, around the monetary policy decisions and other policy announcements in the period from April 2018 to October 2019.

Figure 2 presents intra-day cumulative changes in bond yields and stock returns around the ECB Governing Council meetings of the four largest euro-area countries. The meetings are split in "ex-ante neutral" (left-hand side panels) and "ex-ante dovish" (right-hand side panels) based on the information in the surveys on financial analysts' expectations carried out by Bloomberg the week before the meetings. Two results stand out. First, in the sample period considered, according to analysts' consensus, most Governing Council meetings were expected to deliver some kind of easing in the stance of monetary policy. Expectations of a restart of net asset purchases gradually gathered momentum over the period, moving from 4% of analysts at the end of May 2019, to 58% in mid-July and 82% in early September 2019. Second, market participants' reaction was broadly consistent with ex-ante financial analysts' expectations. In the case of ex-ante neutral meetings, the market reaction was limited and directionless; conversely, in the case of ex-ante dovish meetings, we document declines in yields and rises in stock returns.[16] Thus, in the case of ex-ante dovish meetings, the information revealed after the meeting tended to lift asset prices above the already priced-in effects. This might suggest that the ECB's decisions turned out to be more dovish than initially expected by the median consensus, and helped resolve uncertainty in financial markets.[17]

To sharpen the analysis further, it is important to look not only at Governing Council's meetings, but more generally at those events when ECB communications potentially helped shape investors' expectations about the future monetary policy stance. In this regard, the speech delivered by the President of the ECB on the 18^{th} of June 2019 in Sintra is of particular interest. In fact, the speech turned out to give a strong dovish signal, leading market participants to reassess their expectations, as shown by the substantial rises in bond and stock prices in the euro area (Figure 3).

This evidence suggests that, since June 2019, market participants' expectations of further easing by the ECB, including a restart of net asset purchases, have gradually strengthened,

[16] In the Governing Council on the 6^{th} of June 2019, the ECB set the parameters for a new round of TLTRO operations; however, the market had anticipated more favourable conditions than those decided. This helps explain the drop in bond and stock prices in that circumstance. Moreover, this Governing Council was held just before the speech held by the President of the ECB on the 18^{th} of June 2019 in Sintra, which – as shown next – had a strong positive effect on asset prices.

[17] The consensus expectation, weighted by its probability, should be already incorporated in asset prices. The event study analysis therefore should capture the surprise effect, e.g. when the meeting turns out to be more dovish than expected, as well as the resolution of uncertainty.

and this fact caused a substantial decline in market yields. More importantly for the focus of this note, it suggests that, through asset purchases, the ECB can further reduce risk premiums on government bond yields, as well as on riskier assets.

4.3 Euro-area free float

For the euro area, a quantitative assessment of the effects of the free float on interest rates is provided by Eser et al. (2019). In their model, the term structure of euro-area interest rates is determined by a quantitative measure of duration risk (the duration-adjusted free float mentioned in Sections 2 and 3), and by two standard pricing factors (level and slope of the term structure).[18] Following Li and Wei (2013), the model also takes into account the impact of future asset purchases on market yields (due, for example, to central bankers' statements on reinvestment policy).[19]

The risk-adjusted free-float is defined as the (duration-weighted) share of the government bonds held by "price-sensitive" investors.[20] It is usual to classify as preferred-habitat investors those investors who have an inelastic demand for bonds, such as insurance companies, pension funds, and official investors (Eurosystem, non-euro area central banks, and intra-euro area general government sector); conversely, the remaining types of investors tend to be regarded as investors with elastic demands for bonds. Specifically, Eser et al. (2019)'s measure of free float includes the duration-adjusted holdings of foreign-private investors, banks, money market and other investment funds, non-financial corporations, and households. According to their estimates,[21] in the absence of the PSPP, as of June 2018 10-year sovereign bond yields in the euro area would have been 95 basis points higher.[22] The effect has also been fairly persistent.

[18]The model can be viewed as a reduced-form analysis of the equilibrium model developed by Vayanos and Vila (2019), whose basic insights are presented in Sections 2 and 3.

[19]Bond-market investors' expectations about the PSPP are inferred from the Bloomberg surveys published in the days ahead of the ECB Governing Council meetings. These are the same surveys we use to classify the meetings in ex-ante "neutral" or "dovish" in Figure 2.

[20]More specifically, the free float of duration risk is defined as the ratio between the duration-weighted bond holdings of price-sensitive investors to the duration-weighted total bond supply. The indicator is built on a variety of information and hypotheses. Historical data are computed on the basis of data on government bond holders at the security level. Projections over future time periods are built by means of the ECB announcements on the PSPP parameters, the Bloomberg surveys on market participants' expectations, the ECB forecasts of public debt in euro-area countries, and hypotheses on tapering, reinvestments, market neutrality, and the average maturity of government bonds issuance.

[21]Their model is calibrated, intentionally, over the period from December 2009 to March 2015 (when the ECB's asset purchases of government bonds started), and the price impact of asset purchases is evaluated over the sample period that starts in December 2009 and ends in June 2018.

[22]Due to the lack of a single sovereign bond market in the euro area, zero-coupon yields data are averages across the four largest euro area countries.

In their model, anticipated changes in the future trajectory of the risk-adjusted free float can also affect term premiums (but not expected future short-term rates), and their effect again increases with the maturity of the bond considered. This resembles the mechanism described in Greenwood et al. (2015), whereby forward guidance on quantitative easing (QE) can exert an effect on premiums, independently from actual purchases. Any new expected, or actual, announcement about the APP is bound to have an impact on the term structure of interest rates. For instance, an anticipated free-float reduction in 3 years of 1 percentage point is estimated to lower, on impact, the 5-year yield by 5 basis points; these estimates are obtained in a linear model.

The key driver of Eser et al. (2019)'s price-impact estimates of ECB's asset purchases is the duration-adjusted free float, which we present in Figure 4. Before the start of the APP, in the euro area the duration-adjusted free float was close to 52% of the total bond supply. Since the start of the programme it has declined markedly, but in mid-2018 it still hovered around 38%, suggesting that there is room to make additional net asset purchases and further compress the term premiums. This is consistent with the evidence on the levels reached by term premiums in other countries (Section 4.1) as well as with financial markets participants' response to ECB announcements (Section 4.2).

4.4 Non-linear effects of asset purchases on yields

In Sections 2 and 3, we argued that, in a non-linear PH model, asset purchases should exert a lower price impact for a given amount of bonds removed from the arbitrageurs' portfolio (on a duration-adjusted basis). King (2019) runs a series of simple non-linear regressions of US bond yields of different maturities on a measure of the duration of Treasury debt over the 1971-2015 period allowing for shifts in parameters at the ELB, i.e., in December 2008. By using such simple framework, King shows that the relation between long rates and the duration of Treasury debt in fact weakens at the ELB. By contrast, long-term rates react to short rates more at the ELB than in normal times. King argues that, at the ELB, near-term expectations are constrained, so that even small changes in expectations are particularly informative and produce relatively larger effects on medium- and long-term yields than on short-term ones; in normal times, long-term bond yields instead respond less to changes in short-term rates.

