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Investor strategies and Liquidity Premia in the European Green Bond Market

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Abstract

This paper studies the term structure of the liquidity premium of the European green bond market along three liquidity (short-term, medium-term, and long-term) premia.

If the liquidity premium is an increasing function of bond's maturity, the estimated sizes of liquidity premia are comparable to those found on the German government bond markets. We then show that liquidity premia are moderately sensitive to economic determinants. Moreover, we detect a liquidity clientele effect on the ask side, which contributes to increase all liquidity premia. This clientele effect is, however, mitigated by spillover effects operating from the short-end to the long-end of the term structure and vice versa.

In sum, our results deliver valuable insights on investors' strategies in the European green bond market, notably those of long-term investors who are not only compensated for their higher illiquidity risks but also provide market stability with their buy and hold strategies.

KEYWORDS: Green Bond, Bond Liquidity, Liquidity Premium, Term structure, Spillover effects, Clientele effect.

JEL CODES : G11, G12, G13, Q56

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Any remaining errors or omissions are solely the responsibility of the authors.

I. Introduction

In December 2015, 196 countries attended the 21st Conference of Parties (COP21) and adopted the Paris Agreement on climate change setting a goal to achieve full decarbonisation in the global economy by the end of 2100. According to the recent estimates of OECD, the World Bank and the United Nations (OECD et al., 2018), this goal requires a global yearly investment of 6.3 trillion euros (6.9 trillion dollars) in infrastructure in the following twenty years. To this end, green bond markets have emerged as a promising method of investment for both corporates and countries at a period when bank lending is relatively constrained.

Green bond markets have grown quickly in size and market coverage representing a total of 257.7 billion dollars outstanding in 2019, out of which 46% have been issued in Europe (CBI, 2020). According to Moody's, green bonds issuances, excluding those issued by governments, accounted for 5% of bond issuances in Europe from 2017 to 2019 (CBI, 2019a).

Despite its growing popularity among investors and issuers, a green bond may be viewed as a "lose-lose product" according to Hiro Mizuno, the chief investment officer of Japan's Government Pension Investment Fund, the world's largest pension fund. He recently argued that investors consider green bonds as bonds "with the same credit rating" but they have "to live with less liquidity" while they are more expensive to arrange for issuers.³ If the pricing disadvantage from issuing a green bond, if any, is small and not universal (Zerbib, 2019), the fact that most investors follow buy-and-hold strategies leads to the illiquidity of the green bond market and higher trading costs. As a result, those long-term investors searching for environmental benefits by keeping the green bonds until maturity (Flammer, 2019) may harvest a liquidity premium from these illiquid bonds (Febi et al., 2018).

Understanding the term structure of this liquidity premium is important for at least three reasons. First, investors may opt for short-term and/or for long-term trading strategies given the time dynamics of the liquidity premium. Second, if different risk factors determine different parts of the liquidity premium, appropriate risk management including the use of hedging instruments may differ across bond maturities. Third, if the liquidity premium depends on the bond's time to maturity, investors' portfolio choice problems may be affected.

To the best of our knowledge, no previous papers have attempted to quantify the liquidity premium in any green bond market nor analysed its term structure.

Our paper studies the liquidity premium of the European Green Bond market along its term structure to bridge this gap. This clearly distinguishes our study from existing literature.

³ Source : Asgari, Nikou. "World's top pension fund warns against risk of green-bond fad". *Financial Times*, July 3, 2019. Accessed 2 November 2019. <https://www.ft.com/content/f844f1c2-998e-11e9-8cfb-30c211dcd229>

The French asset manager Mirova (2018) finds that the average bid-ask spread of green bonds (*resp.* ordinary bonds) is 30 bps (*resp.* 20 bps) over the period 2015-2018, which underscores a relative illiquidity of the European green bond market. This illiquidity is an increasing function of the bond maturity and is probably due to the domination of buy and hold strategies from long-term ethical investors (Flammer, 2019). In fact, if these investors bear more illiquidity risks, they are also likely to follow buy and hold strategies to minimise trading costs. Such strategies make the green bond market less active, that is reflected in fewer trades (Ehrtart, 2018) and in wider bid-ask spreads (Fender et al., 2019). Bachelet et al. (2018) show that green bonds issued by corporates offer higher yields due to their lower liquidity and their higher volatility while those issued by public institutions (i.e., supranationals, sovereign and agencies) offers lower yields because they are far more liquid. Febi et al. (2018) document that the bid-ask spread and the zero trading days measures are positively related to the yield differential between the yields of green bonds and ordinary bonds traded on the Luxembourg Green Exchange (LGX hereafter) and on the London Stock Exchange, two leading European market platforms. Therefore, investors harvest a liquidity premium from European green bonds since their lack of liquidity is priced in their yields. Also, the lack of reporting transparency on green bond proceeds creates information asymmetry between issuers and investors resulting in higher adverse selection costs (Cochu et al., 2016). Febi et al. (2018) argue that higher adverse selection costs generate more illiquidity risks that trigger a substantial liquidity premium in the European green bond market.

In this paper, we examine the term structure of this liquidity premium as the difference between the zero coupon yield curves of two green bond segments that differ in terms of level of liquidity and illiquidity risks (De Jong and Driessen, 2015).⁴ Even if most studies recognise that a large part of the yield spread compensates investors for the illiquidity risk of a bond (see, e.g., Bao et al., 2011), disentangling the illiquidity related risk premiums from other factors like the credit risk is subject to strong assumptions (Schuster and Uhrig-Homburg, 2015). Instead, we take an alternative approach. The fact that Green Bonds issued by Supranationals, Sovereigns and Agencies (SSAGBs hereafter) are more liquid than those issued by Corporates (CGBs hereafter) because the size of their issuances is much larger (Bachelet et al., 2018) and their bid-ask spreads are significantly greater (Fender et al., 2019) provides a convenient setting to quantify the liquidity premium. In this respect, we posit that this liquidity premium is

⁴ The liquidity premium covers two aspects: the liquidity level premium and the liquidity risk premium (De Jong and Driessen, 2015). The liquidity level premium compensates for the asset illiquidity itself. As investors prefer liquid assets to illiquid ones, it covers the illiquid asset's trading costs. The liquidity risk premium compensates for the asset exposure to the illiquidity risk i.e. the correlation of its returns with market-wide liquidity shocks. If assets that perform poorly during stress periods do not offer it, investors have no incentive to hold them.

adequately captured by the yield spreads between the yields of SSAGBs and CGBs across different maturities. The availability of a large data set of bonds issued on the Luxembourg Green Exchange (LGX) spanning a large time to maturity segment over a five-year period of time allows us to quantify the liquidity premium and study its term structure without strong assumptions regarding the separation of credit and liquidity risks.

Our methodological framework presents three immediate advantages. First, we estimate the zero-coupon bond yields by using the model of Nelson and Siegel (1987), leading to divide the liquidity premium in three parts: short-term, medium-term and long-term. Second, this liquidity premium can be considered as a robust measure of liquidity since it captures the forward-looking component of liquidity (i.e., investors' expectations on the future market liquidity). Third, opting for the Nelson-Siegel approach to estimate the liquidity premium like two empirical studies related to the European bond market (Kempf et al., 2012; Schuster and Uhrig-Homburg, 2015) allows us to compare directly our liquidity premia estimates to theirs.

In this convenient framework, we study the implications of the three above-mentioned liquidity premia based on 5 years of price data from 2015 to 2019. Important questions that are not yet examined are addressed in our study: What are the respective sizes of the three above-mentioned liquidity premia? Do they behave differently in different economic periods? Are they driven by the same economic determinants independent of the liquidity situation? To what extent do such determinants affect the term structure of bid and ask liquidity premia?

To answer these questions, our study builds upon the insights of a growing body of work that studies the liquidity premium in more mature bond markets.

At a theoretical level, two complementary views may explain why (il)liquidity is priced in bond yields. The trading cost view outlined in the model of Amihud and Mendelson (1986), predicts that illiquid assets must offer investors a higher expected return to compensate them for their larger trading costs (Favero et al., 2010). This prediction refers to the idea of a liquidity *investor clientele*, which is the tendency for long-term (*resp.* short-term) investors with less (*resp.* more) demand for liquidity to hold more illiquid (*resp.* liquid) bonds, leading to a concave relationship between trading costs and expected returns.

The liquidity risk view relies on the observation that illiquidity is not only priced in bond yields because it implies higher trading costs but also because it is itself a risk (Bao et al., 2011). Consequently, short-term investors may refuse to invest in illiquid bonds because their expected returns do not cover the expected trading costs while long-term investors who trade less frequently can afford to invest in illiquid bonds (De Jong and Driessen, 2015). Bonds with intermediate liquidity levels will be held by short-term and long-term investors.

Beber et al. (2019) extend the model of Amihud and Mendelson (1986) assuming risk-averse investors who consider the expected trading cost and the risk-return profile of an asset before investing. In equilibrium, some investors may choose to hold a subset of the assets (generating a partial segmentation) while investors with different horizons hold non-overlapping portfolios (generating a full segmentation), depending on the liquidity and risk-return profile of assets. This *segmentation effect* induces a larger liquidity premium than predicted by Amihud and Mendelson (1986). Furthermore, *spillover effects* from the short end to the long end of the liquidity premium can mitigate this *segmentation* effect. Gehde-Trapp et al. (2018) show that investors that are more (*resp.* less) likely to suffer from liquidity shocks prefer investing in short-term (*resp.* long-term) bonds. In fact, even though short-term bonds do not offer lower bid-ask spreads, they are indeed more liquid due to the lower disutility from awaiting their closer maturity. The model of Gehde-Trapp et al. (2018) predicts two additional important results : (i) a U-shaped liquidity premium, where the very short and very long maturities carry the largest compensation for the illiquidity risk ; (ii) investor-specific portfolio decisions imply a transmission of liquidity shocks from the short end to the long end of the term structure, but not vice versa generating *spillover effects* as in Beber et al. (2019).

At an empirical level, the liquidity premium and its term structure have been extensively studied in the U.S. and European bond markets. Comparing the differential between the yields of zero-coupon Treasury bonds and those of U.S. government secured (RefCorp) bonds, Longstaff (2004) measured a liquidity premium in the U.S. bond market ranging from 10 to 15 bps. On the U.S. Treasury market, Goyenko et al. (2011) found that the liquidity premium of the on-the-run bonds is only driven by volatility while this of off-the-run bonds is also affected by economic variables such as inflation and monetary policy decisions. Although they focus on bid-ask spreads instead of yield differentials, their findings relative to higher liquidity premia in recessions is consistent with the results of Schuster and Uhrig-Homburg (2015). Kempf et al. (2012) compared the yields of the liquid Bunds and those of the less liquid Pfandbrief bonds to estimate the liquidity premium of the German government bond. They estimated an average long-term (*resp.* short-term) premium of 12 bps (*resp.* 10 bps) for the German government bond market by studying the yield differential between Bund and Pfandbrief bonds. If *spillover effects* from the short end to the long end of the liquidity premium are found insignificant, their results, however, indicate that different economic factors determine the term structure of the liquidity premium. While short-term liquidity risks proxied by bond market volatilities influence the short end of the liquidity premium, its long end depends on the long-term economic outlook. Rather, Schuster and Uhrig-Homburg (2015) estimated the liquidity

premium of the German government bond by using the KfW-Bund yield spread (15 bps in normal times), which is slightly higher than this found by Kempf et al. (2012) on the same German government bond market. They also identified partial *segmentation effects* since the liquidity demand of sophisticated arbitrageurs who prefer trading short-dated bonds only determine the short-term liquidity premium.

The contribution of our paper to the above-mentioned literature is threefold.

Our main contribution is to divide the term structure of the liquidity premium of the European Green Bond market in three parts (short-term, medium and long-term) that are studied over a five-year period (2015-2019) never previously used. We document that the average long-term premium is larger (15 bps) than the average short-term liquidity premium (12 bps). These premia estimates are close to those found on the U.S. Treasury market by Longstaff (2004) but are slightly higher than those found on the German government bond market by Kempf et al. (2012). We also note that the evolutions of short-term and long-term liquidity premia are strongly correlated while the medium-term premium has a low impact on their evolutions. In addition, *lead/lag effects* on short-term and long-term liquidity premia are found to be weaker than those observed on the U.S Treasury bond market (Chen et al., 2020)

Our second contribution is to identify the economic determinants of liquidity premia. Using a vector autoregression analysis, which accounts for joint dynamics between liquidity and economic variables, we show that two economic determinants : the uncertainty on economic policy and the economic outlook have a moderate influence on the short-term and long-term liquidity premia while the bond volatility that accounts for short-term liquidation risks (Kempf et al., 2012) only affects the short-term liquidity premium.

Our third contribution lies in the comparison of the bid and ask liquidity premia dynamics. We detect *spillover effects* from the short end to the long end of the liquidity premium and vice versa if we consider ask yields. Our results also indicate that the ask liquidity premium follows a moderate U-shaped form suggesting that a liquidity *clientele effect* occurs on the ask side implying that the buyers of long dated European green bonds are compensated both for higher expected trading costs and higher illiquidity risks.

