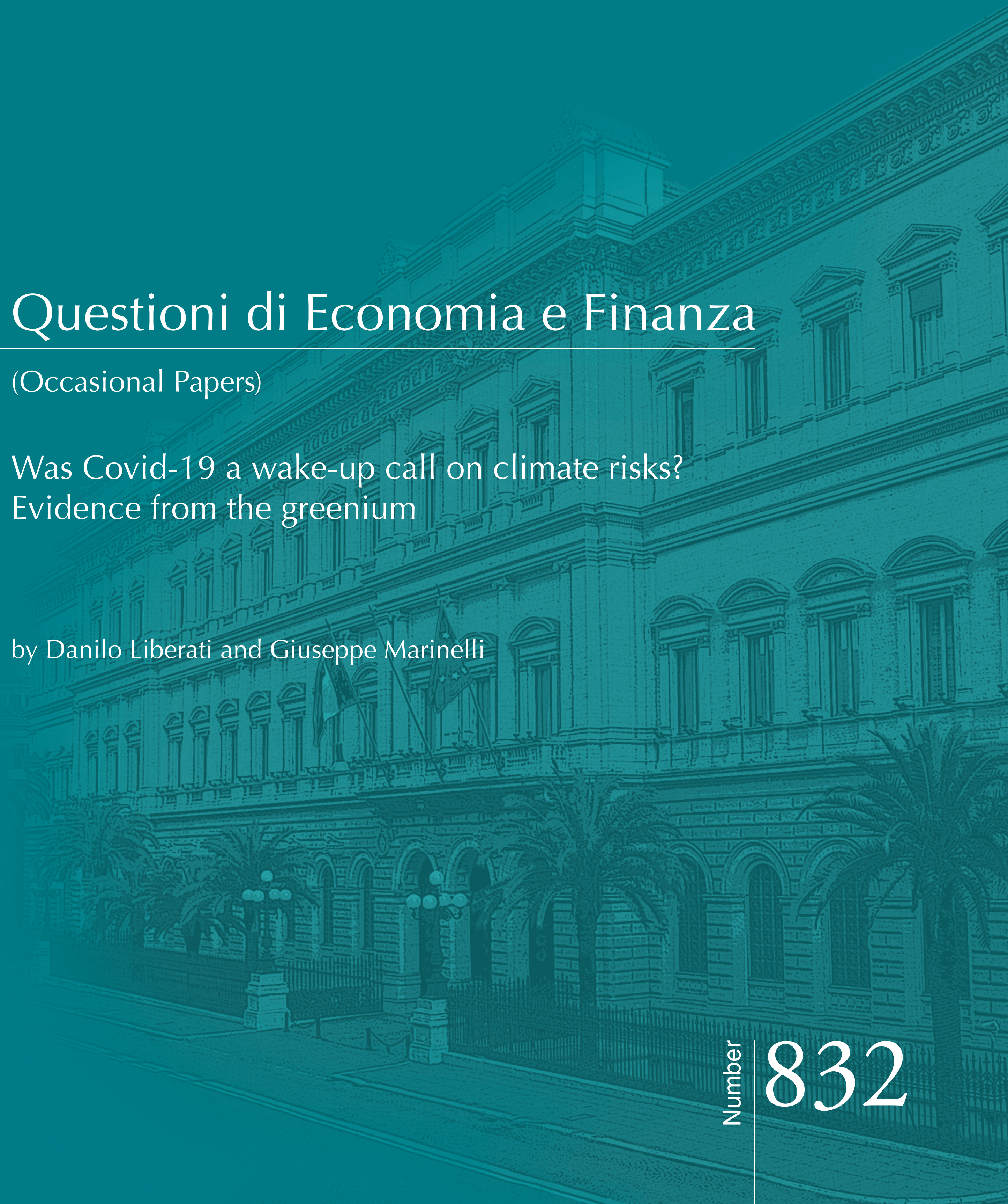
BANCA D'ITALIA
EUROSISTEMA

Questioni di Economia e Finanza

(Occasional Papers)

Was Covid-19 a wake-up call on climate risks? Evidence from the greenium

by Danilo Liberati and Giuseppe Marinelli



Number 832

March 2024

BANCA D'ITALIA
EUROSISTEMA

Questioni di Economia e Finanza

(Occasional Papers)

Was Covid-19 a wake-up call on climate risks? Evidence from the greenium

by Danilo Liberati and Giuseppe Marinelli

Number 832 – March 2024

The series Occasional Papers *presents studies and documents on issues pertaining to the institutional tasks of the Bank of Italy and the Eurosystem. The* Occasional Papers *appear alongside the* Working Papers *series which are specifically aimed at providing original contributions to economic research.*

The Occasional Papers *include studies conducted within the Bank of Italy, sometimes in cooperation with the Eurosystem or other institutions. The views expressed in the studies are those of the authors and do not involve the responsibility of the institutions to which they belong.*

The series is available online at www.bancaditalia.it .

ISSN 1972-6643 (online)

Designed by the Printing and Publishing Division of the Bank of Italy

WAS COVID-19 A WAKE-UP CALL ON CLIMATE RISKS? EVIDENCE FROM THE GREENIUM

by Danilo Liberati* and Giuseppe Marinelli *

Abstract

Building on the work by Liberati and Marinelli (2021), this paper presents a study on the greenium, i.e. the negative yield difference between green bonds and their conventional counterparts. We use a security-by-security data set comprising a large sample of green bonds exchanged on the main global security markets, integrated with the microdata employed in official statistics on security holdings and prices. After showing the existence of the greenium, we employ a twofold approach in order to contribute to the literature on this topic. Firstly, we exploit an econometric strategy based on security-level panel regressions and we find strong evidence for the existence of the greenium and for its increase following the Covid-19 shock; nonetheless, after the end of the state of emergency, we find evidence of a rebound of the greenium of different intensities depending on the issuing sector. Finally, we provide econometric evidence for a persistent excess demand in the green bond secondary market through a non-Walrasian disequilibrium model á la Maddala and Nelson (1974).

JEL Classification: C33, G12, G21, Q56.
Keywords: Green bonds, greenium, Covid-19.
DOI: 10.32057/0.QEF.2023.0832

* Bank of Italy, Economic Research and International Relations.

1 Introduction[1]

The development of the green financial market has become a key factor to address the necessary financial resources towards sustainable investments in order to close the so-called *green finance gap*: according to UNEP (2021) *if the world is to meet targets for climate change, biodiversity, and land degradation, it needs to close a USD 4.1 trillion financing gap by 2050.* The green bonds may represent a viable way to reach this goal since their spread can be fostered from the networking of the main stock exchanges of the world that have launched sustainable/green market segments or have come to participate in the UN Sustainable Stock Exchanges initiative.[2] Nonetheless, the support of the expansion of green investments requires the reduction of "*green-washing*" phenomena and higher transparency: this is the rationale behind the proposal to create a green bond standard by the European Commission.