Effective lower bound. In what follows, we implement for the euro area the analysis carried out by King for the US. Three observations are in order. First, we use the free float to evaluate the effects of bond quantities on rates, whereas King abstracts from PH demand and simply focuses on bond supply.[23] Second, we perform the analysis over a rather short period, ranging from December 2009 to June 2018, when the free-float measure is available. Third, since in the euro area it is not clear cut when the ELB becomes binding, we use the date when the deposit rate is set to zero (July 2012) as cutoff date for the ELB regime, following the extant literature (Wu and Xia, 2017, 2019). We rely on the following two simple regression models:

$$R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x I_t^{ELB} FF_t + \epsilon_t^x \quad (1)$$

$$R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x I_t^{ELB} R_t^1 + \epsilon_t^x \quad (2)$$

where R_t^x denotes the x-maturity OIS rate for the euro area, FF_t is the duration-adjusted free float for the euro area (Figure 4), and I_t^{ELB} is an indicator variable which is 1 during the ELB regime, and 0 otherwise.

Despite the rather short sample period, we find evidence of non-linear effects for the euro area, largely in line with those uncovered for the US by King.[24] Specifically, regardless of the regime (that is, whether the ELB is binding or not), bond yields decrease with the free float, and vice versa, and these effects are stronger for longer-term than shorter-term yields (Table 1, Panel I.A). However, during the ELB, bond yields of any maturity respond less to changes in the free float; for example, in response to a one percent reduction in the free float, the 10-year rate decreases by 7 basis points in the pre-ELB regime, and by 4.5 basis points in the ELB regime (Figure 5, Panel I). Conversely, medium- to longer-term bond yields respond more to changes in the 1-year rate during the ELB regime (Table 1, Panel II.A). Of interest is also the fact that the shape of the rates' impact curve changes in the two regimes; the peak is at the 5-year maturity in the pre-ELB sample period, while it is at the 10-year maturity in the ELB regime (Figure 5, Panel II).

`Shadow-rate gap.` As the starting date for the ELB regime in the euro area is debatable, we replicate the analysis by replacing the dummy variable with the absolute difference between the shadow rate and the effective lower bound. By doing this, the analysis is also more coherent with King's theoretical model, which predicts that the efficacy of asset

[23] King (2019) does not use a measure of the free float, rather he employs the risk-adjusted measure of Treasury supply used by Greenwood and Vayanos (2014), which assumes that the arbitrageurs absorb all the supply: in essence, preferred-habitat demand is not accounted for. For the sake of simplicity, in what follows, we refer to King's measure as the free float.

[24] Different from King (2019), we estimate the regression of rates on the free-float and the 1-year rate separately. This is mainly because our sample period is much shorter, and over this period the free-float and 1-year rate display a substantial degree of collinearity; under forward guidance, term premiums are arguably an important driver of 1-year rates, but term premiums clearly depend on the free float.

purchases (i.e. of the duration channel) should diminish the more the shadow rate is in negative territory relative to the ELB. To measure the absolute shadow-rate gap, we rely on the estimate of the shadow rate and effective lower bound of Pericoli and Taboga (2018). A nice feature of their model is that the ELB is time varying, which accords well with the fact that there is arguably no single date that marks the shift to a binding ELB in the euro area. In fact, it is apparent from Figure 6 that also during the period from August 2012 to June 2018 the shadow-rate gap displays substantial variation, which lends support to the use of a continuous measure such as the shadow-rate gap, rather than of a discrete measure such as the ELB dummy variable, for the euro area.

To sharpen the analysis, we therefore turn to the following regression models:

$$R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x gap_t^{ELB} FF_t + \beta_3^x gap_t^{ELB} + \epsilon_t^x \quad (3)$$

$$R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x gap_t^{ELB} R_t^1 + \beta_3^x gap_t^{ELB} + \epsilon_t^x \quad (4)$$

where gap_t^{ELB} is defined as the absolute difference between the shadow rate and the time-varying lower bound; we set to zero the observations when the ELB is not binding, that is, when the shadow rate is above the ELB.[25] The estimation results are again in line with the predictions of the non-linear PH model. Panel I.B, Table 1, presents Eq. (3) estimates, showing that β_1^xs are positive and β_2^xs are negative. Thus, asset purchases are associated with smaller changes in rates as the shadow rate is more in negative territory, in essence their efficacy declines at the ELB, together with the evolution of the shadow rate. To make the results more readably comparable to those of Figure 5, we show the term structures of β_1^x and $\beta_1^x + \beta_2^x \overline{gap}_t^{ELB}$, where $\overline{gap}_t^{ELB}$ is the sample average of gap_t^{ELB} (Figure 7, Panel I). To delve into the time variation of such effects, we also show $\beta_1^x + \beta_2^x gap_t^{ELB}$ (Figure 7, Panel II). Even during the QE period, the efficacy of the purchases displayed strong time variation. For example, the impact on the 10-year rate ranges from around less than 7 basis points to more than 12 basis points; moreover, in absolute terms, β_2^x decays with maturity x (for $x > 1$), thus the range of variation for the price impact of FF_t on shorter-term rates is wider than that for longer-term rates.

The above analysis of the nonlinearity in the relation between rates and free float due to the evolution of the shadow-rate gap rests on simple regression models that albeit informative can be subject to a number of shortcomings. We therefore provide additional evidence on such relation by implementing a simple exercise that provides the main intuition in a model-free manner. Specifically, we double sort the monthly interest rate of a selected maturity

[25] Data on the ELB and the shadow rate are quarterly. In the baseline analysis, we convert them to monthly frequency using constant interpolation.

first on the shadow-rate gap (Low, Medium, and High), and then on the duration-adjusted free float (Low and High). We therefore allocate rates to six "portfolios" denoted by LL, LH, ML, MH, HL, HH, where the first letter denotes the level of the gap and the second letter that of the free float. For each portfolio, we then compute the average rate of the selected maturity; we consider short, medium, and long rates, respectively, of the 1-, 5- and 10-year tenors. A number of interesting results emerge (Figure 8). First, single-sorted average rates vary inversely with the gap, displaying a monotonic relation across gap portfolios (blue dots). Second, for a given level of the gap, rates are higher when the free-float is also higher; the spread portfolios (LH-LL, MH-ML, and HH-HL) deliver positive differences in rates. Third, the difference in rates is larger when the shadow rate gap is low (LH-LL). Fourth, such differences in rates, i.e. LH-LL, are larger for longer-term rates, which is consistent with the PH theory, as the free float should affect the term premium, which weighs more on longer-term rates than on shorter-term ones.

Turning to Eq. (4), Panel II.B of Table 1 presents estimates for the non-linear impact of the 1-year rate in the regression with the shadow-rate gap. Also in this case, coherently with estimates of Eq. (2), both β_1^x and β_2^x are positive, indicating that short- and longer-term rates tend to move more closely together the more the shadow rate is below the lower bound. In the internet appendix, we show the unconditional impact curves (Figure A1, Panel I), from which it is apparent that the range of variation over time is particularly remarkable at long maturities. For example, the 10-year rate can vary from a minimum of 1.2% to a maximum of 2.7% in response to a one percentage point variation in the 1-year rate (Figure A1, Panel II). Of particular interest is also that the sensitivity of long rates to short rates shows a substantial increase in 2011-2012 and, conversely, a substantial decrease in 2017.

In sum, the multiple pieces of evidence above lend support to the existence of a non-linear relation between rates and the free float, as it weakens at the ELB, and the more the shadow rate is in negative territory. At the same time, the relation between rates and the 1-year rate also changes at the ELB, but it becomes stronger. We can therefore argue that, also for the euro area, the shadow rate is an important metric to try to gauge the efficacy of asset purchases, as well as the transmission of shocks to short rates across the term structure. Latest estimates available show that the shadow-rate gap in the euro area is largely around the levels observed at the start of the ECB's APP (Figure 6, Panel I). If the absolute gap will reduce further (as, for example, in the period from late 2016 to early 2018), future purchases will become even more effective and the disconnect between short and long rates will conversely intensify.