The remainder of the paper is organised as follows. Section 2 presents the European Green Bond market and its liquidity characteristics. Section 3 describes the data and the methodology used to estimate the term structure of the liquidity premium of the European green bond market. Section 4 presents and discusses the results obtained. Section 5 concludes.

II. The European Green Bond Market

2.1. Key features of the European Green Bond market

Over the last decade, green bonds are debt instruments that have emerged as a key financial mechanism for channeling investment into climate change mitigation and adaptation. To date, 95% of green bonds have been issued to fund climate mitigation through energy efficiency, renewables, or public transport (CBI, 2019b). This basic premise is why green bonds have potential to be a critical asset class for financing green transitions. While green bonds are generally used to fund specific projects or types of projects, the risk of default is based on the full balance sheet of the issuer (Coche et al., 2016). The financial rating of green bonds and borrowers is left to the existing credit rating agencies like Moody's and S&P.

Tang and Zhang (2020) documented two effects related to the issuance of green bonds. First, repeat issuers take advantage of better liquidity conditions compared to one-time green borrowers, giving evidence of a reputation effect. Second, the "investor attention" channel of green bond effects so that increasing media exposure can attract investors' attention and the visibility of the issuing firms once the bond obtains the label of 'green'.

The origin of the European green bond market date to 2007 when the EIB issue its « Climate Awareness Bond » focused on renewable energy and energy efficiency projects. Supranational institutions like the International Finance Cooperation (IFC), the World Bank and the EIB have become the largest issuers of green bonds listed in Europe (CBI, 2020). They are viewed by investors as the gold standard in the European Green bond market offering a relatively liquid curve and more choices in terms of tenors than corporate issuers.

Growth of issuances accelerated in 2014, when sub-sovereign issuers, notably European provinces, began issuing green bonds to finance infrastructure projects tied to climate change. These issuances were joined by corporates' and banks' issuances as the market matured. According to the statistics of the Climate Bond Initiative (CBI, 2018), the European green bond primary market represented in 2018, 38.5% (USD 64.4bn) of global green bond issuances (USD 167.3bn) while the US and the Chinese primary markets contributed to 20.4% and 18.2%, respectively. One year after, the European green bond market reached USD 116.7 bn, up 74% from 2018, i.e., 46 % of global green bond issuances (CBI, 2020).

Almost half of all green bonds issued worldwide are now listed on stock exchanges (Ehrhart, 2018). By listing green bonds, stock exchanges provide transparency, visibility, enhanced compliance with market regulation, liquidity and trading facilities to investors. In 2019, USD 167 billion (€150 billion) worth of green bonds were listed on various stock exchanges, representing 65% of the total green bonds issued worldwide. Green bonds issued

on the over-the-counter (OTC) markets account for 16% in 2019 while 19% were not listed or for which information was not available (CBI, 2020).

The first exchanges to launch dedicated green bond listings were in Europe: Oslo, Stockholm and London since 2015. Although the development of such listings entails implicit costs, exchanges provide issuers access without any additional fees compared to ordinary bonds. In Europe, the Luxembourg Stock Exchange (LuxSE hereafter) has overseen the rapid development of the green bond primary market. After having initiated in 2007 the first green bond in Europe (the EIB Climate Awareness bond), it also listed the first sovereign (Polish) green bond and other innovative products such as green covered bonds and hybrid green bonds. In 2016, LuxSE launched the Luxembourg Green Exchange (LGX), a dedicated platform for green, social and sustainable bonds.⁵ At publication, LGX leads the European green bond market in listing green bonds from over 40 issuers, with issuers ranging from Sovereigns, Supranationals, Agencies or development banks (SSA hereafter) to corporates.⁶ Its main competitor are the London Stock Exchange Group (LSEG) and Euronext, which does not have a green bond listing contrary to LGX and LSEG. From Table 1, we can see that LGX is the most active European platform in terms of issuance for a cumulated value of USD 110bn in 2018, followed by the LSEG and Euronext. According to Ehrart (2018), green bonds listed on LGX have on average the longest average maturity estimated between 7 and 8 years, while green bonds with shorter maturities are issued on Nordic exchanges with smaller sizes.

[INSERT TABLE 1 HERE]

The last decade has witnessed an ever-growing appetite for green bonds from investors whose portfolio objectives include an environmentally focused agenda. Those socially responsible investors are usually institutional investors such as insurance companies, investment banks, private banks, international agencies and central banks (e.g., European Central Bank (ECB hereafter)) and asset managers (e.g., pension funds, mutual funds).⁷

Credit Agricole investigated the investor composition of a sample of European green bonds issued in 2016 representing 16% of the global amount issued in 2016. The French bank estimated that 34% of investors were insurers, 30% were pension funds, 11% were investment banks, 10% were international agencies and 15% were private banks (Cochu et al., 2016).

⁵ Social bonds are used exclusively to finance social projects while sustainability bonds are bonds where the proceeds will be exclusively applied to finance or re-finance a combination of both green and social projects.

⁶ LGX cooperates with the Shanghai Stock Exchange (SSE) to give access to international investors to the Chinese green bond market. LuxSE displayed on its website the SSE's China Green Bond Index and the SSE Green Corporate Bond Index. Also, the SSE and LGX jointly launched a bilingual (Chinese and English) platform: Green Bond Channel in 2018 that displays all the relevant price information of the green bonds listed.

⁷ Almost 50 dedicated green bond funds have been set up since 2012, including ten in 2018 (CBI, 2019a).

Three year after, the CBI conducted an investor survey in order to understand more precisely their motivations (CBI, 2019b). 79% of the 48 asset managers surveyed would not invest in a green-labelled bond if the proceeds were not clearly allocated to green projects at the outset. Also, large investors appear to be more inclined to buy a bond with unclear green [use of proceeds] bonds. This could mean that they are more concerned with having an exit strategy than smaller asset managers that are more likely to follow buy and hold strategies with specific green mandates. Moreover, larger asset managers allocate a smaller percentage of their fixed-income portfolio in green bonds. On average, the allocation by an investor was 4.6%; for those who manage at least 68 billion euros (*resp.* up to 21 billion euros) of assets this dropped to 2.8 % (*resp.* rose to 7.4 %). Overall, a significant portion of investors are long-term focused (Cochu et al., 2016 or even ethical (Flammer, 2019) who follow buy and hold strategies. According to the same survey, an investor who decides to allocate funds in green bonds are particularly concerned with their green credentials but also with their pricing and liquidity attributes while credit rating constraints are least important factors.

Conceptually, green bonds have the same credit rating as their issuer's other bond instruments, as they are backed by the same balance sheet. However, their issuance requires a additional disclosure regarding the use of their proceeds compared to ordinary bonds because green bonds must prove their "green" credentials making them more expensive to issue. However, the fact that green bond issues are heavily oversubscribed by investors searching for green investments, has led some to anticipate a negative premium that lower bond yields.

The bulk of empirical studies on green bonds has investigated whether issuers benefit from lower bond yields (i.e. lower financial costs) for their green investments by issuing a green bond rather than an equivalent ordinary bond. Many classes of green bonds have been studied (supranationals, sovereigns, corporates, etc.) that differ in terms of investor base, tax incentives and currency risks. Evidence from primary and secondary markets points to a small and negative yield premium (Fender et al., 2019) that lowers bond yields.

A pioneering study from Barclays concluded that investors must pay a negative green premium of 20 bps (i.e. the difference between the yields of green bonds and those of ordinary bonds) to acquire green bonds in the secondary market. This premium implies that green bonds are priced more tightly to ordinary bonds, which is partly attributable to opportunistic pricing based on strong demand from environmentally focused fund managers (Barclays, 2015). By controlling liquidity differences through the issuance amount, Baker et al. (2018) estimated a negative premium of 6 bps for U.S Municipal green bonds. Put simply, yields at issue for green bonds are 6 bps below yields paid by equivalent ordinary bonds. For a 10-year duration bond,

a yield difference of 6 bps corresponds to a 0.60 percentage-point difference in value, which appears to be economically meaningful. Also, Gianfrate and Peri (2019) measured a negative premium of 18 bps for a sample of 121 Euro-denominated green bonds. If this premium was found to be greater for corporate issuances, it also persists in the secondary market. After controlling for liquidity differences, Zerbib (2019) estimated a moderate negative premium of -2 bps on the secondary market, suggesting that investing green bonds in the long-term leads to a lower yield. This finding is consistent with Flammer (2019) who found that green bond issuances induce a larger ownership by long-term investors. Bachelet et al. (2018) show that green bonds issued by corporates displays a positive premium owing to their lower liquidity and higher volatility while those issued by public institutions (supranationals, sovereign and agencies) exhibit a small negative premium because they are far more liquid. In this respect, a direct relationship between the liquidity of green bonds and their yields is established.

Overall, green bonds are found to be issued at slightly lower yields relative to ordinary bonds owing to the insufficient supply of green bonds and the investors' appetite for the green label. Quite importantly, the shortage of supply and the excess of demand for green bonds imply an illiquid secondary market triggering a liquidity premium (Febi et al. 2018).

2.2. The liquidity of the European Green Bond secondary market

The liquidity of the secondary market is of crucial importance for green bond investors because it impacts both the trading costs and the conditions of an exit strategy. Ehrart (2018) reported that USD 1.6 billion was traded on the European green bond secondary market from Oct 2016 to Sept 2017. Such modest trading activity may result in a significant illiquidity risk, revealing the domination of buy and hold strategies among the investor community. If buy and hold long-term investors provide a guarantee of market stability, their strategies make the green bond market less active (i.e. fewer trades) and liquidity shallower. A second consideration concerns the trading cost, which is proxied by the bid-ask spread. Fender et al. (2019) documented that European green bonds offer wider bid-ask spreads than their ordinary counterparts. The asset manager Mirova (2018) estimated the relative bid-ask spread by comparing the executed prices and the average of other prices offered by three counterparties for a given trade. The difference of bid-ask spreads between those of European green bonds and those of ordinary bonds was on average 10 bps from 2015 to 2018. Such differences in liquidity could arise because of the smaller size of green bond issues (Mirova, 2018).

According to Febi et al. (2018), the shortage of supply and excess demand in the green bond market cause the existence of a liquidity premium. After having studied a sample of 64 green bonds either issued on LGX or issued on LSEG along the period 2013-17, Febi et al.

(2018) reported that the bid-ask spread and the zero trading days (ZTD) that proxy the illiquidity risk are positively related to the green bond yield spreads, which indicates that the illiquidity risk is priced inducing an *ex ante* liquidity premium. In either case, only long-term investors invest in illiquid green bonds. If their trading frequency is lower than the breakeven trading frequency, they can earn an excess return due to the existence of a significant liquidity premium (Febi et al., 2018 ; Fender et al., 2019). Accordingly, long-term investors may overweight their allocation in green bonds with higher liquidity risks to increase the benefits of the liquidity premium. This result is consistent with Chen et al. (2020), who find that investors with low liquidity needs hold more illiquid bonds with higher liquidity premium but demand less bid-ask compensation than investors with higher trading needs may expect.

In the rest of this paper, we examine the term structure of the liquidity premium that prevails in the European green bond market along three liquidity premia: short-term, medium-term and long-term based on two key observations: (i) green bonds issued by corporates (CGBs) are noticeably less liquid than green bonds issued by Supranationals, Sovereigns and Agencies (SSAGBs) owing to higher bid-ask spreads and smaller issuance amount and (ii) CGBs and SSAGBs have similar credit risk profile. Based on these two initial observations, we consider that the CGB-SSAGB yield spread estimated for a large set of bond maturities adequately captures the value of the liquidity premia of the European Green Bond market.

III. Data and Methodological framework

3.1. Data selection and description

We focus our analyses on a sample of labelled green bonds issued on the Luxembourg Green Exchange (LGX), the most active exchange for green bond listings in Europe populated by a diverse and international clientele of fund managers, retail and institutional investors. We select green bonds issued from 2011 with a residual maturity between one year and twenty years and a minimum size amount of 100,000 euros (or equivalent). Also, we consider green bonds that are bullet, offer either a fixed rate or a zero-coupon. Floating Rate Notes (FRNs), index linked bonds are therefore removed from our initial sample.⁸

After applying additional filters, we obtain a final sample of 184 green bonds issued by 51 entities.⁹ It consists of 91 CGBs and 93 SSAGBs denominated in 10 currencies. We study this sample over an extensive 5-year period: January 2015 - December 2019 through their

⁸ We eliminate FRNs and index-linked bonds since they should induce biases in the approximation of the term structure of green bond yields. Indeed, the coupons of FRNs or index-linked bonds are variable making impossible an accurate calculation of their relative bond values and their corresponding yields.

⁹ We exclude bonds that have less than one year of data (prices or quotes), implying that green bonds must be issued before December 31, 2019 or those for which the bid and ask quotations are not available or equal.

closing prices and bid/ask quotes because most of the CGB issues are recorded after 2014. All closing (clean) prices are provided by the LGX exchange. Bid and ask quotations are collected from Bloomberg and are used to estimate absolute bid-ask spreads.