Many studies have verified the existence of a *greenium puzzle*, i.e. a negative premium on green debt securities with respect to conventional counterparts. This might be related to the appetite for green securities due to the concerns regarding environment and climate as theorized by Pastor et al. (2022), so that investors come to evaluate the assets not only in terms of portfolio payoffs but also in light of her own tastes as she would do for consumption goods (Fama and French, 2007). A second explanation can be contextualized in the asset pricing theory (APT) where green bonds would bear lower risk thanks to the certification process which would guarantee a more regular monitoring and, in turn, higher transparency (Fama, 1998). In the same APT context, a third explanation is related to the green assets being less exposed to long-term climate change risks, be them a carbon tax or other physical risks.

As pointed out by Schnabel (2020), the pandemic crisis brought about a *wake-up call* on the correct assessment of climate-related risks. This mechanism is analogous to that described by Goldstein et al. (1998) for the Asian crisis of the 1990s and by Giordano et al. (2013) for the more recent sovereign debt crisis. On the one hand, the pandemic might have triggered the acquisition of new information leading to a higher awareness and to the re-assessment of the climate change risk in the medium-long term. Prior to the shock, the bond fundamentals would have already justified a shift in preferences towards green bonds before but the risks were not correctly perceived by investors. Such wake-up call can be seen as analogous to that of the sovereign debt crisis when fiscal and macroeconomic fundamentals would have justified a shift from riskier bonds of more indebted countries to those issued by Germany even before the outbreak of the crisis. On the other hand, the end of emergency state and the loosing of the restrictions experienced in many countries in the world may have dampen this awareness, weakening the *wake-up call* hypothesis.

The contribution of this paper is twofold. First, we contribute to the debate on the *greenium puzzle* with robust econometric results showing the existence of a negative premium on green bonds and its heterogeneity across sectors and over time due to the Covid-19 shock. To the best of our knowledge, we are the first to study at the same time the extent of the *greenium puzzle* before, during and after the end of the pandemic emergency. Second, we provide econometric evidence for a persistent excess demand in the green bond market by using a non-Walrasian model. The rest of the paper is structured as follows. The next section provides a review of the growing literature on the green bond market; section 3 describes the dataset whereas section 4 shows

[1] We would like to thank Lucia Alessi, Emanuela Basili, Silvia Fabiani, Laura Graziani Palmieri, Luigi Infante, Laura Mellone, Francesca Monacelli, Giorgio Nuzzo, Matteo Piazza, Alfonso Rosolia and Roberto Sabbatini as well as the participants of the Energy and Climate Change Workshop organized by Banca d'Italia in December 2023 for the useful comments. The opinions expressed and conclusions drawn are those of the authors and do not necessarily reflect the views of the Bank of Italy and of the Eurosystem.

[2] See https://sseinitiative.org and https://www.climatebonds.net.

some stylized evidence based on the yield curves analysis. section 5 illustrates the econometric analyses to assess the existence of an excess of demand in the green bond market and to shed light on the determinants of the *greenium*. Finally, section 6 concludes.

2 Literature Review

Empirical literature on the existence and the sign of a premium for investing in green bonds – the so-called *greenium* – has shown mixed results. Most of the empirical papers show a negative yield differential between green bonds and a counterfactual group of conventional securities: the statistical significance and the magnitude of the premium might be included in a quite wide range based on sample, data source, estimation method (matching or panel regressions) and other bonds or issuers' characteristics. Only few works estimate higher returns for green bonds than the conventional ones.[3]

The *greenium puzzle* may be analyzed both at and after the issuance. With respect to the primary market, Ehlers and Packer (2017) estimate a negative yield premium for a small number of bonds in the period 2014-2017. Similar results are obtained by Baker et al. (2022) using a sample of nearly 4,000 US municipal bonds from 2013 to 2018. Gianfrate and Peri (2019) confirms the negative *greenium* also for the euro-denominated green securities suggesting that this advantage persists also in the secondary market consistently to the findings by other studies such as Zerbib (2019), Hachenberg and Schiereck (2018) and Löffler et al. (2021). Moreover, matched – green and conventional – bonds' samples may depend on the specific market characteristics (currency, incentives and norms) as pointed by Maltais and Nykvist (2020) for the Swedish one as well as the matching techniques as remarked by Löffler et al. (2021). Recently, Huang et al. (2023) proposed a new way to estimate the *greenium* based on a concave relationship between the *greenium* and non-green bond yield spread.

Bonds and issuers' characteristics may have a critical role for the size and statistical significance of the *greenium*. As pointed out by Zerbib (2019), the main determinants of the *greenium* are the rating and the issuer type. Fatica et al. (2021) find a negative and statistical significant *greenium* when issuers are supranational institutions or firms but no evidence arises if the issuer is a financial institute; similar results are found by Kapraun et al. (2021) that stress on the importance of considering credit ratings to properly estimate the *greenium*. With respect to only sovereign issuers Doronzo et al. (2021) highlight no significant statistical between yield of green and conventional bonds both in the primary and secondary markets.

Green securities could be on average more liquid and the lower yields may reflect such feature that, in turn, could depend both on the volume and maturities of the bonds. Hence, many papers tries to control for the size of a possible liquidity premium: Baker et al. (2022) use the amount issued as a volume-based metric whereas Karpf and Mandel (2018) includes the number of bonds' transactions within a (previous) month as a sort of turnover measure. Zerbib (2019) refers to the bid-ask spreads to capture the transaction costs and the tightness of the market. All previous works present maturity controls based on issue and maturity's dates.

Issuers' financial characteristics may matter: by focusing on corporates Barua and Chiesa (2019) show a negative relationship between the amount issued of green bonds and growth of revenues even if a positive effects of profitability (ROA) arises. Tang and Zhang (2020) find a statistical significant negative green premium that disappears once firms (as leverage and profitability) and time fixed effects are included. By controlling for issuers' financial and non financial characteristics, Dutordoir et al. (2023) highlight as companies with higher reputational gains from being seen as green and a stricter connected to ecological technologies are more likely

[3]See Bachelet et al. (2019) and Karpf and Mandel (2018).

to issue green instead of traditional securities. Agliardi and Agliardi (2021) construct a two-factor structural model able to reproduce positive and negative sign based on a new source of uncertainty depending also on the firms' cash flows.

A further driver of the *greenium* seems to be the credibility in the green securities: Pietsch and Salakhova (2022) define credible green bonds as those which have been under external review whereas credible issuers as those participating to climate-friendly networks and associations as the United Nations Environment Programme - Financial Initiative (UNEP FI). Similarly, Ehlers and Packer (2017) highlight that third-party validations reduce informational asymmetry and the risk of *greenwashing* whereas Kapraun et al. (2021) find that the existence of a negative green premium is strictly related to the investors' valuation of the green label with respect to the green credibility characteristics of the bonds and/or issuers.