Yield volatilities. In Section 3, we also mentioned that, according to non-linear PH models, the efficacy of additional purchases should increase with yield volatilities; by contrast, the relation between short and long rates should decrease. To shed light on these two theoretical predictions, we center our econometric analysis around the following non-linear specifications:

$$R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x RV_t^{DE} FF_t + \epsilon_t^x \quad (5)$$

$$R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x RV_t^{DE} R_t^1 + \epsilon_t^x \quad (6)$$

where RV_t^{DE} is the monthly realized volatility of 10-year German government bonds (Figure 9). In fact, the sensitivities of rates to the free float seem to increase with volatility, as not only the β_1^x loadings but also the β_2^x loadings are positive and statistically significant (Table 1, Panel I.C). Panel I, Figure 10, shows an upward parallel shift in the impact curve when the average volatility effect is considered. The comparison of Panels II of Figures 7 and 10 reveals that, since the onset of the euro-area QE, the shadow-rate gap induces more time variation than the bond-yield volatility in the effects of the free float on rates.

As in Section 4.4, we resort to a simple and yet informative model-free exercise to complement the regression analysis. We double sort monthly rates first on the level of volatility, RV_t^{DE}, and then on the free float, FF_t. By doing this, we obtain six "portfolios" denoted by LL, LH, ML, MH, HL, HH, where the first letter denotes the level of volatility and the second letter that of the free float. To start with, we find a positive and monotonic relation between the average rate and the level of volatility (Figure 11). This evidence is reminiscent of the existence of a risk-return trade-off in the euro-area bond market, with higher (lower) volatility being associated with lower (higher) bond prices (Ghysels et al., 2014). Moreover, the analysis also suggests that, for low levels of volatility, the spread in rates resulting from double-sorting rates on the free float, LH-LL, is smaller than the spreads obtained for medium and high levels of volatilities, MH-ML and HH-HL, respectively. These findings largely hold for short, medium and long rates.

Turning to the sensitivity of rates to the 1-year rate, we find that β_1^xs are positive whereas β_2^xs are negative (Table 1, Panel II.C), and both loadings increase, in absolute terms, with maturity. In fact, when the average effect of volatility is accounted for, $\beta_1^x + \beta_2^x \overline{RV}_t^{DE}$, the impact curve drops especially at longer maturities (Figure A2, Panel I, in the internet appendix). Panel II instead shows the time-varying loadings of rates on the 1-year rate, $\beta_1^x + \beta_2^x RV_t^{DE}$.

In Figure 9, we present the volatilities of the 10-year interest rates for the four largest euro-area countries. Two observations are in order. First, the bouts in volatilities that we observed since the adoption of QE policies largely stem from events that were largely unrelated to asset purchases or forward guidance (e.g. the US President Trump's election, and the elections in France and Italy). Second and more importantly, with the notable exception of Italy, the volatilities are currently near or above the levels observed in early 2015, and show some signs of upward pressure. Therefore, the current low levels of yield volatilities should not dent the efficacy of additional net purchases by the ECB as compared with the conditions prevailing when the ECB started to buy government bonds. Actually, any rise in volatility that can be due, for example, to further deteriorations of macroeconomic conditions or heightened global uncertainty (caused, for instance, by conflicts over trade policies or technological leadership) would add to the efficacy of net purchases. Thus, other things being equal, any rise in yield volatilities would strengthen the effectiveness of ECB's asset purchases.

5 Concluding remarks

We have assessed, both theoretically and empirically, whether additional asset purchases by the ECB can further reduce term premiums and bond yields in the euro area.

We centered the theoretical examination on the preferred-habitat theory of interest rates, and hence around the duration channel activated by ECB asset purchases. According to this prominent theory, by extracting duration from the market, the ECB can still exert downward pressures on term premiums and rates. At the effective lower bound, however, the duration extracted is no longer sufficient to evaluate the price impact of ECB purchases. In fact, coherently with the theory, we find in the data that asset purchases are more effective the less the shadow rate is in negative territory relative to the short-rate's lower bound, and the higher is the volatility of bond yields. Thus, these variables contribute to determine the state-contingent price effects of additional purchases.

We also document that the current level of term premiums in the euro area does not appear extraordinarily low by international comparison and historical standards. Moreover, our event-study analysis shows that the strengthening of the ECB's monetary policy accommodative stance, started in the summer of 2019, exerted a material downward pressure on bond yields.

The theoretical and empirical evidence suggests that, even when the monetary policy stance is already highly accommodative, or, more generally, the shadow rate is well below the effective lower bound, central bank asset purchases can still be effective, albeit to a lower extent, in reducing long-term bond yields. Therefore, as in the euro area the free float can be reduced even more, one can argue that additional asset purchases are a viable tool at the disposal of the ECB for exerting further downward pressure on term premiums and yields.