Table 2 provides summary statistics that describe the sample of green bonds used. At first glance, SSAGBs have longer average maturities, which can explain that they pay a high coupon. We also notice that SSAGBs have a credit rating close to AAA whereas CGBs are at mid distance between an AAA and AA rating (based on S&P's rating scale). In contrast to their similar credit risk profile, the two green bond segments significantly differ in terms of liquidity. If the issuance amount of CGBs is on average 0.7 times lower than this of SSAGBs, the lower liquidity of the CGB segment is confirmed by its mean bid-ask spread (BAS) figure, which is 20% higher than this of the SSAGB segment. Besides, we find that CGBs have on average 4.3 bookrunners, i.e., two more than the average number for SSAGBs suggesting that corporate issuers increase the size of the syndicate of bookrunner in order to sell their green bonds to a large pool of investors with less difficulty.

[INSERT TABLE 2 HERE]

To confirm the significant difference in terms of liquidity between the CGB and SSAGB segments, we focus on two complementary measures: the bid-ask spreads and the zero trading days (ZTD) to assess the level of green bond market liquidity. Similar to Lesmond et al. (2009) and Febi et al. (2018), we measure ZTD as the proportion of days with zero returns within a month assuming that the daily return is zero when the market is inactive and illiquid (i.e., no trading activity leads to the absence of daily price changes (or returns)).¹⁰

Table 3 reports individual statistics on the level of liquidity and credit risk for the CGB and SSAGB segments split into three maturity ranges: the short end (<5 years), the middle range (5-10 years) and the long end (≥ 10 years). Overall, the average absolute bid-ask spreads of the SSAGBs are 20% tighter than those of the CGBs with a noticeable variability (standard deviation). This liquidity difference is larger if we consider the ZTD for the CGB segment that is twice as high on average. Instead, the CGB segment offers comparable credit ratings and coupon rates whatever the maturity considered. Interestingly, we observe that the more illiquid CGB segment offer better returns across all maturity ranges providing evidence that the illiquidity risk is impounded into yields by investors, a necessary condition for a liquidity premium. Moreover, the average number of bookrunners for CGBs is twice higher than this of SSAGBs and increases as the size of the bond issue augments, suggesting that issuers may fear

¹⁰ It is based on the idea that zero returns arise if the bid-ask spread exceeds the expected change in bond value.

that larger bond issues would be more illiquid. In sum, these results confirm that the CGB segment is significantly less liquid than the SSAGB segment for an equivalent level of credit risk whatever the bond maturity. More importantly, they validate our choice to take the spread between CGBs and SSAGBs yields to measure the liquidity premium of the European green bond market across different maturities.

[INSERT TABLE 3 HERE]

3.2. Estimation of the term structure of liquidity premia

As seen above, we consider that the liquidity premium of the European Green bond market is captured by the yield differential between CGBs and SSAGBs. To summarize its entire term structure information, we employ the Nelson and Siegel (1987) model consistent with the approach of Kempf et al. (2012) and Schuster and Uhrig-Homburg (2015).¹¹ This approach is preferred over the Svensson (1994) model that allows two shape parameters (rather than one in Nelson and Siegel (1987)) but makes their interpretation harder.

Within a Nelson–Siegel (NS) (1987) framework, we estimate a zero coupon yield of bond class $i \in \{\text{CGB}, \text{SSAGB}\}$ at time t for time to maturity T given by the below equation:

$$Y_t^i(T) = \beta_{0,t}^i + \beta_{1,t}^i \left[\frac{1 - e^{-T/\tau_t^i}}{T/\tau_t^i} \right] + \beta_{2,t}^i \left[\frac{1 - e^{-T/\tau_t^i}}{T/\tau_t^i} - e^{-T/\tau_t^i} \right] \quad (1)$$

In order to estimate the four NS parameters ($\beta_{0,t}$, $\beta_{1,t}$, $\beta_{2,t}$, τ_t) for the SSAGB and CGBs segments, we select end-of-month yields with maturities of 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 15 and 20 years for each bond class¹². Further, we run the estimation by minimizing the sum of squared yield differences over all selected maturities and for each bond class. To make the NS estimated parameters comparable, we assume τ_t to be constant over time and identical for the two bond classes i.e., $\tau_t^{\text{CGB}} = \tau_t^{\text{SSAGB}} = \tau_t$ as it is a common practice (see Diebold and Li, 2006).

The estimation procedure provides monthly parameter estimates both for the CGB class ($\beta_{0,t}^{\text{CGB}}; \beta_{1,t}^{\text{CGB}}; \beta_{2,t}^{\text{CGB}}$) and for the SSAGB class ($\beta_{0,t}^{\text{SSAGB}}; \beta_{1,t}^{\text{SSAGB}}; \beta_{2,t}^{\text{SSAGB}}$) in addition to a mean estimate of $\tau=2.98$ generating a maximum factor loading of $\beta_{2,t}$ at about 6 years to maturity. We obtain a mean absolute fitting error of 2.75 bps (*resp.* 2.85 bps) for the SSAGB (*resp.* the CGB)

¹¹ De Pooter (2007) lists three main reasons for which the NS (1987) model is a popular term structure estimation method. First, it provides a parsimonious approximation of the yield curve using only three parameters (contrary to spline methods) that give the model enough flexibility to capture either monotonic, humped or S-type shapes observed in yield curve data. Second, it produces yield curves which have the desirable property of starting off from an instantaneous short rate value of $\beta_{1,t} + \beta_{2,t}$ and levelling off at a finite infinite-maturity constant value of $\beta_{1,t}$. Third, the three NS components have a clear interpretation as short, medium and long-term components.

¹² We exclude bonds with time to maturity less than two years since small errors in their prices would translate to large yield errors (see, e.g., Schuster and Uhrig-Homburg, 2015).

class across maturities. Fitting errors are found to be higher at the very long end of the term structure and lower in its short part. For instance, for the SSAGB (*resp.* CGB) class, mean absolute fitting errors are estimated at 3.8 bps (*resp.* 4.2 bps) for bond maturities of 10 years compared to 2.35 bps (*resp.* 2.2 bps) for bond maturities of 3 years.

We can interpret the NS parameters: $\beta_{0,t}$, $\beta_{1,t}$, $\beta_{2,t}$ in terms of factors, which account for the different segments of the term structure while τ_t affects their own weights. Because $\beta_{0,t}$ determines the level of the long end of the term structure, it is called the long-term factor. $\beta_{2,t}$ is the shape factor that commands medium-term yields whereas $\beta_{1,t}$ is a slope factor that determines the difference between short-term and long-term yields. In this respect, the short-term factor is represented by $\beta_{0,t} + \beta_{1,t}$ that determines the short end of the term structure. We then determine the term structure of the liquidity premium by calculating the following differences between the NS parameters of the two bond classes: $\text{Long}_t \equiv \beta_{0,t}^{\text{CGB}} - \beta_{0,t}^{\text{SSAGB}}$, $\text{Short}_t \equiv \beta_{0,t}^{\text{CGB}} - \beta_{0,t}^{\text{SSAGB}} + \beta_{1,t}^{\text{CGB}} - \beta_{1,t}^{\text{SSAGB}}$, $\text{Shape}_t \equiv \beta_{1,t}^{\text{CGB}} - \beta_{1,t}^{\text{SSAGB}}$. Here, the long-term (*resp.* short-term) factor determines the liquidity premium at the long (*resp.* short) end of the term structure when the shape factor mainly impacts the medium-term liquidity premium.

Fig. 1 shows that the short-term and long-term factors of CGBs and SSAGBs move closely together even if the long-term factors increase more rapidly from the end of 2017. Additionally, the long-term and short-term factors of the CGB segment are always above those of the SSAGB segment, inducing positive short-term and long-term liquidity premia. The shape factors of the CGB segment are lower than those of the SSAGB segment most of the time, leading to a reduction of the liquidity premium for the medium bond maturities.

[INSERT FIGURE 1 HERE]

Fig. 2 shows that the long-term liquidity premium is always larger than the short-term liquidity premium suggesting that long-term investors are more likely to be rewarded for illiquidity risks. Overall, the mean long-term premium is 1.2 times larger (15.4 bps) than the mean short-term liquidity premium (12.2 bps). These estimates are close to those found on the U.S. Treasury market by Longstaff (2004) or on the German government bond market by Schuster and Uhrig-Homburg (2015) but are slightly higher those found than by Kempf et al. (2012) on the same German government bond market. Both short-term and long-term liquidity premia increase until mid-2019 at a comparable pace and slightly decrease after. Consequently, the correlation between these liquidity premia is high (0.73) and statistically significant as is the case with the German government bond market (Kempf et al., 2012).

[INSERT FIGURE 2 HERE]

3.3. Comparison between term structure of liquidity premia and bid-ask spreads

To provide further support that the estimated liquidity premia are mainly caused by liquidity differences between CGBs and SSAGBs, we study its connection with bid-ask spreads for short and long maturities. Fig. 3 plots the evolution of liquidity premia together with the differences in bid-ask spread across two maturities: 3 years (short-term) and 10 years (long-term). Overall, the bid-ask spread evolutions mimic those of the short and long-term illiquidity premia. Also, their large unconditional correlations of 0.69 (*resp.* 0.75) for the 3-Year (*resp.* 10-Year) maturity confirm that the estimated short-term and long-term liquidity premia are directly related to the liquidity and trading costs faced by green bond investors.

[INSERT FIGURE 3 HERE]

IV. Empirical results

4.1. Dynamics of the term structure of the liquidity premium

The graphs of Fig. 1 suggest that the evolutions of the short-term, long-term, and shape factors over the period 2015-2019 are correlated. According to Gehde-Trappe et al. (2018), investor-portfolio decisions induce a transmission of liquidity shocks from the short end to the long end of the term structure. Nonetheless, the reverse effect from long- to short-term maturities does not hold. Goyenko et al. (2011) verify the existence of *spillover effects* from the short- to the long end of the liquidity premium of the U.S. Treasury market in contrast to Kempf et al. (2012) for the German government bond market. Assuming that liquidity shocks are larger for CGBs, *spillover effects* may occur at the short end of the liquidity premium of the European Green Bond market and carry over to longer maturities.

To test this possibility, we estimate an unrestricted VAR-model with 2 lags written as below:

$$\left[\begin{array}{l} \mathbf{Short}_t = \alpha_0^{so} + \sum_{i=1}^2 (\alpha_{i,so}^{so} \mathbf{Short}_{t-i} + \alpha_{i,sa}^{so} \mathbf{Shape}_{t-i} + \alpha_{i,l}^{so} \mathbf{Long}_{t-i}) + \varepsilon_t^{so} \\ \mathbf{Shape}_t = \alpha_0^{sa} + \sum_{i=1}^2 (\alpha_{i,so}^{sa} \mathbf{Short}_{t-i} + \alpha_{i,sa}^{sa} \mathbf{Shape}_{t-i} + \alpha_{i,l}^{sa} \mathbf{Long}_{t-i}) + \varepsilon_t^{sa} \\ \mathbf{Long}_t = \alpha_0^l + \sum_{i=1}^2 (\alpha_{i,so}^l \mathbf{Short}_{t-i} + \alpha_{i,sa}^l \mathbf{Shape}_{t-i} + \alpha_{i,l}^l \mathbf{Long}_{t-i}) + \varepsilon_t^l \end{array} \right. \quad \begin{array}{l} (2a) \\ (2b) \\ (2c) \end{array}$$

where $\varepsilon_t^{so}, \varepsilon_t^{sa}, \varepsilon_t^l$ denote the error terms. The superscripts so, sa, and l represent the short, shape, and long factors, respectively.

We opt for a VAR (2) model in levels to capture potential level relations between the short, shape and long factors that determine the term structure of the liquidity premium.¹³

Table 4 reports the values of the VAR parameter estimates and their significance. Overall, our results indicate a dynamic interaction between the different factors that influence the term structure of the liquidity premium. Past short-term (*resp.* long-term) premium as well as long-term (*resp.* short-term) premium determine the short-term (*resp.* long-term) premium. This first result clearly indicates that the short end interacts with the long end of the term structure of illiquidity premia. A second result consists of the positive and significant signs of the contemporary shape factors for both short-term and long-term premia. This finding means that the liquidity premium tends to follow a moderate U-shape (or J-Shape) as seen in Fig. 1.

Taken together, these two results corroborate our initial conjecture since *spillover effects* operate from the short end of the term structure to its long end via the medium term, confirming in the meantime that liquidity shocks are larger for CGBs across all maturities.

[INSERT TABLE 4 HERE]

4.2. Determinants of the term structure of the liquidity premium

Empirical literature has already provided evidence of the impact of economic factors on the term structure of the liquidity premium. On the German government bond market, Kempf et al. (2012) show that if long-term liquidation risks of investors proxied by their expectations about the long-term economic outlook determine the long end of the liquidity premium, their immediate trading needs drive its short end. Schuster and Uhrig-Homburg (2015) add that the sensitivity of the liquidity premium to economic fundamentals rises in stressful periods.