The green credibility seems to play a certain role also in explaining the dependence between green investing and firms' carbon profiles (Flammer, 2021). Consistently, Alessi et al. (2021) show the existence of a pricing factor linked to climate risk and find a negative statistical significant relationship between the *greenium* and a greenness and environmental transparency index based on the companies' GHG emissions and environmental disclosures. Nevertheless, Ehlers et al. (2020) are quite skeptical on the current firm-level rating based on carbon intensity since they do not find benefits of the green bonds' financing in lowering the carbon emissions of firms.[4]

Exogenous shocks as the Covid-19 pandemic one may affect the magnitude and the significance of the *greenium*. Yi et al. (2021) find that the pandemic shock increased the cumulative abnormal returns of the Chinese green bond markets due to the production stop – in particular for industries financed by green bonds – which determined both a decrease of the demand for green energies and the increase in the duration of the green bond projects. An overreaction to the pandemic in the green bond market with respect a conventional one is also found by Cui et al. (2022) in a time-frequency domain analysis. Cicchiello et al. (2022) find that on the one hand, the credit spread of the green bonds compared with the traditional ones increased and decreased more due to the pandemic and after announcement of the vaccine, respectively. In this respect, a recent analysis by Ayaydin et al. (2022) argue that, following the Covid-19 pandemic, the performance of green securities may outperform that obtained by brown bonds. Arat et al. (2023) find a statistically significant enlargement of the negative *greenium* by comparing the periods before and after the pandemic shock.[5] Moreover, based on the new definition of ESG risk scores – measuring firms' exposure to ESG-related risks – provided by Morningstar, Ferriani and Natoli (2020) show how, after the Covid-19 outbreak, investors preferred to invest in low-ESG-risk funds (that have performed better than their peers) in order to hedge against further market downturns.[6]

Finally, the sharp global rise of the issued green bonds may depend on both supply and demand factors: issuers can gain from the lower funding cost whereas investors can diversify their portfolios and risks; moreover, both kind of agents might incorporate climate change targets in their utility functions. Ferriani (2023) find that firms with more sustainable profiles benefit from lower financing costs during the early stage of the pandemic due to both non-pecuniary motivations as well as risk-based considerations of investors. Pietsch and Salakhova (2022) study the *greenium* dynamics over time in the period 2016-2021 by showing it is partially driven by investors demand. Anyway, there is not a clear evidence about the leading force that drives the green bond market: by exploiting a recent survey over 800 large investors from around the world

[4]See Hammoudeh et al. (2020) for an overview on the relationship between green bonds and the main financial and environmental variables.

[5]Zaghini (2023) estimates that the yield on green bonds decreased by more than 20 b.p. after the Pandemic Emergency Purchase Programme (PEPP) and additional premium is found if securities are at the same time green and eligible for the programme.

[6]See Faiella and Malvolti (2020) for an assessment of the climate risk for the Italian finance.

RBC (2021) highlights that only the 15% of the participants answer that there are sufficient fixed income product offerings that incorporate ESG factors.[7] Wulandari et al. (2018) argue that the shortage of supply and the excess of demand in green bonds market is mainly due to the lack of fiscal incentive for green investment and to the different standards and classifications of green securities. Since the perceived and persistent excess for green assets, equilibrium models could be not adequate to describe this market. Hence, non-Walrasian approaches as models á la Fair and Jaffee (1972) and Maddala and Nelson (1974), that are usually implemented to study the credit market[8] may be more suitable to the analyze the green bond market's peculiarities.

3 Data

We construct our data set by following the web-scraping procedure already used by Liberati and Marinelli (2021) but on an longer time span extending until the end of 2022. The data set includes only green bonds *stricto sensu* listed on dedicated ESG bond market segments of the main stock exchanges around the world and those whose information is exploitable from other public data sources.[9] Since the same security might be listed on different platforms or used by more reports we drop duplications and we obtain an initial list of green debt securities which comprises 20,045 non-duplicated ISIN codes.[10] covering the period from June 2017 to December 2022.

We collect information on green and non-green securities, on issuers' characteristics from the Bank of Italy Security Data Base and the European Central Bank Centralised Security Data Base (CSDB) where we find 5,711 out of the 20,045 initial green bonds for a total volume of euro 1,769 billions (see Table A.2). This represents the dataset used for the yields curve and *greenium* estimation presented in section 4 and subsection 5.2, respectively.

Finally, we expand our database with information on issuers' and holders' characteristics: some holders' features are obtainable both at individual and sectoral level drawing from Bank of Italy supervisory statistics on individual banks' and mutual funds' balance-sheets and from the Bank of Italy Security Holdings Statistics (SHS-S) for portfolios' information of other institutional sectors (insurance corporations and pensions funds, households and non-financial corporations), respectively. By consecutively merging all databases we obtain a sample 3,072 green bonds corresponding to a issued volume of euro 1,473.5 billions (see Table A.3). This represents the dataset used for the disequilibrium model employed in subsection 5.1.

4 Yield Curves Analysis

As described in section 2, the empirical literature on *greenium* highlights mixed results. In order to provide first evidence on this aspect, we carried out the estimation of the yield curves' using a dataset which consists of monthly observations on the prices of debt securities issued by financial and non-financial corporations resident in the euro area and in the rest of the world. Data are drawn from the Bank of Italy Security Data Base reporting information on end-of-month instruments' prices and yields at single security (ISIN code) level. The descriptive statistics on

[7] Similar shares are found in the previous editions of the survey.

[8] See Ito and Ueda (1981) and Burlon et al. (2016) for examples of non-Walrasian models applied to the credit market.

[9] For more details on the data construction see Liberati and Marinelli (2021) in which the analysis is related to the broader sample of ESG bonds. Table A.1 reports the complete list of the data sources.

[10] In some cases the ISIN codes are not available. In particular, for US and Canadian securities we retrieve their CUSIP codes – specific identifiers used by the North-American States – and convert them into ISIN codes by using the Luhn algorithm specified in ISO/IEC 7812-1.

the distribution of the yields-to-maturity of the debt securities selected into the sample (Table A.4 and Table A.5) indicate that the euro-denominated green bonds are characterized by higher yields in the first two years of the sample period and by lower yields in the subsequent two years. On the other hand, the USD-denominated green securities issued by corporations show lower yields over the whole sample whereas an opposite picture arises by looking at those issued by the Government.

The Nelson and Siegel (1987) yield curve model is the one we chose to characterize the relationship between yields and residual maturities of the debt securities in our sample. The Nelson-Siegel approach and its Svensson (1994) refinement are the two most widely used specifications across central banks for the estimation of yield curves, as summarized by Bank for International Settlements (2005). According to such model, the yield $y_t(\tau)$ of a zero coupon bond with time to maturity τ at the end of month t is given by a function of four parameters:

$$y_t^{NS}(\tau_s) = \beta_{1,t} - \beta_{2,t}\left[\frac{1 - exp(-\lambda_t\tau_s)}{\lambda_t\tau_s}\right] - \beta_{3,t}\left[\frac{1 - exp(-\lambda_t\tau_s)}{\lambda_t\tau_s} - exp(-\lambda_t\tau_s)\right] \tag{1}$$