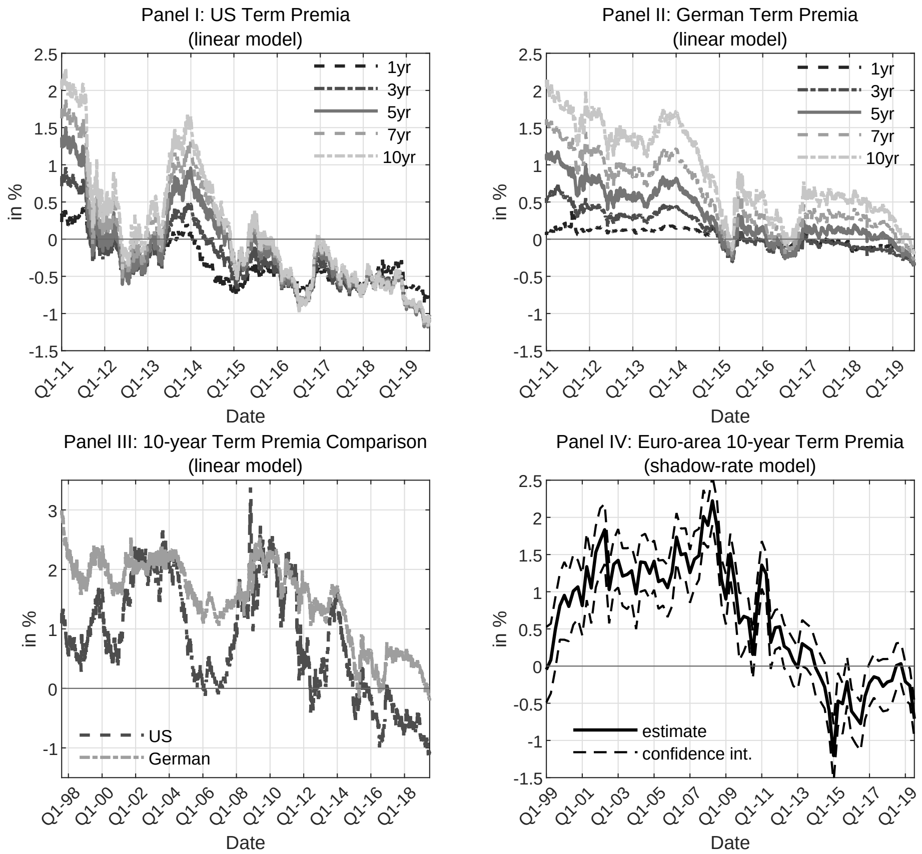
6 Tables and figures

Table 1: Euro-area OIS rates, free float, and 1-year rate

	Panel I: Free float						**Panel II: 1-year rate**				
	Panel I.A: Regressions with ELB dummy						Panel II.A: Regressions with ELB dummy				
	β_0^x	β_1^x	β_2^x	$\beta_1^x + \beta_2^x$	R^2		β_0^x	β_1^x	β_2^x	$\beta_1^x + \beta_2^x$	R^2
3-yr	-1.42^{***}	0.05^{***}	-0.02^{***}	0.03^{***}	0.70	3-yr	0.38^{***}	1.33^{***}	0.02	1.36^{***}	0.96
	[-6.15]	[9.43]	[-7.41]	[5.87]			[16.06]	[17.82]	[0.21]	[19.74]	
5-yr	-1.42^{***}	0.06^{***}	-0.02^{***}	0.03^{***}	0.71	5-yr	0.78^{***}	1.43^{***}	0.39^{**}	1.82^{***}	0.93
	[-3.92]	[7.70]	[-8.05]	[4.37]			[19.85]	[14.47]	[2.30]	[15.75]	
7-yr	-1.42^{***}	0.07^{***}	-0.03^{***}	0.04^{***}	0.72	7-yr	1.16^{***}	1.41^{***}	0.76^{***}	2.17^{***}	0.92
	[-3.29]	[7.47]	[-8.37]	[4.24]			[24.45]	[12.68]	[3.87]	[15.80]	
10-yr	-1.27^{***}	0.07^{***}	-0.03^{***}	0.04^{***}	0.71	10-yr	1.60^{***}	1.33^{***}	1.06^{***}	2.38^{***}	0.90
	[-2.72]	[7.44]	[-8.18]	[4.30]			[30.06]	[11.64]	[5.15]	[16.22]	
	Panel I.B: Regressions with shadow-rate gap						Panel II.B: Regressions with shadow-rate gap				
	β_0^x	β_1^x	β_2^x	β_3^x	R^2		β_0^x	β_1^x	β_2^x	β_3^x	R^2
3-yr	-4.31^{***}	0.11^{***}	-0.02^{***}	0.52^{**}	0.82	3-yr	0.48^{***}	1.17^{***}	0.06^{**}	-0.04^{***}	0.98
	[-8.57]	[9.62]	[-3.53]	[2.27]			[16.93]	[22.45]	[2.53]	[-3.54]	
5-yr	-4.25^{***}	0.12^{***}	-0.02^{***}	0.36	0.83	5-yr	0.91^{***}	1.20^{***}	0.18^{***}	-0.05^{***}	0.97
	[-7.75]	[9.87]	[-2.78]	[1.35]			[22.43]	[22.58]	[6.52]	[-3.78]	
7-yr	-4.16^{***}	0.13^{***}	-0.02^{**}	0.27	0.82	7-yr	1.24^{***}	1.20^{***}	0.27^{***}	-0.04^{**}	0.96
	[-7.24]	[10.06]	[-2.34]	[0.92]			[25.51]	[22.67]	[8.74]	[-2.52]	
10-yr	-3.92^{***}	0.13^{***}	-0.01^{**}	0.24	0.80	10-yr	1.60^{***}	1.17^{***}	0.33^{***}	-0.03	0.94
	[-6.67]	[10.10]	[-2.10]	[0.76]			[28.49]	[22.42]	[9.43]	[-1.25]	
	Panel I.C: Regressions with volatility						Panel II.C: Regressions with volatility				
	β_0^x	β_1^x	β_2^x		R^2		β_0^x	β_1^x	β_2^x		R^2
3-yr	-2.76^{***}	0.05^{***}	0.04^{***}		0.54	3-yr	0.41^{***}	1.55^{***}	-0.45^{*}		0.97
	[-8.08]	[7.44]	[4.88]				[16.86]	[12.93]	[-1.78]		
5-yr	-3.02^{***}	0.06^{***}	0.05^{***}		0.54	5-yr	0.76^{***}	1.99^{***}	-0.95^{***}		0.94
	[-6.66]	[6.54]	[5.36]				[21.99]	[12.03]	[-2.96]		
7-yr	-3.13^{***}	0.07^{***}	0.05^{***}		0.54	7-yr	1.09^{***}	2.27^{***}	-1.35^{***}		0.93
	[-6.17]	[6.51]	[5.54]				[26.96]	[11.49]	[-3.61]		
10-yr	-2.98^{***}	0.07^{***}	0.05^{***}		0.53	10-yr	1.49^{***}	2.43^{***}	-1.66^{***}		0.91
	[-5.66]	[6.61]	[5.50]				[33.13]	[11.06]	[-4.05]		

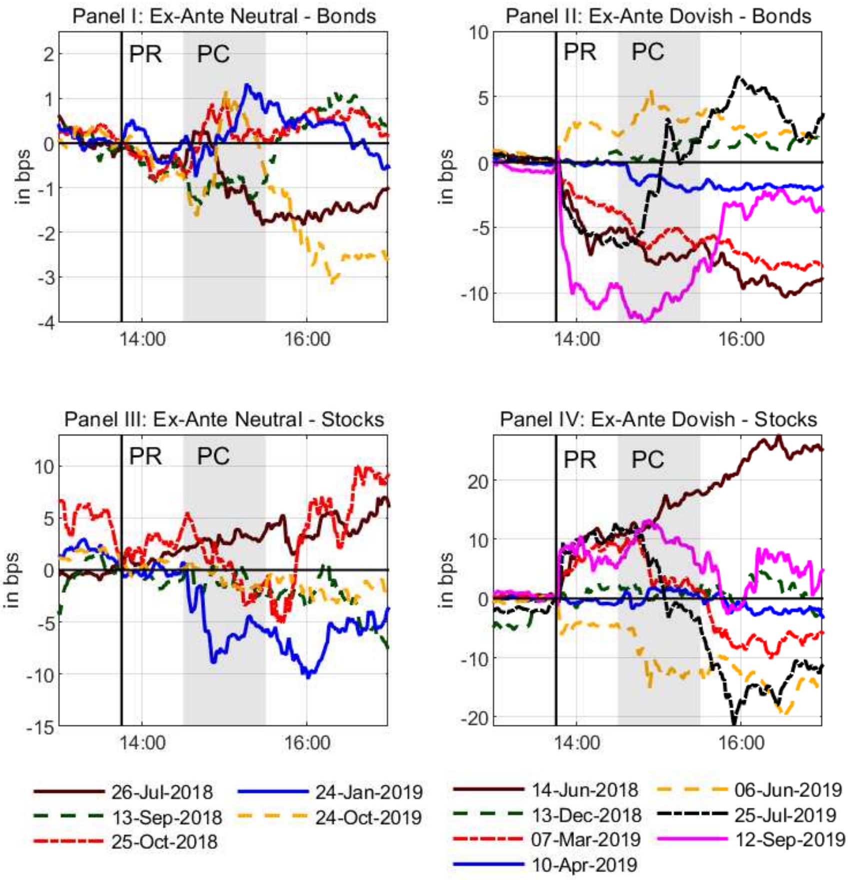
The table shows the estimates resulting from the non-linear regressions of euro-area OIS rates of selected maturities on the duration-adjusted free float (Panel I) and on the 1-year OIS rate (Panel II). Panel I.A and II.A present, respectively, the estimates from the following regressions: $R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x I_t^{ELB} FF_t + \epsilon_t^x$ and $R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x I_t^{ELB} R_t^1 + \epsilon_t^x$ where R_t^x denotes the x-maturity OIS rate, FF_t denotes the duration-adjusted free float (see Figure 4), and I_t^{ELB}, for $t = 1, ..., T$, is a dummy variable that takes value 0 from December 2009 to July 2012, and value 1 from August 2012 to June 2018. Panel I.B and II.B present, respectively, the estimates from the following regressions: $R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x gap_t FF_t + \beta_3^x gap_t + \epsilon_t^x$ and $R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x gap_t R_t^1 + \beta_3^x gap_t + \epsilon_t^x$, where gap_t is defined as the absolute difference between the shadow rate and the time-varying lower bound (Figure 6, Panel II). Panel I.C and II.C present, respectively, the estimates from the following regressions: $R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x RV_t^{DE} FF_t + \epsilon_t^x$ and $R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x RV_t^{DE} R_t^1 + \epsilon_t^x$ where RV_t^{DE} is the monthly realized volatility for the 10-year German yield (see Figure 9). t-stats, in squared brackets, are computed using Newey-West standard errors with optimal number of lags. ***, **, and * denote significance, respectively, at the 1-, 5- and 10-percent levels. The sample period is from December 2009 to June 2018 at a monthly frequency.