We use the Business Confidence (BCI) Climate economic index calculated by the OECD to assess the Economic Outlook (denoted *EcoOutlook*). It provides information on future

¹³ To account for a potential influence of past (monthly) changes in the liquidity premia, a lag length of two is selected. This value is suggested by the calculated Akaike (AIC) and Schwartz (SIC) information criteria.

economic developments, based upon opinion surveys on developments in production, orders and stocks of finished goods in the industry sector. Investors consider the BCI index as a reliable and a leading indicator used to anticipate turning points in economic activity.

In addition to Economic Outlook, Broadstock and Cheng (2019) show that three macro-level factors: stock market volatility, policy uncertainty and oil prices contribute to either reinforce or destabilize the green bond market development. Because the macroeconomic factors used by Broadstock and Cheng (2019) impact on the evolution of the green bond market, they are also likely to affect the level of the liquidity premium (Kempf et al., 2012) and the behaviour of long-term investors (De Jong et Driessen, 2015)

Akin to Broadstock and Cheng (2019), we use the Economic policy uncertainty index (denoted *EcoPoluncity*) measured for the European area that is based on big-data and textual analysis methods to quantify the level of overall uncertainty in economic policy.¹⁴

We also consider the financial market volatility to capture the role of short-term trading needs on the level of liquidity for two main reasons. First, in periods when a lot of information flows into the market exacerbating volatility, fund managers or investors often modify their asset allocation more frequently. Second, when financial markets are confronted with higher price instability, investors tend to prefer investing on traditional assets.

We employ two complementary measures of financial market volatility. The first one, *BondVol*, captures the volatility of the bond market. We use the daily yields of a 2-Year Green bond and take its standard deviation within a month as our measure *BondVol*. In addition, we include a measure of stock market volatility for investors' strategies that involve stock and bond markets at the same time. *StockVol* are the end-of-month values of VTOXX, the benchmark volatility index of the European blue-chip stock (Euro STOXX 50 index) market to proxy for stock market volatility. Moreover, we use a set of control variables that may have a temporary or permanent impact on the liquidity premium. A first variable controls for a changing liquidity difference between the CGB and the SSAGB segments over time. To capture the liquidity difference between the two segments, we calculate the ratio of the volume issued in the CGB class and the total volume issued in both classes over the previous 6 months. We construct separate measures for three different maturity ranges (<5 years, 5 to 10 years, and >10 years) which roughly capture the short end, the middle range, and the long end of the term structure. We call them *Ratio^{short}*, *Ratio^{medium}*, and *Ratio^{long}*, respectively.

We then control for the influence of credit risk. Although CGBs and SSAGBs have a very low default risk, there may be a perception that CGBs carry some credit risks. In either case,

¹⁴ Monthly data are available online : https://www.policyuncertainty.com/europe_monthly.html

the CGB-SSAGB spread would be not entirely liquidity driven. We take the spread between the Bloomberg EUR Eurozone index of AA+/AA bond yields and the Bloomberg EUR Eurozone index of BBB bond yields as our proxy for credit risk as in Reboredo and Ugolini (2019). This spread captures the dynamics of credit risk over time. At the short end, we take a maturity of 1 year ($Credit^{short}$). For the middle segment of the term structure, we take values for 5 years ($Credit^{medium}$). Since no values are available for 10 years, we also take values for 5 years at the long end ($Credit^{long} = Credit^{medium}$). We select end-of-month values.

To control for the possible effect of energy price changes (e.g., oil price variations) on investors' demand for green bonds, we use a variable $EnergyRet$ that accounts for the monthly changes of the S&P GSCI Energy Spot Index as in Reboredo and Ugolini (2019). Indeed, Broadstock and Cheng (2019) explain that lower oil prices because they induce higher oil demand may alter the demand for green bonds.

Finally, Zerbib (2019) and Tolliver et al. (2020) argue that tax incentives attached to certain green bond investments such as the tax-exempted U.S. Municipal green bonds may attract long-term investors who seek to be hedged against inflation, default, and volatility. In this respect, we construct a variable $USGreenMktPerf$ that reflects the monthly variations of the S&P U.S. Municipal Green Bond index to assess the influence of the U.S. Municipal Green Bond market performance on the demand for European green bonds.¹⁵

In order to investigate the influence of these economic and control variables on the different segments of the liquidity premium, we incorporate them in the previous VAR(2) model in a VARX-model. Table 5 presents summary statistics of these economic variables.

[INSERT TABLE 5 HERE]

¹⁵ Investors do not pay any income tax on interest from the U.S. municipal green bonds they hold so issuers may offer lower coupon rate to them in compensation.

Specifically, in this VARX model, we regress the three factors of the liquidity premium with 2 lags on the set of exogenous (economic) variables above presented such that:

$$\left[\begin{aligned} \mathbf{Short}_t &= \delta_0^{so} + \delta_1^{so} EcoOutlook_t + \delta_2^{so} EcoPoluncy_t + \delta_3^{so} BondVol_t + \delta_4^{so} StockVol_t + \delta_5^{so} EnergyRet_t \\ &+ \delta_6^{so} USMunGreenPerf_t + \delta_7^{so} Credit_t^{short} + \delta_8^{so} Ratio_t^{short} + \sum_{i=1}^2 \left(\alpha_{i,so}^{so} Short_{t-i} + \alpha_{i,sa}^{so} Shape_{t-i} + \alpha_{i,l}^{so} Long_{t-i} \right) + \varepsilon_t^{so} \end{aligned} \right. \quad (3a)$$

$$\left[\begin{aligned} \mathbf{Shape}_t &= \delta_0^{sa} + \delta_1^{sa} EcoOutlook_t + \delta_2^{sa} EcoPoluncy_t + \delta_3^{sa} BondVol_t + \delta_4^{sa} StockVol_t + \delta_5^{sa} EnergyRet_t \\ &+ \delta_6^{sa} USMunGreenPerf_t + \delta_7^{sa} Credit_t^{medium} + \delta_8^{sa} Ratio_t^{medium} + \sum_{i=1}^2 \left(\alpha_{i,so}^{sa} Short_{t-i} + \alpha_{i,sa}^{sa} Shape_{t-i} + \alpha_{i,l}^{sa} Long_{t-i} \right) + \varepsilon_t^{sa} \end{aligned} \right. \quad (3b)$$

$$\left[\begin{aligned} \mathbf{Long}_t &= \delta_0^l + \delta_1^l EcoOutlook_t + \delta_2^l EcoPoluncy_t + \delta_3^l BondVol_t + \delta_4^l StockVol_t + \delta_5^l EnergyRet_t \\ &+ \delta_6^l USMunGreenPerf_t + \delta_7^l Credit_t^{long} + \delta_8^l Ratio_t^{long} + \sum_{i=1}^2 \left(\alpha_{i,so}^l Short_{t-i} + \alpha_{i,sa}^l Shape_{t-i} + \alpha_{i,l}^l Long_{t-i} \right) + \varepsilon_t^l \end{aligned} \right. \quad (3c)$$

where $\varepsilon_t^{so}, \varepsilon_t^{sa}, \varepsilon_t^l$ denote the error terms. The superscripts so, sa, and l represent the short, shape, and long factors, respectively. The variables *EcoOutlook*, *EcoPoluncy*, *BondVol*, *StockVolatility*, *EnergyRet*, *USMunGreenPerf.*, *Credit* and *Ratio* are defined above.

Table 6 displays the values of the VARX model parameters estimated over the period: January 2005 to December 2019 and their significance. We first note that the short and long factors are significant with one lag both at the short and long end of the term structure of the liquidity premium, confirming the results of Table 4.

The Business Climate index (BCI) that proxies the economic outlook are found to be the main influential economic variables on the three liquidity premia. Since all coefficients are negative, a higher figure of BCI, which indicates a positive business outlook contributes to reduce the three liquidity premia. In particular, if the BCI index increases by 5%, the long-term liquidity premium decreases by almost 5 bps, 20% of the average long-term premium *Ceteris Paribus*. The second main factor that impacts liquidity premia is economic policy uncertainty. We find that the higher this uncertainty, the higher the liquidity premia. Also, an intriguing result is that the short-term (*resp.* medium and long-term) liquidity premium is negatively (*resp.* positively) related to the bond volatility. This difference is explained by the influence of short-term liquidation risks of investors proxied by bond volatility that determine the short-term liquidity premium. Indeed, the column *short* reports a positive and significant coefficient of bond volatility. By contrast, the column *long* displays a negative but insignificant coefficient of bond volatility so this variable does not affect the medium and long-term liquidity premia.

Next, we observe that the ratio of recently issued bonds is insignificant for all three factors. Possibly, investors do not regularly re-assess their notion of liquidity differences between CGBs and SSAGBs and prefer to follow a passive buy and hold strategy.

Interestingly, the coefficient of the *U.SMunGreenPerf.* variable is positive indicating that the long-term liquidity premium is positively related to the U.S. Municipal Green Bond market returns. This result is important in the context of the development of competing regional green bond markets. Indeed, it implies that long-term investors may claim for better yields from illiquid European green bonds because of a greater long-term liquidity premium but also because they can obtain better returns from U.S. Municipal green bonds that present the advantage to offer income tax exemptions on coupon interests.

Finally, the coefficients of stock volatility and energy returns are found to be statistically insignificant so these variables do not affect the three liquidity premia.

Overall, Table 6 results indicate that the term structure of the liquidity premium reflect different regimes of short and long-term liquidation risks. For instance, if we consider a high regime of bond volatility that increases short-term liquidation risks coupled with bad economic outlook that increase long-term liquidation risks (Kempf et al., 2012), an upward sloping CGB vs. SSAGB liquidity premium is likely. Moreover, the short and long factors with one lag are only significant at 5% level for the short-term and long-term liquidity premia. This suggests a moderate influence of *spillover effects* from the short end to the long end of the liquidity premium and vice-versa but also moderate *lead/lag effects*. Generally speaking, our findings confirm the effect of bond maturity on liquidity premium dynamics.

[INSERT TABLE 6 HERE]

We now test the second implication of the model of Kempf et al. (2012). We examine whether the impact of short-term (*resp.* long-term) liquidation risk on the liquidity premium is larger, the shorter (*resp.* longer) the maturity of the bond. We therefore ran regressions like in Eqs. (3a)–(3b)–(3c) with maturity-specific illiquidity premia as explained variables.

Table 7 provides the regression results for maturities between 2 years and 20 years. Longer-term economic prospects (*resp.* political uncertainty) gain (*resp.* lose) importance for bonds with longer maturities. As in Table 6, the coefficient of bond volatility is found to be more significant for shorter maturities. Overall, Table 7 results indicate a relative smooth transition in terms of coefficients from short-term to long-term premia. Most noticeably, the results for the 2-Year and 3-Year premium and the 15-Year premium are close to those for the short and long factors estimated in Table 6 respectively. In this respect, these results validate the second prediction of Kempf et al. (2012) about the role played by short-term and long-term illiquidity risks on the short-term and long-term liquidity premia respectively.

[INSERT TABLE 7 HERE]

4.3. Dynamics of the ask and bid liquidity premia

The model of Gehde-Trapp et al. (2018) predicts opposing shapes for the term structure of the ask and bid liquidity premia due to a liquidity *clientele effect* that operates in both sides. This effect produces two results. The ask liquidity premium increases at the short end and flattens out for longer maturities while the bid liquidity premium decreases at the short end and flattens out for longer maturities. On empirical side, Gehde-Trapp et al. (2018) and Chen et al. (2018) detected a such *clientele effect* on the German government bond market and on the U.S. Treasury market respectively. In the next paragraph, we test the potential influence of the *clientele effect* on the ask and bid liquidity premia of the European green bond market.

We begin by calculating the ask and bid liquidity premia separately. For that purpose, we estimate the NS parameters for the CGB and SSAGB segment given zero coupon ask and bid yields by applying the same methodology described in Eq. (1).

We then formulate and calculate the ask and bid liquidity premia as below:

$$\begin{cases} \text{Liquiditypremium}(T)_{\text{ask},t} = y_{\text{ask},t}^{\text{CGB}}(T) - y_{\text{ask},t}^{\text{SSAGB}}(T) \\ \text{Liquiditypremium}(T)_{\text{bid},t} = y_{\text{bid},t}^{\text{CGB}}(T) - y_{\text{bid},t}^{\text{SSAGB}}(T) \end{cases} \quad (4)$$

Applying the same VARX model expressed in Eqs. (3a), (3b), (3c) allows us to test the existence of the liquidity *clientele effect* and *spillover effects*.

As in Table 6, Table 8 shows significant short and long coefficients with one lag at 5% level for both the column short and long liquidity premia. Their magnitudes are noticeably higher for the ask side. This finding is important for green bond buyers since it signals a pronounced *spillover effects* from the short end to the long end of the ask liquidity premium.

In the *ask yield spreads* column, we note that the coefficients of bond volatility, economic policy uncertainty and economic outlook are significant with signs identical to those found in Table 6 for short-, medium-, and long-term premia. However, the coefficients of bond volatility and economic outlook are not significant for bid yield spreads. In the same column, we observe that the short and long (*resp.* shape) factors have a significant and positive (*resp.* negative) relationship with their respective coefficients estimated with one lag. The positive sign of the short and long factors is indicative of the liquidity *clientele effect* predicted by Gehde-Trapp et al. (2018) while the low but significantly negative sign of the shape factor contributes to a moderate U-shape of the ask liquidity premium. By contrast, the *bid yield spreads* column displays less significant coefficients for the short factor and insignificant coefficients for the medium and long factors. This suggests the absence of liquidity *clientele effect* on the bid medium- and long-term liquidity premia.