where $\beta_{1,t}$, $\beta_{2,t}$ and $\beta_{3,t}$ can be seen as three latent factors whose loadings are represented by $L_1(\tau,\lambda) = 1$, $L_2(\tau,\lambda) = \frac{1-exp(-\lambda\tau)}{\lambda\tau}$ and $L_3(\tau,\lambda) = \frac{1-exp(-\lambda\tau)}{\lambda\tau} - exp(-\lambda\tau)$. The three latent factors can be interpreted in terms of curve characteristics, the level L_t, the slope S_t and the curvature C_t respectively associated to the long-term, short-term and medium-term factors. Such interpretation derives from the observation of the factor loadings with the first one being constant and equal to one, thus the corresponding factor $\beta_{1,t}$ can be viewed as a long-term factor. The second loading is equal to one on the shortest maturity and rapidly decays to zero, hence it can interpreted as the short-term factor. The third factor loading is equal to zero at the beginning, increases, reaches its maximum and finally decays to zero in the long-term, which leads to the medium-term interpretation of the corresponding factor. The functional form of the third factor is governed by the λ parameter determining the maturity that maximizes the loading. The estimation entails the minimization of the residuals of the Nelson-Siegel specification[11] with respect to the vector of unknown parameters $\begin{pmatrix}\beta_1 & \beta_2 & \beta_3 & \lambda\end{pmatrix}$.

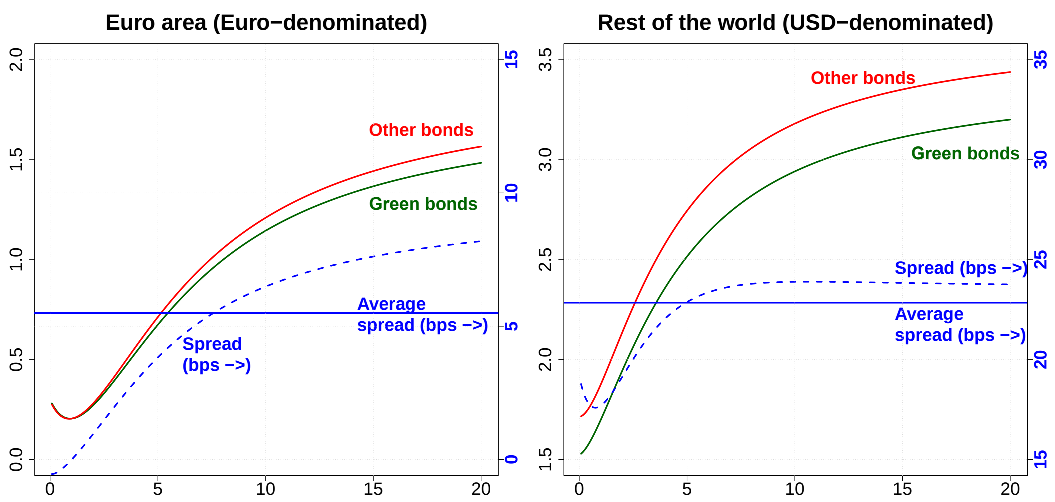
$$\begin{aligned} \underset{\{\beta_{1,t},\beta_{2,t},\beta_{3,t},\lambda_t\}}{\text{minimize}} \quad & Med\left(\left|y_t(\tau_s) - y_t^{NS}(\tau_s)\right|\right) \\ s.t. \quad & \beta_{1,t} > 0 \\ & \beta_{1,t} + \beta_{2,t} > 0 \\ & \lambda_t > 0 \end{aligned} \tag{2}$$

In accordance with other studies such as Ibanez (2015), three constraints were imposed to the optimization, i.e. a positive λ and $\beta_1 > 0$ and $\beta_1 + \beta_2 > 0$. In each monthly reference date between June 2017 and December 2022 we run the estimation on the original sample and subsequently draw 250 samples of securities belonging to 8 categories based on the disaggregation by green/non-green, currency of denomination (euro and USD) and institutional sector of the issuer (non-financial and financial corporations). We omit the securities issued by the government sector as the sample would be extremely small giving rise to unreliable estimates. The securities selected into each of the 8 subsamples are those with an investment grade rating, i.e. equal or

[11] The model has been estimated for each month of the sample period using a non-linear optimization procedure aimed at minimizing the median absolute errors (MAE) through the Augmented Lagrangian Minimization Algorithm for optimizing smooth nonlinear objective functions with constraints. The estimation is carried out on the subsamples of green euro and USD-denominated securities and of conventional euro and USD-denominated ones issued by non-financial and financial corporations.

over $BBB-$ whereas all the remaining securities with a rating below that threshold have not been considered in the estimation of the yield curve. By doing so, we make sure that the securities are homogeneous in terms of riskiness. The result of the estimation is a data set of more than 132,000 observations[12] comprising the estimated vector of parameters $\begin{pmatrix}\beta_1 & \beta_2 & \beta_3 & \lambda\end{pmatrix}$ for each of the 8 categories of bonds in each month of the sample period. Next we evaluate the 132,000 estimated yield curves at each residual maturity between 1 month and 20 years (240 residual maturities in 1 month steps). The estimation results are reported in Table A.7 with the break-down of the sample into the 4 subcategories of instruments by type and issuer country of residence. The final estimate of the yield curve is obtained by collapsing the data set by instrument, reference area, reference date and residual maturity through the calculation of the mean of the 250 yields corresponding each to one of the drawn samples.

Figure 1: **Average yield curves between 2017 and 2022 - Non-financial corporations**
(percentage values and basis points)



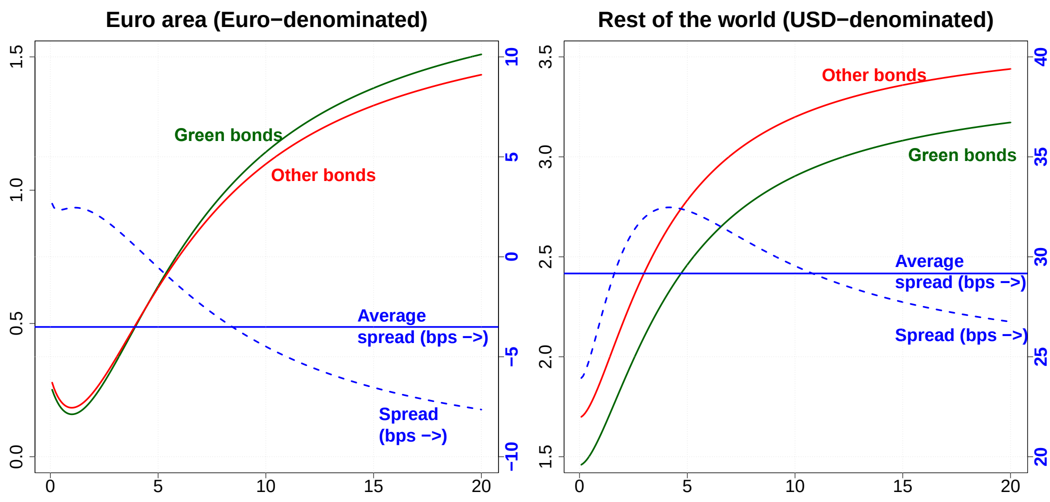
Source: elaborations on data drawn from the Bank of Italy Security Data Base. This figure depicts the average estimated yield curves estimated according to the Nelson-Siegel specification using end-of-month yields-to-maturity for green and non-green debt securities between June 2017 and December 2022. The figure depicts the average yields by residual maturity – expressed in years – of green and non-green instruments and their difference in terms of basis points over the sample period.