Figure 1: Term premium estimates



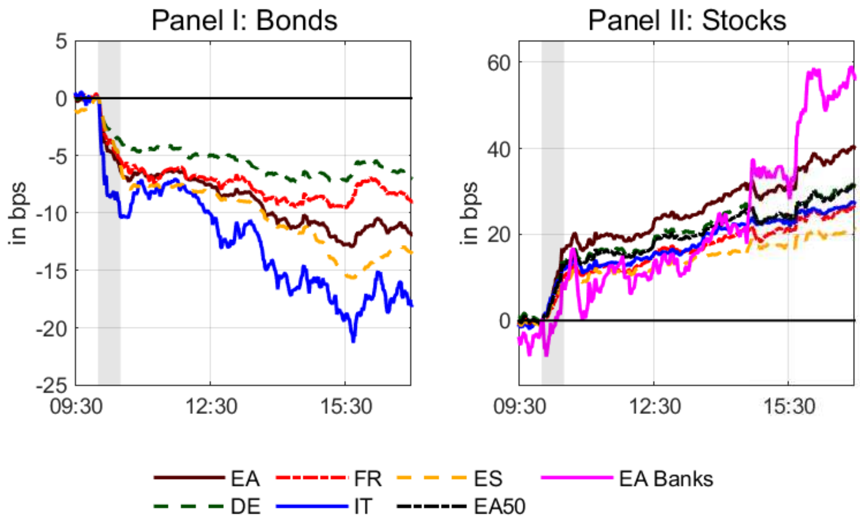
Note: Estimates of United States (Panel I) and German (Panel II) monthly term premiums of selected maturities using the method of Adrian et al. (2013). Panel III shows a comparison of the 10-year term premiums. Panel IV instead presents the euro-area 10-year term premium implied in end-of-quarter OIS rates estimated using the term structure model of Pericoli and Taboga (2018), whereby the short rate follows a shadow rate process with a time-varying effective lower bound; the confidence interval is based on the first and ninth deciles of the posterior distribution of the draws.

Figure 2: Responses of selected asset prices to ECB's monetary policy decisions



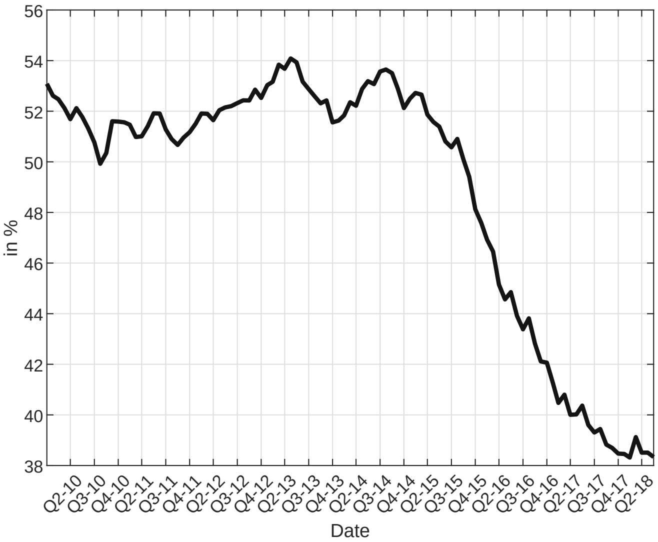
Note: The figure shows the intra-day response of government bond yields (top panels) and share price indices (bottom panels) of the four largest euro-area countries to ECB's monetary policy decisions (from April 2018 to October 2019). Euro-area government bond yields are constructed as the equally-weighted average of the 10-year government bond yields for Germany, France, Italy and Spain. The stock index we consider is the Euro Stoxx index. The Governing Councils are classified as "ex-ante neutral" (Panel I and III), or "ex-ante dovish" (Panel II and IV), on the basis of the Bloomberg surveys about the expected ECB's monetary policy decisions. "PR" and "PC" areas refer to press release and press conference, respectively. Data are sampled every minute. Units are in basis points.

Figure 3: Responses of selected asset prices to the ECB President's speech in Sintra



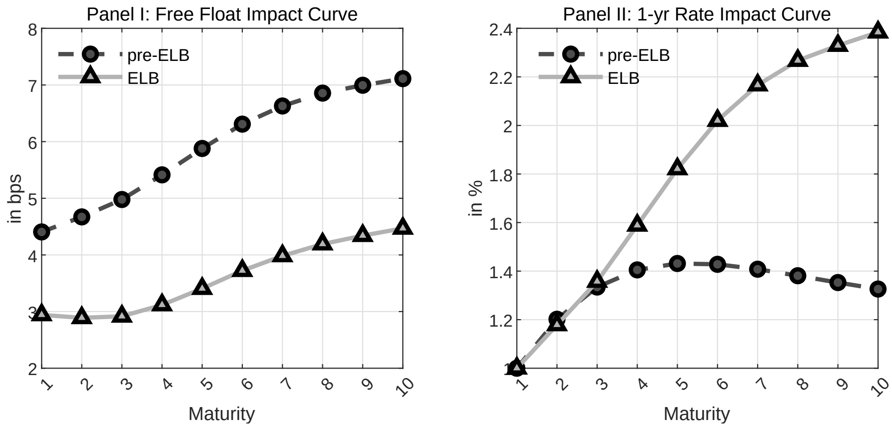
Note: The figure shows the intra-day response of government bond yields (Panel I) and share price indices (Panel II) of selected euro-area countries to the ECB President's speech in Sintra on 18 June 2019. Specifically, we consider bonds and stocks for the euro area (EA), Germany (DE), France (FR), Italy (IT), and Spain (ES); euro-area government bond yields are constructed as the equally-weighted average of the 10-year government bond yields for the above-mentioned countries. In Panel II, we also include the response of the Euro Stoxx 50 (EA50) and Euro Stoxx Banks (EA Banks) indices. The shaded areas refer to the speech time. Data are sampled every minute. Units are in basis points.