To summarise our main findings, the three liquidity premia namely the short-term, medium- and the long-term liquidity premia interact with each other. This is mainly due to the existence of *spillover effects* (that are greater if we consider ask yields) from the short end to the long end of the liquidity premium and vice versa. However, weak *lead/lag effects* from the short end to the long end of the liquidity premium are reported. Moreover, two economic factors i.e. the uncertainty on economic policy and the economic outlook are found to affect simultaneously the three liquidity premia while the bond volatility only influences the short liquidity premium. Interestingly, the liquidity *clientele effect* is shown to be more pronounced on the ask side affecting the purchase strategies of short-term and long-term green bond investors and the compensation for their liquidity risks (Gehde-Trapp et al., 2018). Also, our results suggest that the ask liquidity premium increases with the bond maturity, signaling the existence of a liquidity *clientele effect* in the buy side compensating for higher liquidity risks borne by long-term investors (buyers) in the European Green Bond market.

[INSERT TABLE 8 HERE]

4.4. The liquidity premium of the on-the-run bonds vs. the off-the-run bonds

We implement a first set of robustness tests using original bond yields. Indeed, we may argue that the NS approach makes estimates biased owing to its smoothing effect on the yield curve. We test this possibility by running the VARX model based on original yield spreads.

We proceed in three steps. Firstly, we select three maturities that stand for the short end, medium and long end of the CGB and SSAGB yield curves, then compute the corresponding 2-Year, 5-Year, and 15-Year yield spreads. Second, we separate from our final sample the on-the-run bonds that are recently issued (issuance have occurred for 2 years maximum) and have not yet matured from the off-the-run bonds that have either have a shorter time to maturity or matured before December 2019. Indeed, De Jong et Driessen (2015) note that studies have documented a small (*resp.* greater) liquidity premium for the on-the-run (*resp.* off-the-run) treasury and government bonds. Thirdly, we estimate the VARX-model based on bond yield spreads separately for the on-run bonds sample and for the off run-bonds sample.

Table 9 shows the values of coefficients for the two samples: the on-the-run bonds and the off-the run-bonds. We observe that their magnitude and signs are similar to those displayed in Table 6 especially for the on-the-run bonds. Therefore, employing original data in our VARX model does not affect significantly the results obtained with NS estimates. The coefficients of Economic Outlook are significantly positive for the short and long liquidity premia while the Bond Volatility coefficient is significantly negative for the short-term liquidity premium. Then, the Economic policy uncertainty coefficient is only positive for the short and the long-term

liquidity premium of the on-the-run bonds. Instead, the liquidity of the off-the-run bonds are insensitive to the uncertainty surrounding economic decisions probably because they are closer to maturity making buy and hold strategies less risky. Finally, we detect *spillover effects* from the short end to the long end but not vice versa since short factors with one lag are significant at 1% level for both the short and the long column.

[INSERT TABLE 9 HERE]

4.5. Identifying structural breaks in the term structure of the liquidity premium

Last but not least, we conduct a second set of robustness tests based on the assumption that the three liquidity premia estimates can capture specific illiquidity events. Specifically, we consider the possibility that there are one or more breaks in the liquidity premia estimates.

We use the same methods as Brooks et al. (2015), who apply tests for multiple breakpoint estimation (Bai and Perron, 1998) to the term structure of CMT and LIBOR rates. Bai and Perron (1998) provided a suite of tests to detect the presence of one or more structural breaks in time series and ascertain their location. We search for a maximum of five breaks, the largest number allowed by the Bai and Perron (1998) procedure and use a trimming region of 15% as it is often used (e.g., Narayan et al., 2013 ; Brooks et al., 2015).¹⁶

We apply the above Bai and Perron (1998) procedure to the estimates of the regression made under Eqs. (3a), (3b), (3c) accounting for potential serial correlation and heteroscedasticity. The *UDmax* and the *WDmax* test statistics, reported in the first two rows, indicate that the null hypothesis of zero breaks is rejected at 5% in favor of the alternative hypothesis of an unknown number of breaks given a maximum of five breaks.¹⁷ Since the null hypothesis of no structural break is rejected by the double maximum test, we then use the Bai and Perron (1998) sequential $SupF_T(L+1|L)$ procedure to determine the optimal number and location of structural breaks,. The $SupF_T(1|0)$ is the only significant test statistic for the three liquidity premia indicating that there is one structural break in their times series.

We identify this break in November 2017, where a spate of green bond issues propelled the world green bond market through the 100 billion euros barrier for the first time. This month saw two new and six repeat corporates come to the LGX market anticipating the One Planet Summit of Paris that took place in December 2017. This considerable flow of green bond issuances on LGX was not without implications on trading costs.¹⁸ As illustrated in Fig.1, the

¹⁶ The trimming region provides the maximum possible number of breaks (=5 here) and minimum regime size.

¹⁷ The UDmax statistic is the maximum value of the SupFt(L) F-statistic, while the WDmax statistic weights the individual statistics so as to equalize the p-values across values of m =5 breaks.

¹⁸ Ten green bonds were issued in November 2017 : two by the World Bank/IFC and eight by corporates.

difference in bid-ask spreads between CGBs and SSAGBs decreased by 2 bps between November 2017 and January 2018 for the 2-Year and the 10-Year maturities. In the same period, the short-term and long-term liquidity premia decreased by almost 10%.

[INSERT TABLE 10 HERE]

After identifying the structural change in November 2017, we test the validity of Table 6 results across two sub-periods : January 2015-November 2017 and December 2017-December 2019 by estimating the regression model shown in Eqs. (3a), (3b), (3c).

Table 11 reports values of coefficients for Economic Outlook, Economic Policy Uncertainty, Bond Volatility, U.S. Mun. Green Perf. similar to those shown in Table 6 both in terms of sign and significance. Also, we notice that their magnitudes are comparable.

These findings are consistent with those of Kempf et al. (2012) and Chen et al. (2018) to the extent that the influence of economic variables on the three (short-term, medium-term, and long-term) liquidity premia is moderate. Quite importantly, they confirm the relevance of our VARX model to analyse the impact of economic factors on the different liquidity premia that characterise the European green bond market.

For the first period (January 2005-November 2017), we find that the short and long coefficients with one lag are only significant at 5% level for the short-term and long-term liquidity premia. This result provides evidence of *spillover effects* from the short end to the long end of the liquidity premium and vice versa as well as moderate *lead/lag effects*.

Moving to the second period (November 2017–December 2019), two interesting insights emerge. The first insight shows that the short coefficient with one lag displayed in the column long remains positive but becomes insignificant, suggesting the absence of *spillover effects* from the short end to the long end of the liquidity premium. The second insight concerns the insignificance of the coefficient Economic Policy Uncertainty, meaning that the long-term liquidity premium becomes insensitive to the uncertainty around the economic policy that proxies long-term liquidation risks of investors (Kempf et al., 2012) from 2018.

In sum, the results of Table 11 are qualitatively similar to the results presented in Tables 6 and 7. In this way, they underscore the relevance of our VARX model to study the economic determinants of the liquidity premium of the European green bond market.

[INSERT TABLE 11 HERE]

V. Conclusions

Mobilising retail and institutional investors to deploy billions of dollars in capital for climate investments is essential to finance the large-scale infrastructure changes needed to transition to a low carbon economy (Cochu et al., 2016). Among the available financing options, the green bond market has emerged in the midst of the global financial crisis in 2008, a liquidity driven crisis culminating in an economic recession. However, if buy and hold investment strategies are found to be dominant in the European green bond market providing market stability, these long-term strategies make it less active and illiquid (Ehrart, 2018).

Quite importantly, Febi et al. (2018) note that two liquidity proxies i.e., the bid-ask spread and the zero trading days (ZTD) are positively related to the green bond yield spreads. If liquidity is effectively priced in green bond yields, it implies that green bond investors may harvest a liquidity premium. This liquidity premium i.e. the compensation demanded by investors for holding illiquid assets has been well documented in more mature bond markets. Several studies have reported a significant liquidity component in corporate bond yield spreads (see, e.g., Longstaff, 2004 ; Bao et al., 2011 ; Goyenko et al., 2011 ; Kempf et al., 2012). However, no papers have attempted to estimate such liquidity premium and its behavior across different bond maturities to the best of our knowledge.

To fill this gap in the literature, we argue that the liquidity premium of the European green bond market is adequately captured by the spread between the yields of Green Bonds issued by Corporates (CGBs) and those issued by Supranationals, Sovereigns and Agencies (SSAGBs). If the corporate bond market is less liquid than the government bond market in Europe (Biais et al., 2006), the green bond market is no exception of the rule. Indeed, CGBs are noticeably less liquid than those issued by SSAGBs in terms of size and bid-ask spreads.

The main contribution of our study is to quantify the liquidity premium of the European green bond market and analyse its term structure over a five-year period: 2015-2019, which has never been used. To do this, we estimate three liquidity premia (short, medium and long) using a Nelson-Siegel (1987) approach that allows us to estimate a good-in sample fit of the term structure. Next, we examine the interactions between the different liquidity premia and their relationships with bid-ask spreads. We then extend our analysis by controlling the influence of economic factors on these liquidity premia using a vector autoregression (VAR) model similar to Kempf et al. (2012). Finally, we test the possibility of a liquidity *clientele effect* by opposing shapes of ask and bid liquidity premia as in Gehde-Trapp et al. (2018).

Our results enrich the literature on bond markets in several respects. First, we estimate an average long-term premium (15 bps) larger than the average short-term liquidity premium (12 bps). These estimates are close to those found on the U.S. Treasury market (Longstaff, 2004) or on the German government bond market (Schuster and Uhrig-Homburg, 2015) but are slightly higher than those found on the same German government bond market by Kempf et al. (2012). Second, we show that the short-term and long-term liquidity premia are moderately sensitive to economic factors to a lower extent compared to the U.S Treasury bond market (Chen et al., 2018). Third, we find that the liquidity *clientele effect* influences the ask liquidity premium affecting the purchase strategies of short-term and long-term green bond investors and the compensation for their liquidity risks (Gehde-Trapp et al., 2018). Fourth, we provide evidence of *spillover effects* from the short end to the long end of the liquidity premium, which are more pronounced at the ask side and for the on-the-run-bonds.

Taken together, our findings deliver valuable insights on the strategies of investors that are confronted to an illiquid green bond market (Ehrtart, 2018). Specifically, long-term investors require compensation for their expected trading costs plus for investing in long-term illiquid bonds. From a policy-making perspective, this illiquidity mainly due to the domination of buy and hold strategies may be a positive feature for two reasons. Firstly, it has encouraged new corporates to issue green bonds to broaden their long-term investor base. Secondly, it is unlikely that, during crisis, these ethical investors (Flammer, 2019) will rush to sell their holdings, providing more stability in stress periods. From an investor perspective, if the liquidity premium reward for the risk of illiquidity, this illiquidity may, however, preclude the use of dynamic (rebalancing) portfolio strategies including green bonds by investors.

One possible solution to this illiquidity issue is related to a more proactive stance of the European Central Bank (ECB) (Fender et al., 2019). From 2018, the ECB has spent about 6 billion euros to buy green bonds (i.e., 20% of the 31 billion euros of eligible green bonds) as part of a revamp of its quantitative easing programme. In this context, the term structure of the liquidity premium may be a relevant tool for the ECB to adapt their purchases of public and private green bonds across different maturities in order not to destabilise one of the two segments of the European Green bond market (namely the CGB and the SSAGB).

Two avenues for further research may be identified. A possible extension of this work would be to study the liquidity premium of the U.S. green bond market in order to assess if tax incentives notably applied to the U.S. Municipal green bonds may affect its term structure. An other direction would be to assess the role of market makers and active brokers on the liquidity premiums of the exchange-based versus the OTC green bond secondary market.