Overall, once we calculate the average values of the yields across the various maturities, we can compare the average yield curve derived from the subsample of green debt securities to the one derived from the subsample of non-green bonds issued by non-financial corporations distinguishing euro-denominated from USD-denominated instruments. The average yield curve of euro-denominated green bonds lies below the non-green curve (Figure 1) resulting in a constantly negative spread between green and non-green bonds. More precisely, the yield spread on euro-denominated bonds increases in the residual maturity of the instruments: for the up-to-one-year maturity no premium is highlighted, then it rapidly grows to 4 basis points at 5 years and ends at 7 basis points at the 20-year maturity (Figure 1, left panel). The yield spread between USD-denominated green bonds and non-green bonds starts from high values at very short maturities and subsequently increases at an analogous pace reaching 24 basis points at 20-year residual

[12] 66 reference dates between June 2017 and December 2022 × 251 samples (250 drawn samples + the original one) × 8 categories (green/conventional-sector-currency).

maturity (Figure 1, right panel). The same exercise has been carried out on the sample of securities issued by financial corporations and its results are shown in Figure 2 with the same currency breakdown. For Euro-denominated green bonds the yield of the green bonds is greater than that related to the conventional securities at very short maturities whereas an opposite picture arises after 6 years. Hence, we find a *greenium* on euro-denominated securities which is decreasing in the residual maturity with an overall mean value of the yield spread is slightly less then zero (Figure 2, left panel). On the other hand the average spread is 28 basis points for USD-denominated bonds with the range being between 24 and 33 basis points depending on the maturity (Figure 2, right panel).

Figure 2: **Average yield curves between 2017 and 2022 - Financial corporations**
(percentage values and basis points)



Source: elaborations on data drawn from the Bank of Italy Security Data Base. This figure depicts the average estimated yield curves estimated according to the Nelson-Siegel specification using end-of-month yields-to-maturity for green and non-green debt securities between June 2017 and December 2022. The figure depicts the average yields by residual maturity – expressed in years – of green and non-green instruments and their difference in terms of basis points over the sample period.

5 Econometric analysis

This section presents an econometric analysis to test whether a persistent excess demand in the secondary market of green securities (subsection 5.1) exists and a security-level panel regression analysis with high-dimensional fixed effects (subsection 5.2) to corroborate results of the yield-curve-based approach shown in section 4 by focusing on the role of the Covid-19 shock.

5.1 Is there an excess demand for green bonds?

The recent developments of the green bond market reflected both the increase of green securities' issuances and the appetite for sustainable assets due to preferences' changes of investors. Disentangling the contribution of the supply and demand sides of the market is a crucial issue in order to understand whether excess demand for green bonds plays a significant role. We propose a non-market clearing approach based on a disequilibrium model á la Fair and Jaffee (1972) and Maddala and Nelson (1974) to estimate a system that consists of a demand equation, a supply equation and a "short-side rule" for which the observed quantity of green bonds is the minimum between the demand and supply quantities. Differently from an equilibrium model where a market clearing rule is implemented, in the disequilibrium model the securities' price is an exogenous variable[13] and possible mismatches between supply and demand might lead to aggregate excess supply or demand.

5.1.1 The supply and demand equations

We define a supply function f^S as the correspondence between seller, buyer and match-specific characteristics (X) and the amount $Q^S_{i,h,s,t}$ of green security s that the seller i prefers to sell to the buyer h at time t. Similarly, we define a demand function f^D as a correspondence between seller, buyer and the match-specific characteristics and the amount $Q^D_{i,h,s,t}$ of green security s that the buyer h prefer to buy from seller i at time t. Formally:

$$Q^S_{i,h,s,t} = f^S\left(X^S_{i,h,t}, X^{S,D}_{i,h,s,t}\right) + \varepsilon^S_{i,h,s,t} \tag{3}$$

$$Q^D_{i,h,s,t} = f^D\left(X^D_{i,h,t}, X^{S,D}_{i,h,s,t}\right) + \varepsilon^D_{i,h,s,t} \tag{4}$$

Equation 3 and Equation 4 specify as the supplied and demanded quantities depend on both supply and demand specific variables as well as regressors that are common to both sides of the market. In particular, $X^S_{i,h,t}$ are supply specific factors that can depend on the seller, buyer or match, respectively as well as $X^D_{i,h,t}$ are demand specific factors depending on the seller, buyer or match, respectively. Then, common characteristics ($X^{S,D}_{i,h,s,t}$) may be related to the agents or securities and issuers' features; notice that among the bonds' characteristics there are the securities' prices $P_{s,t}$ computed as the inverse of the yields-to-maturity of the bonds.

A peculiarity of the bond market with respect to the credit one is that a generic issuer can issue more securities that can be exchanged among different holders at the same market conditions. Hence, on the primary market the transaction counterparties are issuers and investors whereas on the secondary market – which is the focus of this work – the matches arise between sellers and buyers who might have information on the main features of the issuer and on the issued securities. Hence, sellers could not observe some of the characteristics of the buyers and vice versa. After the identification of green bonds (section 3), we obtain characteristics for securities from CSDB and basic information on issuers and holders (country of residence and ESA 2010 Sector) from SHS-S. In particular, we interpret the current (at time t) securities' holders as the buyers and those of the previous period (at time $t-1$) as sellers.

Since the same security could be held from the same sectors across different countries, the observational units of our final dataset are constructed by the unique combination of the ISIN code, the ESA sector and the residence country of the holders. The time dimension is defined on quarterly frequency from 2017:q2 to 2022:q4.

[13] In this respect, Maddala (1986) explains as the class of "directional" disequilibrium models using a sample separation rule based on the sign of price variation to split data in excess demand state with respect to those in excess supply state, is logically inconsistent since implies that the price is endogenous and the number of equations used to estimate the model is not enough. To restore a consistency a price determination equation should be introduced.

5.1.2 The "short side" rule and estimation results

To close the non-Walrasian model, Equation 5 introduces a "short-side rule" by which the observed quantity of green bonds is the minimum between the demand and supplied quantities; to the best of our knowledge, this is the first paper that applies this methodology to this market. Hence,

$$Q_{i,h,s,t} = min\left(Q^S_{i,h,s,t}, Q^D_{i,h,s,t}\right) \tag{5}$$

As long as there is at least a specific supply variable and a specific demand variable the system of Equation 3, Equation 4 and Equation 5 is identified. Finally, supply and demand' shocks ($\varepsilon^S_{i,h,s,t}$ and $\varepsilon^D_{i,h,s,t}$, respectively) are assumed uncorrelated. Both sellers and buyers do know the characteristics of the green securities: price, rating (RATING), the residual maturity (MATURITY) and the total issued amount (AMOUNT, used as a proxy for the liquidity status of the issuance) and the currency-time fixed effects enter both in the demand and supply equations. Similarly, the main characteristics of the issuers (country of residence and the institutional sector) are common knowledge in the market.