Figure 4: Euro-area duration-adjusted free float



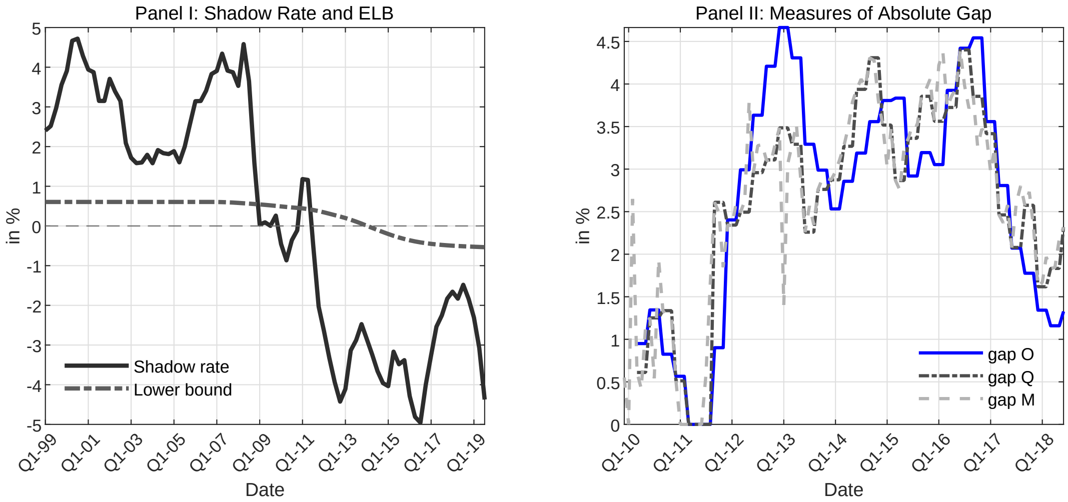
Note: The figure shows the duration-adjusted free float for the four largest countries of the euro area, computed by Eser et al. (2019). It is given by the ratio between the duration-weighted bond holdings of price-sensitive investors and the duration-weighted total bond supply. Source: Eser et al. (2019).

Figure 5: Free float and 1-year rate impact on rates at the ELB



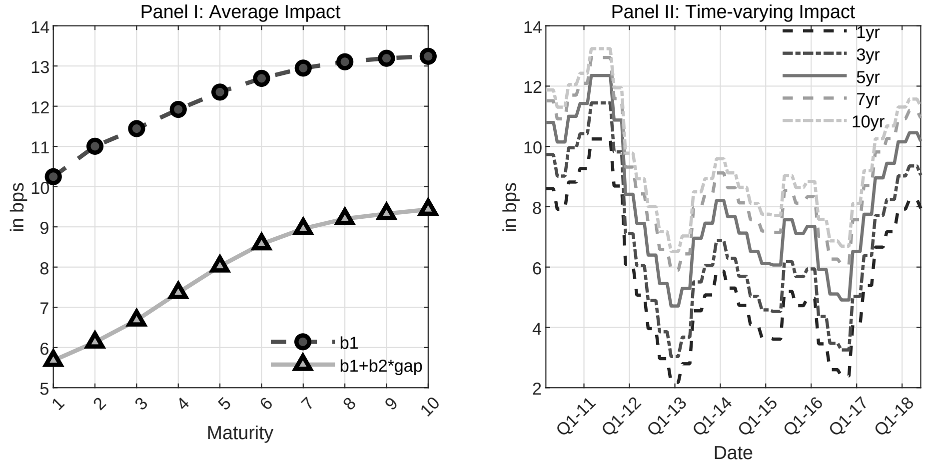
Note: The figure shows the impact curve for OIS rates of maturities from 1 to 10 years. In Panel I, we regress the x-maturity rate on the duration-adjusted free float plain and interacted with the ELB dummy ($R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x I_t^{ELB} FF_t + \epsilon_t^x$). In Panel II, we regress the x-maturity rate on the 1-year rate plain and interacted with the ELB dummy ($R_t^x = \beta_0^x + \beta_1^x R_t^{1yr} + \beta_2^x I_t^{ELB} R_t^1 + \epsilon_t^x$). The dummy variable I_t^{ELB} takes value 0 from December 2009 to July 2012, and value 1 from August 2012 to June 2018. The sample period is from December 2009 to June 2018 at a monthly frequency.

Figure 6: Euro-area shadow rate, effective lower bound, and gap



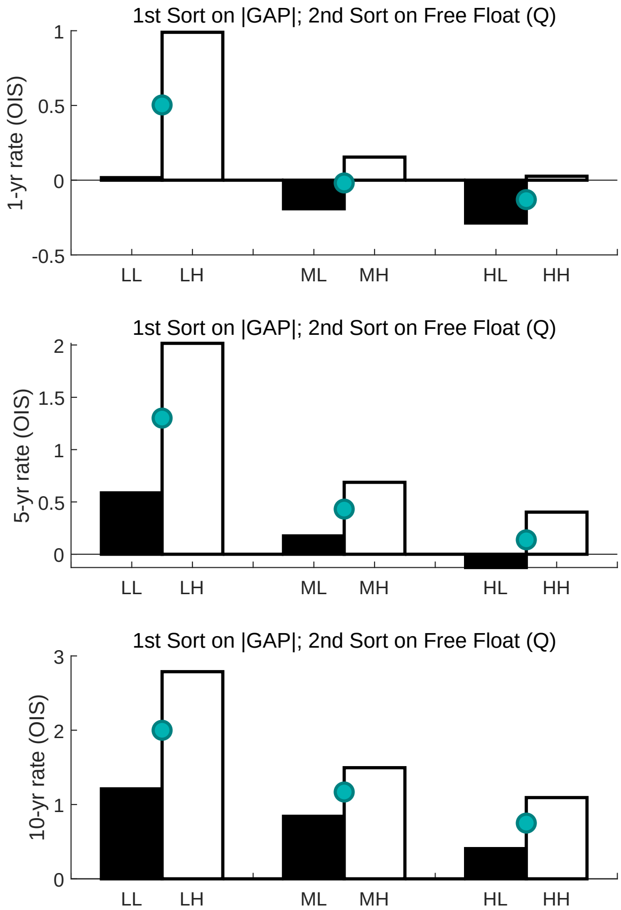
Note: Panel I presents the shadow rate and the time-varying lower bound estimates by Pericoli and Taboga (2018) using end-of-quarter OIS rates for the euro area. Data are at quarterly frequency for the period from March 1999 to September 2019. Panel II presents measures of the shadow rate gap at monthly frequency. The measure *gap O*, or gap_t^{ELB} in equations (3) and (4), is defined as the absolute difference between the shadow rate and the time-varying lower bound (we set to zero the observations when the ELB is not binding, i.e. when the shadow rate is above the ELB); the variable is converted to monthly frequency through constant interpolation. The measure *gap Q* is the fitted value of the regression of *gap O* on the level, square and cube of the first three principal components of the OIS term structure; the variable is converted to monthly frequency through constant interpolation. The measure *gap M* is constructed by multiplying the loadings of the regression used for *gap Q* by the level, square and cube of the first three principal components at monthly frequency. Panel II data are at monthly frequency and only refer to the free-float sample period, from December 2009 to June 2018.