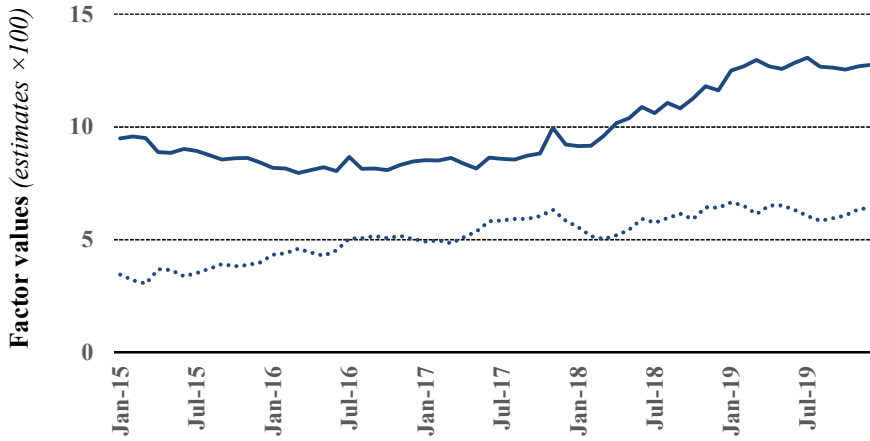
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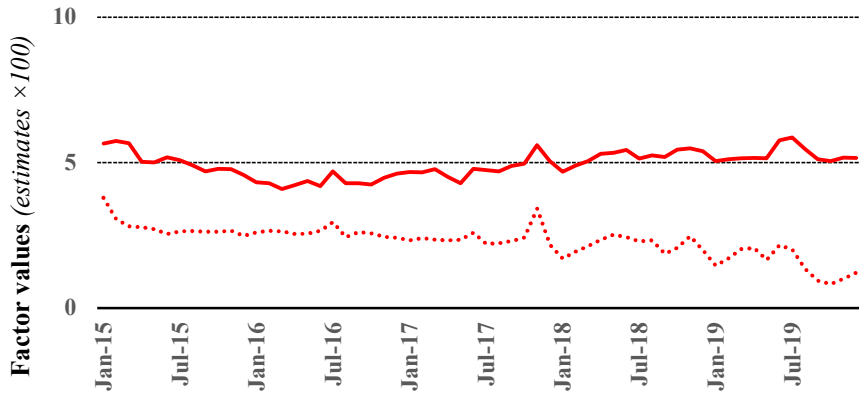
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VII. Appendix

Part A : Long-term factors



Part B : Short-term factors



Part C : Shape factors

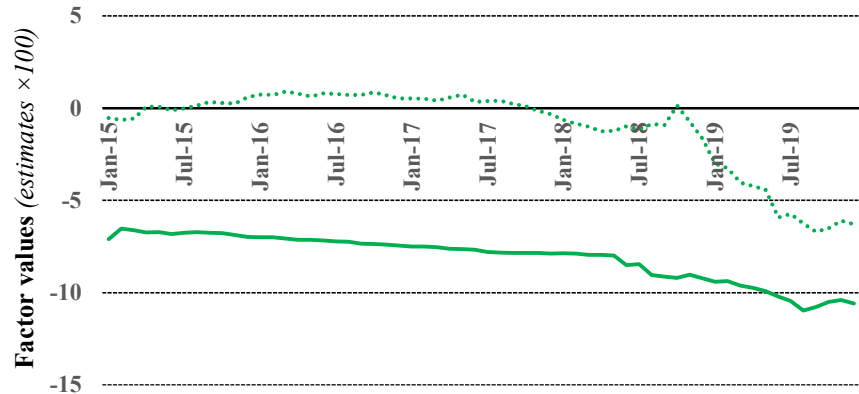


Fig. 1. Term structure factors. This figure presents the evolution of the term structure factors estimated over a 5-year period (January 2015-December 2019). The solid lines depict the factors for the Corporate (CGB) segment and the dashed lines the factors for the segment of Supranationals, Sovereign and Agencies (SSAGB) segment. Part A provides the estimates of the long-term factors ($\beta_{0,t}$); Parts B and C the estimates of the short-term factors ($\beta_{1,t}$) and the shape factors ($\beta_{2,t}$) respectively.

Estimations are run by minimizing the sum of squared yield differences according to Eq. (1) for end-of-month yields with maturities of 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 13, 15 and 20 years for each segment.

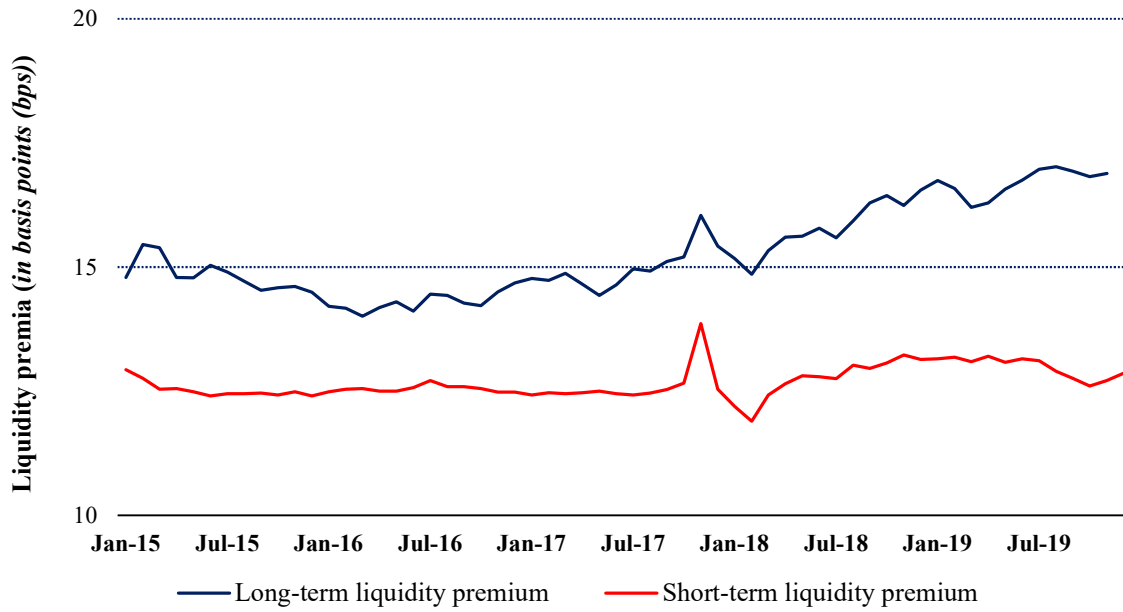


Fig 2. Short-term and long-term liquidity premia. This figure shows the evolution of the short-term and the long-term liquidity premia over the period: January 2015-December 2019 (60 monthly observations). The red line outlines the short-term liquidity premium, which is the difference between the short-term factors of the Corporate Green Bond (CGB) segment and those of the Sovereign Green Bond (SSAGB) segment i.e., $\beta_{0,t}^{CGB} - \beta_{0,t}^{SSAGB} + \beta_{1,t}^{CGB} - \beta_{1,t}^{SSAGB}$. The blue line depicts the long-term liquidity premium that is the difference between the long-term factors of the CGB and SSAGB segment respectively i.e., $\beta_{0,t}^{CGB} - \beta_{0,t}^{SSAGB}$.

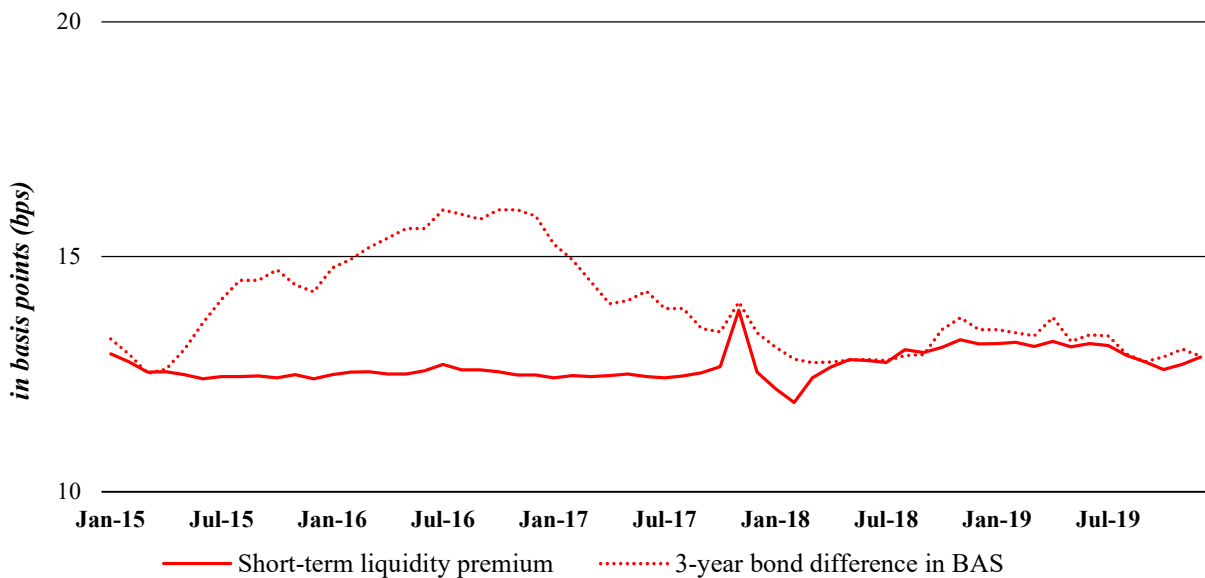
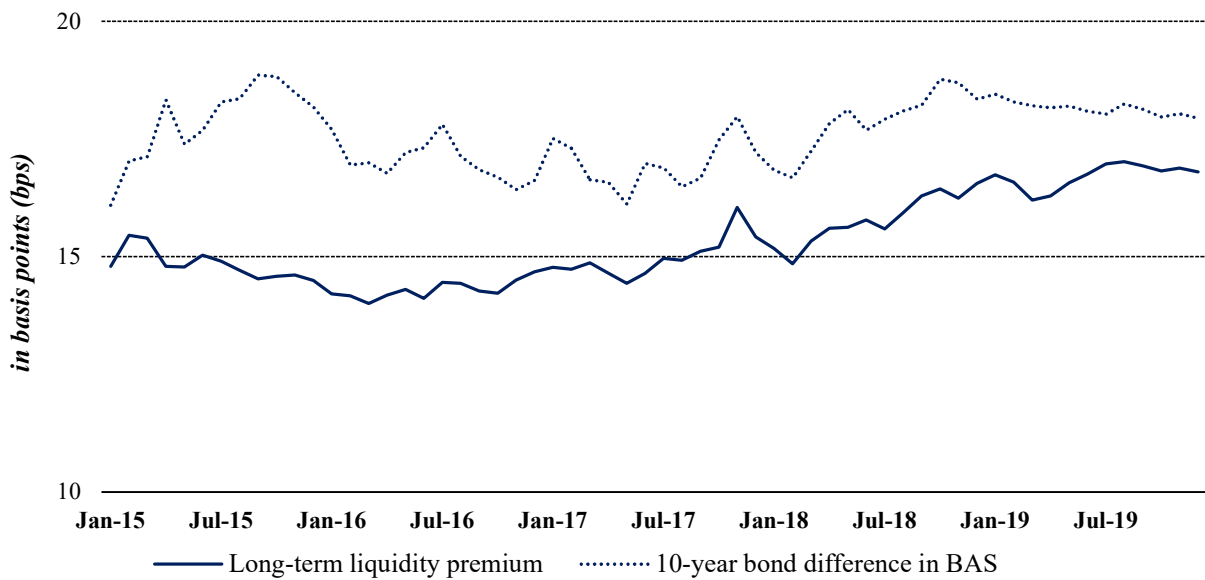


Fig. 3. Liquidity premiums and bid-ask spreads. This figure plots the evolution of liquidity premiums (solid lines) together with the absolute bid-ask spread differences between CGBs and SSAGBs (dotted lines) over the period January 2015-December 2019 (60 monthly observations). The upper graph depicts the evolution of the difference in absolute bid-ask spreads (difference in BAS) and this of liquidity premium of bonds with a maturity of ten years. The lower graph presents the evolution of the difference in absolute bid-ask spreads and this of liquidity premium of bonds with a maturity of 3 years.

Table 1. European Green Bond Primary market and exchanges activity (2018-2019)

Name	Type of section	2018 Issuance (in USD Million)	2019 Issuance (in USD Million)	Average market share (in %)
LuxSE/LGX*	Green bonds	25	28	25.7%
LSEG (LSE & Borsa Italiana)	Green and Social bonds	18.2	18.25	17.7%
German Exchanges	Green bonds	10.24	15.2	12.3%
HFEX	Green and Sustainable bonds	5.2	6.3	5.6%
Euronext**	Green and Sustainable bonds	14.66	27.5	20.4%
Swiss Stock Exchange	Green bonds	4.52	3.9	4.1%
SGX	Green and Social bonds	3.67	6.8	5.1%
Nasdaq Nordic	Green and Sustainable bonds	3.64	3.75	3.6%
Others***		5.34	6.03	5.5%
TOTAL		90.47	115.73	100%

Notes: The average market share is the proportion of bond issuance amount for a given exchange among the full amount issued by exchanges between 2018 and 2019.

* The green bond listing of LGX (Luxemburg Green Exchange) has been active since September 2016.

** Euronext exchanges include Paris (9.3%), Dublin (6.1%), Brussels (2.2%) and Amsterdam (2.8%) platforms.

*** Other German stock exchanges are the following: Frankfurt (5.1%), Berlin (3.5%), Stuttgart (2%), Munich (1%), Dusseldorf (0.7%) and are owned by the Deutsche Boerse Group.