On the one hand, time-varying fixed effects on the holders (country of residence and institutional sector) are assumed as demand specific factors. Since we do not have any specific information on the sellers, we consider the *lagged* share of the holdings' outstanding amount out of the total value of the issued volumes for each security by residence country and economic sector of the holders. Table A.8 reports the main descriptive statistics of our final sample of green securities and their issuers with reference to the final quarter of each year.

Estimations' results of the disequilibrium model are reported in Table 1. We consider logarithmic values both for quantities (QUANTITY and AMOUNT) and prices (PRICE). First we estimate a model where we do not control for the pandemic: by looking at the supply side of the model (Table 1, Column 3) we can observe a positive and statistically significant coefficient associated both to (PRICE) and to the total amount issued; similarly, also the residual maturity and the quadratic form of securities' rating do have a positive and significant impact on green bonds' supply. On the other hand, as expected, the total issued amount and the rating have positive significant impacts on the green bond demand (Table 1, Column 1). Furthermore, non-linear effects of the residual maturity are confirmed whereas the coefficient associated to the price is not statistically significant.[14] In this respect, the outbreak of the pandemic might have affected the sign and magnitude of demand and supply.

In order to assess the role of the Covid-19 shock, we introduce a pandemic indicator variable being equal to one from March 2020 and zero before. Results for the demand equation (Table 1, Column 2) provide evidence for the usual relationship between prices and quantities: the coefficient associated to PRICE is always negative and statistically significant. Furthermore, the coefficient associated to the interaction between COVID and PRICE is significant and positive for both sides of the market (Table 1, Columns 2 and 4). Such evidence follows the usual economic mechanisms for the supply equation whereas we do not find the usual expected inverse relationship for the demand equation: this result – consistent with the *greenium puzzle* – could depend on the fact that investors' preferences for sustainable assets might be properly incorporated in the prices. All in all, after the Covid-19 shock, investors are willing to buy more green securities at the price set before the pandemic or to maintain the same orders if prices increase.[15]

Our results can be also summarized in aggregate form with the derivation of the predicted demand and supply of green bonds based on the estimated models. Overall, the minimum quantity closing the disequilibrium model described in equation Equation 5 is always demand-driven over the entire sample period (Figure 3). Excess demand slightly increased after the Covid-

[14] The same results are obtained by using the linear form of the rating.

[15] Faccini et al. (2023) find that transition climate risks are not well priced in U.S. stocks.

Table 1: Disequilibrium model - Estimation Results

This table reports the estimation results of a non-Walrasian disequilibrium model a la Maddala and Nelson (1974). The explanatory variables are the price of the securities (PRICE), the log amount issued AMOUNT, the residual maturity of the security in terms of years (MATURITY), the quadratic form of the RATING mapped into a numeric sequence of integers and the COVID indicator variable being equal to one from March 2020 and zero before.

QUANTITY	DEMAND EQUATION COVID		SUPPLY EQUATION COVID	
	NO	YES	NO	YES
PRICE	-0.0042	-0.0326***	0.0330***	-0.0125
	(0.0046)	(0.0078)	(0.0058)	(0.0096)
COVID		0.4225		-0.0186
		(0.7703)		(0.4913)
COVID x PRICE		0.0392***		0.0630***
		(0.0086)		(0.0106)
AMOUNT	0.2105***	0.2102***	0.0974***	0.0970***
	(0.0038)	(0.0038)	(0.0048)	(0.0048)
MATURITY	-0.0097	-0.0062	0.0317***	0.0374***
	(0.0074)	(0.0075)	(0.092)	(0.093)
MATURITY^2	-0.0023**	-0.0027***	-0.0015	-0.0022*
	(0.0009)	(0.0009)	(0.0011)	(0.0011)
MATURITY^3	0.0001***	0.0002***	0.0001	0.0001**
	(0.0000)	(0.0000)	(0.0000)	(0.0000)
RATING^2	0.0010***	0.0010***	0.0023***	0.0021***
	(0.0001)	(0.0001)	(0.0001)	(0.0001)
Issuer Country x Time FE	Yes	Yes	Yes	Yes
Issuer Sector x Time FE	Yes	Yes	Yes	Yes
Currency x Time FE	Yes	Yes	Yes	Yes
Holder Country x Time FE	Yes	Yes	No	No
Holder Sector x Time FE	Yes	Yes	No	No
Lagged share by Holder Country	No	No	Yes	Yes
Lagged share by Holder Sector	No	No	Yes	Yes
N	300,552	300,552	300,552	300,552
R^2	0.403	0.403	0.403	0.403

Standard errors in parentheses
* $p < .10$, ** $p < .05$, *** $p < .01$

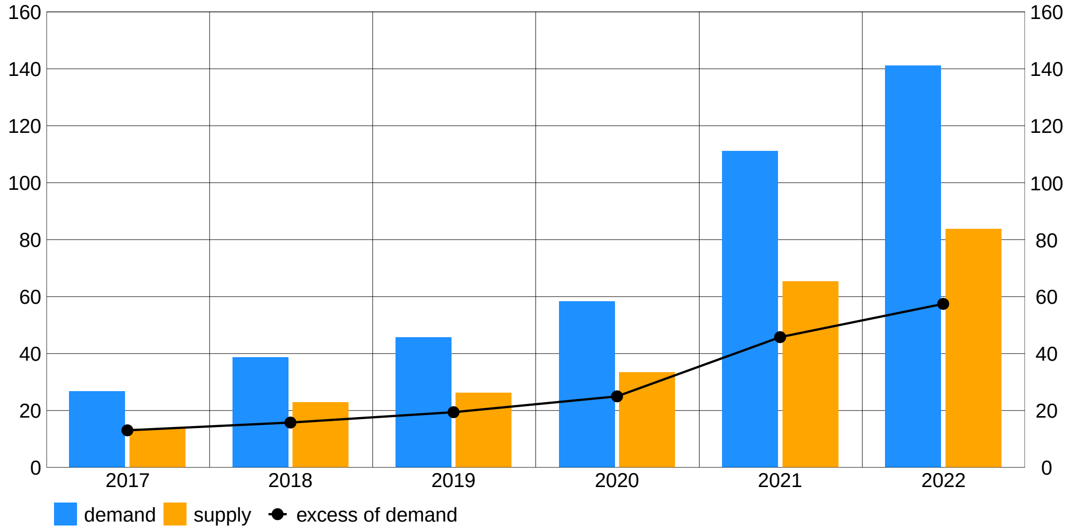
19 shock and further rose during 2021 whereas at the end of 2022 we observe a deceleration given by flatter line between the two years.[16] By using a simple t-test, Table A.9 reveals the significance of the pandemic outbreak since the differences of predicted means of excess demand related to the sample group observations before and post Covid-19 shock are statistically significant.