Figure 7: Non-linear impact of free float on rates: shadow rate gap interaction



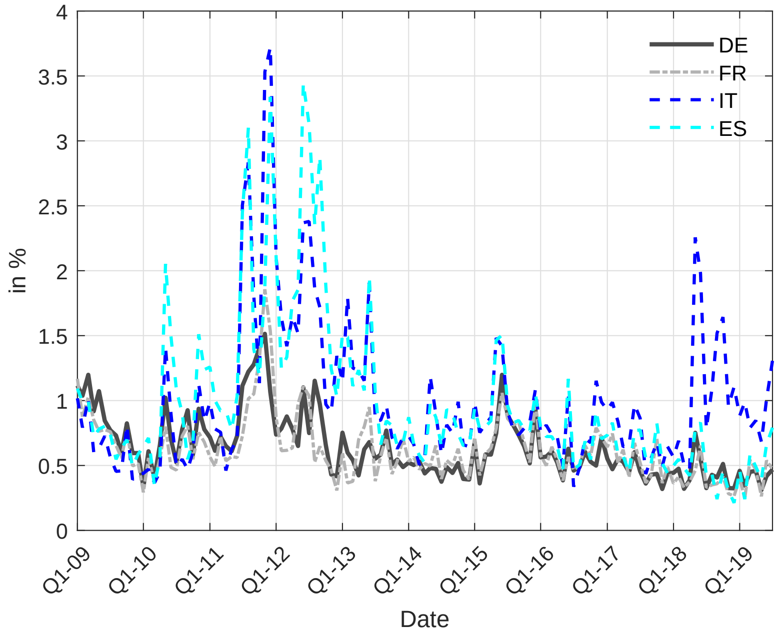
Note: The figure shows the average and time-varying impacts of the free float on OIS rates with maturities from 1 to 10 years obtained from running a series of OLS regressions $R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x gap_t^{ELB} FF_t + \beta_3^x gap_t^{ELB} + \epsilon_t^x$, where R_t^x is the x-maturity rate, gap_t^{ELB} is defined as the absolute difference between the shadow rate and the time-varying lower bound (Figure 6, Panel II), and FF_t is the duration-adjusted free float (Figure 4). Panel I presents the average loadings β_1^x and $\beta_1^x + \beta_2^x \overline{gap}_t^{ELB}$, where $\overline{gap}_t^{ELB}$ is the sample average of gap_t^{ELB}; Panel II shows the time-varying loadings $\beta_1^x + \beta_2^x gap_t^{ELB}$. The sample period is from December 2009 to June 2018 at a monthly frequency.

Figure 8: Average rates double sorted on shadow-rate gap and free float



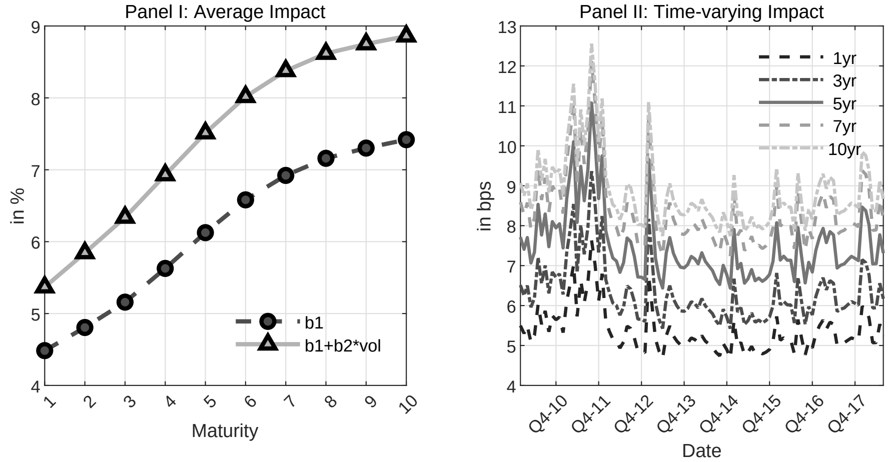
Note: The figure shows the average OIS rate of the selected maturity for each portfolio. Portfolios are obtained by double sorting the monthly rate by the shadow rate absolute gap (Low, Medium, and High) of Figure 6 and then by the duration-adjusted free float (Low and High) of Figure 4. The double-sorted portfolios are denoted by LL, LH, ML, MH, HL, HH, where the first letter denotes the level of the first sorting variable (gap), and the second letter that of the free float. The circle marker denotes the average OIS rate obtained by the first sorts on the gap. The sample covers the period from December 2009 to June 2018.

Figure 9: Euro-area bond yield realized volatilities



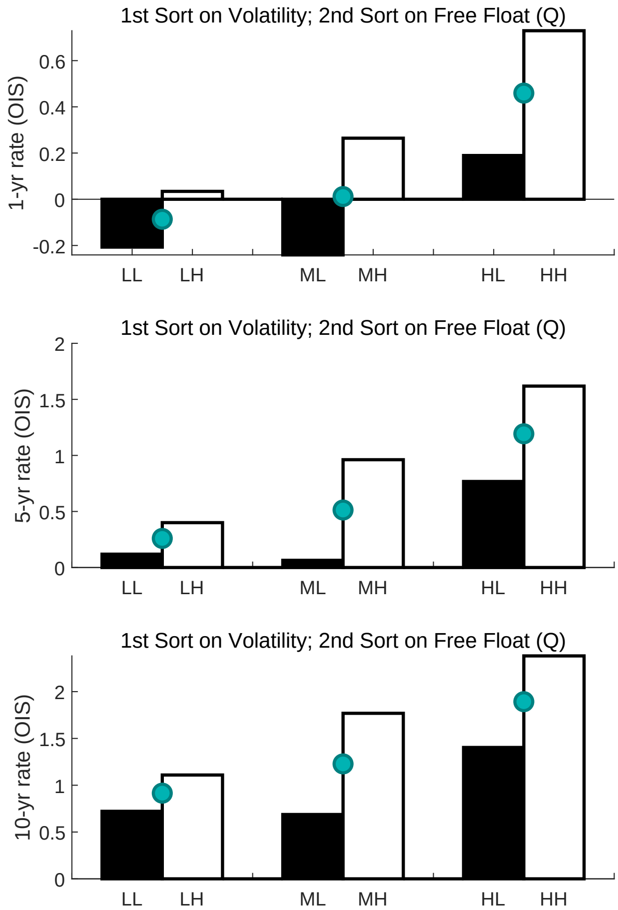
Note: The figure shows monthly realized volatilities for the four largest euro area countries (Germany, DE; France, FR; Italy, IT; Spain, ES). Realized volatilities are computed using squared daily first differences in yields. The resulting volatilities are then annualized. Source: Bloomberg and authors' calculations.

Figure 10: Non-linear impact of free float on rates: 10-year yield volatility interaction