Table 2. Summary statistics of the green bond sample

	SSAGBs	CGBs	Total
Number of bonds	93	91	184
Average (bond) issuance size (<i>in million EUR</i>)	837.785	605.955	723.494
Average number of bookrunners	2.3	4.3	3.3
Average bid-ask spread (<i>in bps</i>)	31.98	37.71	34.82
Average maturity (<i>in years</i>)	7.34	6.95	7.10
Average coupon (<i>in %</i>)	3.14	2.78	2.97
Average rating	1.10	1.60	1.36
Average monthly Return (<i>in %</i>)	0.0074	0.0076	0.0075

Notes: Monthly (absolute) Bid-Ask spread are calculated using quote data provided by Bloomberg while Monthly Returns are computed based on closing prices recorded by LGX, resulting in 60 observation months over the five-year period January 1, 2015 to December 30, 2019. the average rating is assessed on the basis of the Moody's rating obtained for the green bond issued (or on the basis of the S&P rating if the Moody's rating is not available) given the following scale : 1 (*Prime* – rating : AAA), 2 (*High Grade* – rating: Aa1, Aa2 or Aa3), 3 (*Upper Medium Grade* – rating: A1, A2 or A3),..., 9 (*Default imminent* – rating : Caa3, Ca or C), and 10 (*In default* – rating D).

Table 3. Characteristics of the two green bond sets: SSAGB and CGB*Panel A.* SSAGB sample

	< 5 years		5 years < x < 10 years		> 10 years	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Monthly Bid-Ask Spread (<i>in bps</i>)	26.32	17.21	31.24	16.72	35.35	17.30
Zero Trading Days (ZTD) (<i>per month</i>)	0.44	0.38	0.42	0.34	0.56	0.44
Number of bookrunners	2.4	1.1	2.2	1.4	2.4	1.4
Average Coupon (<i>in %</i>)	3.34	1.83	3.20	1.70	3.09	1.27
Average Rating	1.09	0.05	1.14	0.10	1.00	0.00
Average Monthly Return (<i>in %</i>)	0.0063	0.0097	0.0076	0.0115	0.0083	0.0099
<i>Number of bonds</i>	14		53		27	

Panel B. CGB sample

	< 5 years		5 years < x < 10 years		x > 10 years	
	Mean	St. Dev.	Mean	St. Dev.	Mean	St. Dev.
Monthly Bid-Ask Spread (<i>in bps</i>)	31.40	11.65	38.05	21.04	43.28	23.02
Zero Trading Days (ZTD) (<i>per month</i>)	1.02	0.92	0.86	0.61	0.79	0.59
Number of bookrunners	3.4	1.7	4.5	2.7	4.2	2.1
Average Coupon (<i>in %</i>)	2.53	1.62	2.77	1.33	2.94	1.30
Average Rating	1.55	0.21	1.67	0.35	1.52	0.18
Average Monthly Return (<i>in %</i>)	0.0075	0.008	0.0078	0.0112	0.0095	0.011
<i>Number of bonds</i>	22		47		22	

Notes: This table displays descriptive statistics that are computed based on green bond price and quote data observed from January 1, 2015 to December 30, 2019. Monthly (absolute) Bid-Ask spread are calculated using only quote data provided by Bloomberg while Zero Trading days (ZTD) and Monthly Returns are computed based on closing prices recorded by LGX, resulting in 60 observation months. The average rating is assessed on the basis of the Moody's rating obtained for the green bond issued (or on the basis of the S&P rating if the Moody's rating is not available) given the following scale : 1 (*Prime* – rating : AAA), 2 (*High Grade* – rating: Aa1, Aa2 or Aa3), 3 (*Upper Medium Grade* – rating: A1, A2 or A3),..., 9 (*Default imminent* – rating : Caa3, Ca or C), and 10 (*In default* – rating D).

Table 4. Joint dynamics of liquidity premia: VAR(2) model

	Short	Shape	Long
<i>Constant</i>	-3.309 (2.543)	1.993 (3.791)	1.270** (0.476)
<i>Short (t-1)</i>	2.265** (0.820)	-2.690* (1.223)	0.335* (0.154)
<i>Short (t-2)</i>	-1.397* (0.650)	2.411* (1.119)	-0.167 (0.141)
<i>Shape (t-1)</i>	0.761* (0.545)	-0.639 (0.812)	0.209* (0.102)
<i>Shape (t-2)</i>	-0.627* (0.496)	1.418* (0.739)	-0.094 (0.092)
<i>Long (t-1)</i>	1.315* (0.676)	-2.621* (1.231)	1.228** (0.155)
<i>Long (t-2)</i>	-0.917 (0.687)	1.686 (1.025)	-0.136 (0.129)
R²	0.94	0.95	0.91

Notes: This table shows the results for the VAR (2)-model presented in Eqs. (2a), (2b) and (2c) estimated over the period January 2015–December 2019 (60 observations).

$\beta_{0,t}^{CGB} - \beta_{0,t}^{SSAGB} + \beta_{1,t}^{CGB} - \beta_{1,t}^{SSAGB}$, $\beta_{1,t}^{CGB} - \beta_{1,t}^{SSAGB}$ and $\beta_{2,t}^{CGB} - \beta_{2,t}^{SSAGB}$ are the long-term factor, the short-term factor, and the shape factor of the term structure of illiquidity premia, respectively. Standard errors of the coefficients are put in parentheses and are based on the Newey and West's (1987) covariance matrix estimator with 6 lags.

* (resp. **) means that the coefficient is significant at 5% (resp. 1%) level.

Table 5. Summary statistics of possible drivers of liquidity premia

	Mean	Std. Dev.	Median	Min.	Max
<i>Economic Outlook</i>	0.696	0.511	0.490	-0.230	1.630
<i>Economic Policy Uncertainty</i>	219.8	61.6	213.4	131.7	433.3
<i>Bond Volatility (in %)</i>	4.42	1.52	3.85	2.35	8.12
<i>Stock Volatility (in %)</i>	18.87	5.13	17.65	11.99	32.31
<i>Energy Ret. (in %)</i>	0.05	8.16	0.99	-19.78	17.73
<i>U.S. Mun. Green Perf. (in %)</i>	0.32	1.31	0.48	-5.69	2.58
<i>Credit</i>	138.3	16.0	143.9	109.6	163.8
<i>Ratio^{short} (in %)</i>	41.92	25.96	53.85	0.00	68.18
<i>Ratio^{medium} (in %)</i>	46.59	8.31	50.00	28.00	56.67
<i>Ratio^{long} (in %)</i>	45.96	7.90	46.43	25.00	55.10

Notes: This table shows monthly statistics of potential drivers of liquidity premia observed over the period January 2015–December 2019. *Economic Outlook* is the value of the BCI business expectations index. *Economic Policy uncertainty* is the value of the monthly Economic Policy Uncertainty index used by Broadstock and Cheng (2019). *Bond Volatility* captures the volatility of the green bond market. We calculate it as the standard deviation of the daily yields (in percentage points) of the S&P Green Bond index within a month. *Stock Volatility* is the end-of-month value of the VSTOXX, the benchmark volatility index of the European stock market (STOXX50). *Energy Ret.* is the monthly return of the benchmark S&P Energy index. *U.S. Mun. Green Perf.* is the monthly return of the U.S. municipal (non-taxable) green bond market. *Credit* is the spread between the Bloomberg EUR Eurozone index of financial AA+/AA bond yields and the Bloomberg EUR Eurozone index of financial BBB bond yields, measured in percentage points. *Ratio* is the ratio of the volume issued in the CGB market and the total volume issued in both markets (SSAGB and CGB) over the previous 6 months.

We construct separate measures for *short-term* bonds (<5 years), *medium-term* bonds (5–9 years), and *long-term* bonds (>10 years).

Table 6. Drivers of liquidity premia: VARX model

	Short	Shape	Long
<i>Constant</i>	3.986 (5.161)	-18.707** (7.120)	2.247** (0.886)
<i>Economic Outlook</i>	-0.961* (0.348)	-1.014* (0.509)	-1.085* (0.046)
<i>Economic policy Uncertainty</i>	0.0025* (0.0012)	-0.0022 (0.0019)	0.0006* (0.0003)
<i>Bond Volatility</i>	-97.37* (62.10)	101.88 (160.03)	-41.44 (25.78)
<i>Stock Volatility</i>	0.0176 (0.026)	-0.019 (0.0379)	-0.002 (0.0049)
<i>Energy Ret.</i>	0.4365 (0.982)	-1.166 (1.321)	0.233 (0.181)
<i>U.S. Mun. Green Perf.</i>	1.885 (1.203)	-2.689 (4.641)	1.967* (0.959)
<i>Credit</i>	-0.060 (0.022)	-0.048 (0.029)	-0.005 (0.003)
<i>Ratio</i>	-0.593 (1.086)	-8.918 (5.394)	0.159 (0.581)
<i>Short (t-1)</i>	1.793** (0.882)	-2.384* (1.185)	0.245 (0.171)
<i>Short (t-2)</i>	-0.036 (0.887)	-0.581 (1.333)	0.023 (0.172)
<i>Shape (t-1)</i>	0.729 (0.580)	-0.918 (0.854)	0.144 (0.112)
<i>Shape (t-2)</i>	0.007 (0.578)	-0.3989 (0.858)	0.019 (0.112)
<i>Long (t-1)</i>	0.343 (0.970)	-1.319 (1.402)	1.049** (0.201)
<i>Long (t-2)</i>	0.129 (0.825)	-0.673 (1.241)	0.063 (0.161)
R²	0.96	0.97	0.93

Notes: This table shows the results for the VARX-model presented in Eqs. (5a), (5b) and (5c) estimated over the period January 2015–December 2019 (60 observations).

$\beta_{0,t}^{CGB} - \beta_{0,t}^{SSAGB} + \beta_{1,t}^{CGB} - \beta_{1,t}^{SSAGB}$, $\beta_{1,t}^{CGB} - \beta_{1,t}^{SSAGB}$ and $\beta_{2,t}^{CGB} - \beta_{2,t}^{SSAGB}$ are the long-term factor, the short-term factor, and the shape factor of the term structure of illiquidity premia, respectively.

The exogenous variables are defined as in Table 5. Standard errors of the coefficients are expressed in parentheses and they are based on the Newey and West's (1987) covariance matrix estimator with 6 lags.

* (resp. **) means that the coefficient is significant at 5% (resp. 1%) level.

Table 7. Drivers of liquidity premia for different maturities

	2-Year Premium	3-Year Premium	4-Year Premium	5-Year Premium	10-Year Premium	15-Year Premium	20-Year Premium
<i>Constant</i>	4.504** (0.094)	2.631** (0.205)	2.072** (0.379)	-11.092** (2.973)	-13.099** (2.001)	21.249** (2.388)	-4.523** (0.894)
<i>Economic Outlook</i>	-0.029* (0.007)	0.050* (0.023)	0.165 (0.081)	-0.596* (0.291)	-1.071** (0.440)	-1.564* (0.89)	-1.770* (0.96)
<i>Economic Policy Uncertainty</i>	0.0003** (0.0001)	0.0004* (0.0002)	-0.0004 (0.0003)	-0.008 (0.003)	0.005** (0.001)	0.003* (0.0014)	0.0003 (0.0004)
<i>Bond Volatility</i>	-3.103* (1.794)	-5.643* (3.338)	7.577 (7.699)	1150.322 (801.749)	294.437 (172.910)	-192.470 (172.682)	38.957 (28.709)
<i>Stock Volatility</i>	0.003 (0.001)	0.0003 (0.0003)	0.005 (0.006)	-0.182 (0.159)	-0.015 (0.024)	-0.050 (0.041)	-0.029 (0.023)
<i>Energy Ret.</i>	-0.166 (0.126)	0.117 (0.185)	0.238 (0.174)	0.992 (1.207)	2.569 (1.959)	0.878* (0.534)	0.613* (0.303)
<i>U.S. Mun. Green Perf.</i>	0.084 (0.159)	0.247 (0.592)	-0.552 (0.369)	-19.569 (5.903)	2.671* (1.203)	3.340 (2.237)	2.859* (1.399)
<i>Credit Ratio</i>	-0.004* (0.002)	-0.001 (0.001)	0.002 (0.003)	-0.176* (0.042)	-0.050 (0.109)	-0.077 (0.090)	0.073 (0.107)
	-0.195* (0.031)	0.047 (0.091)	-0.135 (0.133)	-2.004* (0.901)	-1.418 (1.289)	1.771 (2.107)	1.753 (0.941)
R²	0.69	0.27	0.29	0.63	0.73	0.91	0.90

Notes: This table shows the results of a regression model similar to Eqs. (3a), (3b), (3c) estimated over the period January 2015–December 2019 (60 observations). Hence, the endogenous variable is the illiquidity premium for bonds with a maturity fixed between 2 years and 15 years. The exogenous variables are defined as in Table 5.

We use the ratio based on short-term bonds (<5 years) as an explanatory variable for the 2-Year, 3-Year, 4-Year, and 5-Year premia, the ratio based on medium-term bonds (5–10 years) for the 5-Year premia, and the ratio based on long-term bonds (10 years and more) for the 10-Year, 15-Year, and 20-Year premia respectively. Standard errors of the coefficients are expressed in parentheses and are based on the Newey and West's (1987) covariance matrix estimator with 6 lags.

* (*resp.* **) means that the coefficient is significant at 5% (*resp.* 1%) level.