5.2 The Greenium Puzzle

The estimation of the yield curves, albeit carried out on rather homogeneous cross-section samples of securities, might be subject to some factors we do not control for, as shown by Table A.6 where

[16]The Next Generation EU (NGEU) was adopted by the European Commission in July 2020: as part of NGEU, the first green bonds' issuance by the European Commission program was in October 2021. Hinsche (2021) finds an expected *greenium* for the NGEU green bonds. Moreover, Eliet-Doillet and Maino (2022) find that after the ECB announcement to incorporate climate criteria into its unconventional monetary policy operations, ECB-eligible (for asset purchase programs) green bonds' yield-to-maturity (outstanding amounts) decreased (increases) compared to equivalent conventional bonds.

Figure 3: **Predicted excess demand of green bonds**
(euro billions)



Source: authors' calculations based on model "COVID = YES".

one can notice that, depending on the particular subsample we are focusing on, green bonds are structurally different from conventional ones. Green securities could be on average more liquid and the lower yields may reflect such feature. We have carefully selected a subsample of the available securities based on their investment grade rating, this nonetheless could be not enough if green bonds are characterized by higher ratings even within the investment grade subsample. A third factor we have not been considering is the security listing on an exchange market thus leading on principle to higher transparency and to a more reliable observed price. We could easily solve such potential pitfalls by selecting narrower samples of securities for the estimation of the yield curve or we could run our optimization procedures by minimizing a weighted measure of errors accounting for the amount issued of the security. A viable alternative could be a regression analysis based on the data at security level with the following linear fixed effects model specification accounting for all the above-mentioned confounding factors:

$$\begin{aligned} y_{s,t} &= \gamma_e GREEN_{s,t} + \gamma_c COVID_t + \gamma_p POST\_COVID_t + \\ &+ \theta^\intercal X_{s,t} + \eta_{i,t} + \eta_{c,t} + \eta_{u,t} + \varepsilon_{s,t} \end{aligned} \tag{6}$$

where the yield to maturity of security s at the end of month t is regressed on the GREEN indicator variable being equal to one for the securities classified as green and zero otherwise. Additionally, the model includes an $X_{s,t}$ vector of time-varying control variables consisting of a third degree polynomial in the residual maturity $M_{s,t}$, the indicator variable LISTED equal to one if the security is traded on an exchange, the quadratic form of the rating of the security and the logarithm of the issued amount. The model is saturated with issuer-time fixed effects ($\eta_{i,t}$) in order to account for unobserved time-varying characteristics of the issuer such as managerial skills, size of the firm, financial structure, etc... We further saturate the model with country-time fixed effects ($\eta_{c,t}$) to account for economy-wide shocks and the financial cycle affecting the dynamics of GDP, real interest rates, government debt. Finally we control for the currency of denomination of the securities which usually coincides with the country but in the case of monetary unions and of international corporations issuing in several currencies could a factor to control for ($\eta_{u,t}$). The model is estimated on the three institutional sectors, i.e. non-financial corporations, financial corporations and the government sector. The specification is additionally enriched by the interaction of the GREEN indicator variable with a three-level pandemic factor variable being equal to zero in the pre-pandemic period (before March 2020), equal to one during the pandemic (between March 2020 and March 2022; COVID) and equal to two for the period following the first quarter of 2022 (POST COVID) in order to capture the end of the emergency state in most of the countries in the world and the lift of all the restrictions.[17] Such variables are interacted with the GREEN indicator so as to capture the effects of the Covid-19 pandemic on the green market yields and isolate them from the base difference. The GREEN interaction with the post pandemic dummy should account for the normalization period for which we want to investigate whether the greenium can be still observed.

In the baseline model we find that if the bond is traded on an exchange then, as expected, this leads to a lower yield of 3-14 basis points depending on the sector (Table 2). A higher rating determines a lower yield as this incorporates lower risk premia, the larger the amount issued, the lower the yield which is attributable to benefits of securities that are traded in larger volumes and by a larger number of investors. The coefficients of the GREEN indicator variable are all statistically significant across the three sectors in the baseline model. The *greenium*, i.e. the difference between the yields on green bonds and the yields on their non-green counterparts, is estimated to be 5 basis points for the non-financial corporations, is even higher (14 basis points) for financial corporations whereas is smaller the government sector (3 basis points). On the one hand, such findings are slightly greater than the one found by Zerbib (2019) that on average finds a *greenium* equal to 2 basis points by running a matching estimation on Bloomberg database; then they show that such negative premium is more pronounced for low-rating bonds and when the issuer is a financial institution. On the other hand, our results are lower than those reported by Fatica et al. (2021) who run a regression analysis on a Dealogic DCM and CBI data: by controlling for maturity, currency, rating and bond size they find a large *greenium* for non financial institutions (22 bps) and no significant difference for the financial ones. As for the securities issued by Governments, our results are consistent with anecdotal findings by Banca d'Italia (2021) related the emission the first Italian green bond in March 2021.

Next, we investigate whether the Covid-19 shock had an effect on the yield spread between green securities and conventional counterparts. To this end we interact three-level factor pandemic indicator variable with the GREEN indicator in order to estimate the possible additional premium during the pandemic period following the Covid-19 outbreak and, subsequently, after the end of the emergency state and the loosing of the restrictions experienced in many countries in the world (following the first quarter of 2022). The magnitude and the significance of all the control variables remain the same as in the baseline model. We find that the base effect of the green label on the yield remains quite unchanged across sectors and that the pandemic shock has induced an additional negative premium on green bonds issued by non-financial and financial corporations (5 basis points) whereas we do not find evidence of an additional negative premium on those issued by the government sector (GREEN x COVID). Hence, by observing only the pandemic period between March 2020 and March 2022, the estimation results of the model seem to provide a picture which is mostly consistent with the *wake-up call* hypothesis. However, after the end of the emergency state, the interaction between the GREEN indicator variable and the pandemic one (GREEN x POST COVID) more than offsets the extra-premium found during the pandemic phase for the green bonds issued by non-financial and financial corporations with a reduction of the negative *greenium* by 6 and 7 basis points, respectively, when compared to the pre-pandemic period. The post pandemic rebound of the *greenium* suggests that investors only temporarily took into account climate concerns or that they overreacted with the pricing

[17]For example, in Italy the emergency state ended on 31th March 2022.

Table 2: **Determinants of Bond Yields - Debt Securities Sample**

This table reports the estimation results of a linear fixed effects model where the outcome variable is the yield to maturity of a security measured at the end of the month. The explanatory variables are the residual maturity of the security in terms of years (MATURITY), the indicator variable LISTED being equal to one if the security is listed on an exchange, the RATING mapped into a numeric sequence of integers, the log amount issued AMOUNT, the indicator variable GREEN and the three-level pandemic factor variable being equal to zero before March 2020, equal to one between March 2020 and March 2022 (COVID) and equal to two for the period following the first quarter of 2022 (POST COVID).