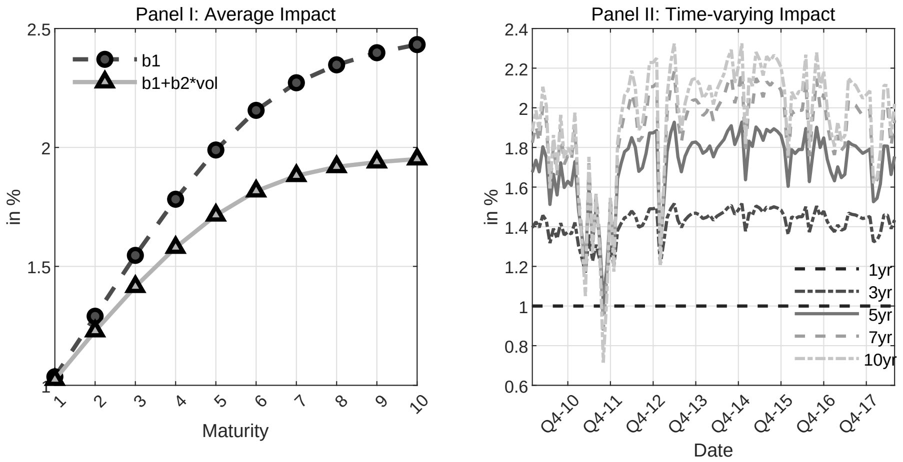
Note: The figure shows the average and time-varying impacts of the free float on OIS rates with maturities from 1- to 10 years obtained from running a series of OLS regressions $R_t^x = \beta_0^x + \beta_1^x FF_t + \beta_2^x RV_t^{DE} FF_t + \epsilon_t^x$ where R_t^x is the x-maturity rate, RV_t^{DE} is monthly realized volatilities for 10-year German yield (see Figure 9), and FF_t is the duration-adjusted free float (see Figure 4). Panel I presents the average loadings β_1^x and $\beta_1^x + \beta_2^x \overline{RV}_t^{DE}$, where $\overline{RV}_t^{DE}$ is the sample average of RV_t^{DE}; Panel II shows the time-varying loadings $\beta_1^x + \beta_2^x RV_t^{DE}$. The sample period is from December 2009 to June 2018 at a monthly frequency.

Figure 11: Average rates double sorted on yield volatility and free float



Note: The figure shows the average OIS rate of the selected maturity for each portfolio. Portfolios are obtained by double sorting monthly rate by the shadow rate absolute gap (Low, Medium, and High) and then by duration-adjusted free float (Low and High). The double-sorted portfolios are denoted by LL, LH, ML, MH, HL, HH, where the first letter denotes the level of the first sorting variable, i.e. the 10-year German yield realized volatility (see Figure 9), and the second letter that of the second sorting variable, i.e. the free float. The circle marker denotes the average OIS rate obtained by the first sorts on the volatility. The sample covers the period from December 2009 to June 2018.

Figure 12: Non-linear impact of 1-year rate on rates: 10-year yield volatility interaction



Note: The figure shows the average and time-varying impacts of the free float on OIS rates with maturities from 1 to 10 years obtained from running a series of OLS regressions $R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x RV_t^{DE} R_t^1 + \epsilon_t^x$, where R_t^x is the x-maturity rate, and RV_t^{DE} is monthly realized volatilities for 10-year German yield (see Figure 9). Panel I presents the average loadings β_1^x and $\beta_1^x + \beta_2^x \overline{RV}_t^{DE}$, where $\overline{RV}_t^{DE}$ is the sample average of RV_t^{DE}; Panel II shows the time-varying loadings $\beta_1^x + \beta_2^x RV_t^{DE}$. The sample period is from December 2009 to June 2018 at a monthly frequency.

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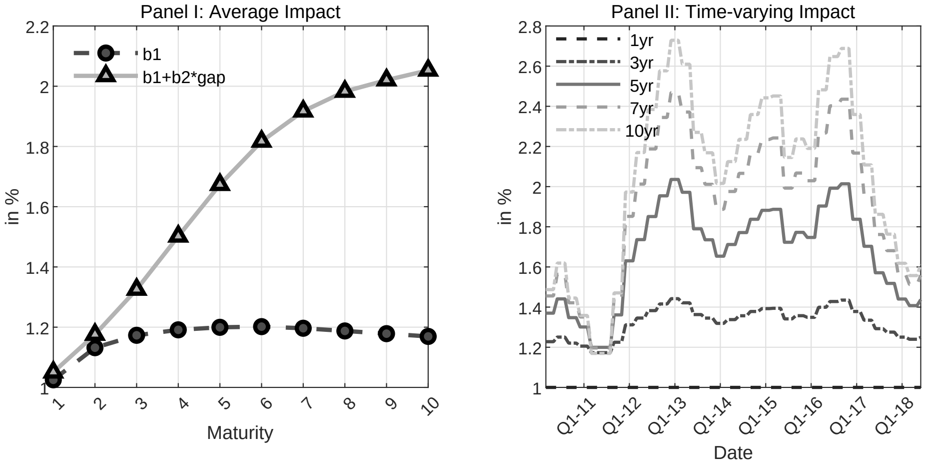
Internet Appendix to

The effectiveness of the ECB's Asset Purchases at the Lower Bound

by

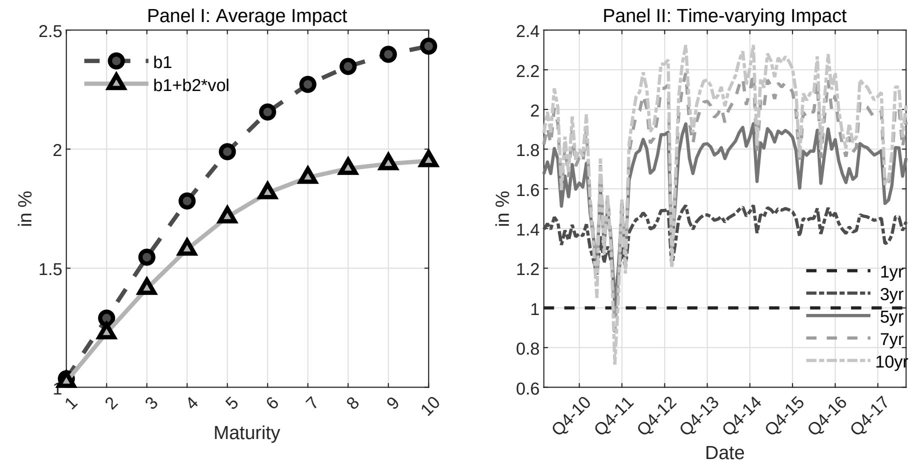
Giuseppe Grande, Adriana Grasso, and Gabriele Zinna

Figure A1: Non-linear impact of 1-year rate on rates: shadow rate gap interaction



Note: The figure shows the average and time-varying impacts of the free float on OIS rates with maturities from 1 to 10 years obtained from running a series of OLS regressions $R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x gap_t^{ELB} R_t^{1yr} + \beta_3^x gap_t^{ELB} + \epsilon_t^x$, where R_t^x is the x-maturity rate, and gap_t^{ELB} is defined as the absolute difference between the shadow rate and the time-varying lower bound (Figure 6, Panel II). Panel I presents the average loadings β_1^x and $\beta_1^x + \beta_2^x \overline{gap}_t^{ELB}$, where $\overline{gap}_t^{ELB}$ is the sample average of gap_t^{ELB}; Panel II shows the time-varying loadings $\beta_1^x + \beta_2^x gap_t^{ELB}$. The sample period is from December 2009 to June 2018 at a monthly frequency.

Figure A2: Non-linear impact of 1-year rate on rates: 10-year yield volatility interaction



Note: The figure shows the average and time-varying impacts of the free float on OIS rates with maturities from 1 to 10 years obtained from running a series of OLS regressions $R_t^x = \beta_0^x + \beta_1^x R_t^1 + \beta_2^x RV_t^{DE} R_t^1 + \epsilon_t^x$, where R_t^x is the x-maturity rate, and RV_t^{DE} is monthly realized volatilities for 10-year German yield (see Figure 9). Panel I presents the average loadings β_1^x and $\beta_1^x + \beta_2^x \overline{RV}_t^{DE}$, where $\overline{RV}_t^{DE}$ is the sample average of RV_t^{DE}; Panel II shows the time-varying loadings $\beta_1^x + \beta_2^x RV_t^{DE}$. The sample period is from December 2009 to June 2018 at a monthly frequency.