Table 8. VARX-model estimated with ask and bid yield spreads from the original data

	<i>Ask yield spreads</i>			<i>Bid yield spreads</i>		
	Short	Medium	Long	Short	Medium	Long
<i>Constant</i>	0.142** (0.053)	1.434 (1.662)	-0.246 (0.567)	0.161** (0.062)	2.184 (2.087)	-0.111 (0.693)
<i>Economic Outlook</i>	-0.01** (0.002)	-0.009 (0.065)	-0.045* (0.023)	-0.001 (0.002)	-0.042 (0.072)	0.041* (0.020)
<i>Economic Policy Uncertainty</i>	0.0002** (0.0001)	-0.0002 (0.0002)	0.00002 (0.0001)	0.0001 (0.00001)	0.0002 (0.0002)	0.0001 (0.0001)
<i>Bond Volatility</i>	-0.819* (0.512)	20.627 (16.747)	2.312 (5.976)	-0.707 (0.500)	-22.213 (17.742)	0.925 (6.090)
<i>Stock Volatility</i>	-0.0001 (0.0001)	-0.0018 (0.004)	0.0013 (0.0014)	-0.00001 (0.0001)	-0.002 (0.004)	0.0014 (0.0014)
<i>Energy Ret.</i>	-0.006 (0.004)	-0.124 -0.123	-0.042 -0.048	-0.005 (0.004)	-0.156 (0.128)	-0.041 (0.049)
<i>U.S. Mun. Green Perf.</i>	0.049 (0.026)	0.034 (0.814)	0.416* (0.205)	0.054 (0.026)	0.182 (0.869)	0.405 (0.294)
<i>Credit</i>	0.00003 (0.0001)	-0.002 (0.003)	0.002* (0.001)	-0.00004 (0.0001)	-0.0008 (0.003)	0.0015 (0.001)
<i>Ratio</i>	-0.003 (0.006)	0.169 (0.411)	0.059 (0.152)	-0.002 (0.005)	0.168 (0.433)	0.055 (0.155)
<i>Short (t-1)</i>	0.422** (0.156)	-2.699 (1.648)	0.338* (0.162)	0.378* (0.179)	-2.463 (5.121)	1.034 (1.813)
<i>Short (t-2)</i>	0.264* (0.131)	-0.563 (0.490)	0.199 (0.456)	0.181* (0.087)	-2.082 (4.237)	-1.150 (1.473)
<i>Medium (t-1)</i>	-0.001 (0.005)	-0.891* (0.559)	0.088 (0.059)	-0.001 (0.005)	0.475 (0.158)	0.065 (0.057)
<i>Medium (t-2)</i>	-0.004 (0.005)	0.021 (0.165)	-0.086 (0.061)	-0.002 (0.005)	0.095 (0.162)	-0.072 (0.058)
<i>Long (t-1)</i>	0.032* (0.014)	0.071 (0.437)	0.953** (0.158)	0.017 (0.014)	-0.011 (0.454)	0.952** (0.260)
<i>Long (t-2)</i>	-0.004 (0.013)	0.150 (0.394)	-0.215 (0.144)	-0.007 (0.013)	0.147 (0.416)	-0.196 (0.147)
R²	0.86	0.92	0.96	0.84	0.95	0.96

Notes: This table presents the results of a regression model similar to this to this shown in Eqs. (3a), (3b), (3c) estimated over the period: January 2015–December 2019 (60 observations). We run our VAR regressions based on the ask yield or the bid yields spreads. *Short(t)* is the 2-Year (ask or bid) yield spread, *Medium(t)* the 5-Year (ask or bid) yield spread and *Long(t)* the 15-Year (ask or bid) yield spread.

The exogenous variables are defined as in Table 5.

Standard errors of the coefficients are in parentheses and are based on the Newey and West's (1987) covariance matrix estimator with 6 lags.

* (*resp.* **) means that the coefficient is significant at 5% (*resp.* 1%) level.

Table 9. VARX-model estimated with yield spreads obtained from the original data: On-the-run bonds vs. Off-the-run bonds

	<i>On-run bonds</i>			<i>Off-run bonds</i>		
	Short	Medium	Long	Short	Medium	Long
<i>Constant</i>	1.235* (0.640)	1.195 (2.946)	1.978** (0.883)	0.061 (0.047)	-1.111 (0.683)	-0.369 (0.235)
<i>Economic Outlook</i>	-0.004* (0.002)	-0.059 (0.072)	-0.065** (0.022)	-0.006* (0.003)	0.029 (0.069)	0.045* (0.032)
<i>Economic Policy Uncertainty</i>	0.0002* (0.0001)	-0.00015 (0.0002)	0.0001 (0.0006)	0.0002* (0.0001)	0.0005 (0.0002)	0.0003* (0.0007)
<i>Bond Volatility</i>	-0.997* (0.482)	-17.946 (17.150)	6.994 (5.450)	-0.183* (0.087)	3.929 (2.996)	2.959 (5.744)
<i>Stock Volatility</i>	-0.0001 (0.0001)	-0.0013 (0.004)	-0.002 (0.001)	0.0001 (0.0002)	-0.0009 (0.004)	0.002 (0.001)
<i>Energy Ret.</i>	-0.0001 (0.001)	0.0004 (0.003)	-0.002 (0.0015)	0.0144 (0.009)	0.205 (0.135)	-0.037 (0.044)
<i>U.S. Mun. Green Perf.</i>	0.052 (0.045)	0.058 (0.814)	0.052* (0.259)	0.089 (0.046)	-0.538 (0.886)	0.578* (0.265)
<i>Credit</i>	-0.0046 (0.004)	-0.174 (0.136)	0.014* (0.047)	-0.0001 (0.0002)	-0.004 (0.002)	0.002* (0.001)
<i>Ratio</i>	-0.0013 (0.005)	0.141 (0.434)	-0.029 (0.139)	-0.0022 (0.010)	0.390 (0.419)	-0.012 (0.145)
<i>Short (t-1)</i>	0.304** (0.115)	-1.679 (5.161)	-1.192 (1.699)	0.712** (0.153)	-3.580 (2.502)	-0.327 (0.972)
<i>Short (t-2)</i>	0.274* (0.129)	-1.061 (4.565)	-0.885 (1.435)	0.038 (0.163)	3.094 (2.938)	0.698 (0.971)
<i>Medium (t-1)</i>	-0.002 (0.005)	-0.946** (0.165)	-0.017 (0.055)	-0.0029 (0.0076)	0.033 (0.150)	-0.0027 (0.048)
<i>Medium (t-2)</i>	-0.003 (0.005)	-0.033 (0.169)	0.001 (0.096)	-0.0074 (0.007)	0.140 (0.131)	-0.041 (0.043)
<i>Long (t-1)</i>	0.011 (0.016)	0.311 (0.512)	0.691** (0.169)	0.0034 (0.025)	-0.329 (0.491)	0.962 (0.598)
<i>Long (t-2)</i>	0.004 (0.012)	-0.287 (0.433)	-0.127 (0.141)	0.016 (0.022)	0.089 (0.429)	-0.233 (0.192)
R²	0.87	0.94	0.96	0.68	0.74	0.96

Notes: This table shows the results of a regression model similar to this shown in Eqs. (3a), (3b), (3c) estimated over the period: January 2015–December 2019 (60 observations). **On-the-run bonds** are bonds that are recently issued (issuance have occurred for 1 year at least and 2 years maximum) and have not yet matured. **Off-the-run bonds** have either have a shorter time to maturity or even already matured. *Short(t)* is the 2-Year yield spread, *Medium(t)* the 5-Year yield spread and *Long(t)* the 15-Year yield spread.

The exogenous variables are defined as in Table 5.

Standard errors of the coefficients are in parentheses and are based on the Newey and West's (1987) covariance matrix estimator with 6 lags.

* (*resp.* **) means that the coefficient is significant at 5% (*resp.* 1%) level.

Table 10. Estimated number of breaks and break dates for the three liquidity premia.

	NS(1987) estimates			Estimated from original data		
	Short	Shape	Long	3-Year	5-Year	15-Year
<i>UDmax</i>	19.93**	209.68**	99.07**	7.96	207.93**	37.80**
<i>WDmax</i> _{5%}	19.93**	209.68**	99.07**	9.96	207.93**	37.80**
<i>SupF</i> _T (1 0)	19.93**	209.68**	99.07**	9.96	207.93**	37.80**
<i>SupF</i> _T (2 1)	2.08	9.48	9.44	8.84	6.25	3.80**
<i>SupF</i> _T (3 2)	4.27	10.27	4.24	8.42	2.36	8.09**
Number of breaks	1	1	1	0	1	1
Break Date	2017:11	2017 :11	2017 :11		2017:11	2017:11

Note : This table reports the double maximum test of breaks in the means of three illiquidity premia estimated with the NS model (short, shape, long) or obtained from original data (3-Year, 5-Year and 15-Year premium). Two double maximum tests that test the null hypothesis of no structural break —*UDmax* and *WDmax*—are reported in the first two rows. Rows 3–5 report the sequential *SupF*_T(*L* + 1/*L*) *F*-statistic for *L*=1,2,3 to determine the number and location of structural breaks. The location are determined according to the Bai and Perron (1998) critical values, which are 8.58, 10.13 and 11.14 for *SupF*_T(1|0), *SupF*_T(2|1), *SupF*_T(3|2) respectively given a 15% trimming rate. The sample period is from January 2015 to December 2019 on a monthly basis (60 observations). * (*resp.* **) means that the coefficient is significant at 5% (*resp.* 1%) level.

Table 11. VARX-model estimated over two sub-periods: January 2005–November 2017 vs. December 2017–December 2019

	<i>January 2005–November 2017</i>			<i>December 2017–December 2019</i>		
	Short	Medium	Long	Short	Medium	Long
<i>Constant</i>	0.412 (7.016)	-20.944** (9.207)	2.763 (1.518)	-7.549 (17.562)	12.561 (5.780)	1.381 (2.375)
<i>Economic Outlook</i>	-0.904* (0.371)	0.188 (0.418)	-1.001* (0.494)	-2.084* (1.002)	3.833 (2.588)	-0.403* (0.16563)
<i>Economic Policy Uncertainty</i>	0.002** (0.0009)	-0.002 (0.002)	0.0005* (0.0002)	-0.004* (0.002)	-0.009 (0.0085)	0.001 (0.001)
<i>Bond Volatility</i>	-30.517* (13.075)	42.374 (79.305)	-27.164 (53.059)	-173.242* (87.449)	-688.581 (838.537)	825.403 (569.569)
<i>Stock Volatility</i>	0.002 (0.012)	0.006 (0.020)	-0.002 (0.003)	0.110 (0.100)	-0.100 (0.153)	-0.015 (0.016)
<i>Energy Ret.</i>	-0.717 (0.5424)	0.451 (0.928)	0.149 (0.153)	-0.808 (3.195)	-1.422 (4.464)	1.117 (0.965)
<i>U.S. Mun. Green Perf.</i>	-1.432 (2.745)	0.432 (4.049)	-0.890* (0.448)	25.974 (15.051)	-30.408 (22.002)	3.720* (1.895)
<i>Credit</i>	-0.038 (0.038)	-0.016 (0.017)	-0.006 (0.005)	0.144 (0.118)	-0.183 (0.187)	-0.017 (0.013)
<i>Ratio</i>	-1.327 (1.064)	4.141 (3.918)	0.179 (0.646)	6.662 (7.239)	-4.878 (3.495)	0.496 (2.763)
<i>Short (t-1)</i>	0.872** (0.290)	-0.801 (0.813)	0.370* (0.139)	1.221** (0.629)	-2.618 (1.530)	0.473 (0.472)
<i>Short (t-2)</i>	-0.253 (0.439)	-0.450 (0.705)	0.103 (0.116)	-0.981 (3.615)	-1.189 (5.314)	0.211 (0.554)
<i>Medium (t-1)</i>	0.517 (0.429)	-0.491 (0.649)	0.071 (0.107)	0.281 (1.934)	-1.461 (2.798)	0.295 (0.292)
<i>Medium (t-2)</i>	-0.120 (0.323)	0.230 (0.485)	-0.004 (0.079)	-0.347 (2.304)	-0.814 (3.378)	0.072 (0.352)
<i>Long (t-1)</i>	1.172 (0.735)	-1.733 (1.903)	0.715** (0.314)	1.419 (4.388)	-3.249 (6.387)	0.964** (0.366)
<i>Long (t-2)</i>	0.241 (0.377)	0.013 (0.599)	0.088 (0.099)	-3.150 (4.493)	-0.212 (6.871)	0.944 (0.717)
R²	0.87	0.81	0.76	0.96	0.97	0.97

Notes: This table shows the results of the regression similar to this shown in Eqs. (3a), (3b), (3c) that is estimated over two periods: January 2015–November 2017 (35 observations) and December 2017–December 2019 (25 observations).

Standard errors of the coefficients are in parentheses and are based on the Newey and West's (1987) covariance matrix estimator with 6 lags.

* (*resp.* **) means that the coefficient is significant at 5% (*resp.* 1%) level.