	Corporations		Government	Corporations		Government
	Non-financial	Financial		Non-financial	Financial	
	(1)	(2)	(3)	(4)	(5)	(6)
GREEN	-0.0475***	-0.1391***	-0.0298**	-0.0387***	-0.1354***	-0.0251
	(0.0064)	(0.0071)	(0.0133)	(0.0137)	(0.0149)	(0.0247)
GREEN x COVID				-0.0504***	-0.0540***	-0.0092
				(0.0163)	(0.0182)	(0.0319)
GREEN x POST COVID				0.0641***	0.0699***	-0.0028
				(0.0184)	(0.0197)	(0.0350)
LISTED	-0.0349***	-0.0538***	0.0074	-0.0349***	-0.0539***	0.0074
	(0.0030)	(0.0040)	(0.0061)	(0.0030)	(0.0040)	(0.0061)
RATING	-0.3294***	-0.2191***	-0.2467***	-0.3293***	-0.2191***	-0.2467***
	(0.0026)	(0.0008)	(0.0022)	(0.0026)	(0.0008)	(0.0022)
AMOUNT	-0.0251***	-0.0844***	-0.0100***	-0.0250***	-0.0844***	-0.0100***
	(0.0006)	(0.0011)	(0.0005)	(0.0006)	(0.0011)	(0.0005)
MATURITY	0.2841***	0.2881***	0.1909***	0.2840***	0.2880***	0.1909***
	(0.0019)	(0.0025)	(0.0041)	(0.0019)	(0.0025)	(0.0041)
$MATURITY^2$	-0.0128***	-0.0140***	-0.0048***	-0.0128***	-0.0140***	-0.0048***
	(0.0002)	(0.0003)	(0.0005)	(0.0002)	(0.0003)	(0.0005)
$MATURITY^3$	0.0002***	0.0003***	-0.0000	0.0002***	0.0003***	-0.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0000)
Issuer x Time FE	Yes	Yes	No	Yes	Yes	No
Country x Time FE	Yes	Yes	Yes	Yes	Yes	Yes
Currency x Time FE	Yes	Yes	Yes	Yes	Yes	Yes
N	430,146	456,655	133,024	430146	456,655	133,024
Adjusted R^2	0.939	0.862	0.908	0.939	0.862	0.908

during the pandemic with a subsequent adjustment in the opposite direction once the pandemic has come to conclusion.

6 Conclusions

Green bonds are certainly bound to be a key financial instrument to channel financial resources into green, sustainable and social projects. The adoption of such instruments by corporations and governments has rapidly increased in the last five years, with a dramatic expansion of the volumes issued and of the number of issuers operating on the market. We compiled a comprehensive list of green securities, partly web-scraped and partly hand-collected, by exploiting only publicly available information from a wide variety of online sources. Next we merged this list with microdata used for official statistics on securities' holdings and prices as well as banks' and investment funds' balance-sheets.

First, by applying a non-Walrasian disequilibrium model we show that in the secondary market of green bonds a persistent excess demand exists. In this respect, demand is mainly affected by securities' prices and the liquidity of the market as well as by the issuers' financial conditions. Second, we analyzed yields on green debt securities in order to contribute to the literature debate on the *greenium puzzle*, i.e. the negative premium on green bonds when compared to conventional ones with the same characteristics in terms of liquidity, riskiness and maturity. We find evidence for a statistically significant negative premium on green bonds with heterogeneity across sectors and over time. The negative premium is estimated to be 4 basis points for the non-financial corporations whereas it is higher (14 basis points) for the financial sector. We also find evidence of an additional negative premium equal to 5 basis points following the Covid-19 shock with a rebound after the end of the pandemic.

7 Bibliography

Agliardi, E. and Agliardi, R. (2021). Corporate green bonds: Understanding the greenium in a two-factor structural model. *Environmental and Resource Economics*, 80:257–278.

Alessi, L., Ossola, E., and Panzica, R. (2021). What greenium matters in the stock market? the role of greenhouse gas emissions and environmental disclosures. *Journal of Financial Stability*, 54:100689.

Arat, E., Hachenberg, B., Kiesel, F., and Schiereck, D. (2023). Greenium, credit rating, and the covid19 pandemic. *Journal of Asset Management.*

Ayaydin, H., Danisoglu, S., and Nuray Guner, Z. (2022). For the love of the environment: An analysis of green versus brown bonds during the covid-19 pandemic. *Finance Research Letters*, 47(Part A):102576.

Bachelet, J. M., Becchetti, L., and Manfredonia, S. (2019). The green bonds premium puzzle: The role of issuer characteristics and third-party verification. *Sustainability*, 11(4).

Baker, M., Bergstresser, D., Serafeim, G., and Wurgler, J. (2022). The pricing and ownership of u.s. green bonds. *Annual Review of Financial Economics.*

Banca d'Italia (2021). Financial Stability Report. Financial Stability Report 1-2021, Banca d'Italia.

Bank for International Settlements (2005). Zero-coupon yield curves: technical documentation. BIS Papers 25, Bank for International Settlements.

Barua, S. and Chiesa, M. (2019). Sustainable financing practices through green bonds: What affects the funding size? *Business Strategy and the Environment*, 28(6):1131–1147.

Burlon, L., Fantino, D., Nobili, A., and Sene, G. (2016). The quantity of corporate credit rationing with matched bank-firm data. Temi di discussione (Economic working papers) 1058, Bank of Italy, Economic Research and International Relations Area.

Cicchiello, A. F., Cotuno, M., Monferrá, S., and Perdichizzi, S. (2022). Credit spreads in the european green bond market: A daily analysis of the covid19 pandemic impact. *Journal of International Financial Management & Accounting*, 33:357–375.

Cui, T., Suleman, M. T., and Zhang, H. (2022). Do the green bonds overreact to the covid-19 pandemic? *Finance Research Letters*, 49:103095.

Doronzo, R., Siracusa, V., and Antonelli, S. (2021). Green bonds: the sovereign issuers' perspective. Markets, Infrastructures, Payment Systems 3, Bank of Italy.

Dutordoir, M., Li, S., and Neto, J. Q. F. (2023). Issuer motivations for corporate green bond offerings. *British Journal of Management*, 00:1–25.

Ehlers, T., Mojon, B., and Packer, F. (2020). Green bonds and carbon emissions: exploring the case for a rating system at the firm level. *BIS Quarterly Review.*

Ehlers, T. and Packer, F. (2017). Green bond finance and certification. *BIS Quarterly Review.*

Eliet-Doillet, A. and Maino, A. (2022). Can unconventional monetary policy contribute to climate action? Research Paper Series 22-35, Swiss Finance Institute.

Faccini, R., Matin, R., and Skiadopoulos, G. (2023). Dissecting climate risks: Are they reflected in stock prices? *Jornal of Banking & Finance*, page 106948.

Faiella, I. and Malvolti, D. (2020). The climate risk for the finance in Italy. Questioni di Economia e Finanza (Occasional Papers) 545, Bank of Italy, Economic Research and International Relations Area.

Fair, R. C. and Jaffee, D. M. (1972). Methods of estimation for markets in disequilibrium. *Econometrica*, 40(3):497–514.

Fama, E. F. (1998). Determining the number of priced state variables in the icapm. *Journal of Financial and Quantitative Analysis*, 33(2):217–231.

Fama, E. F. and French, K. R. (2007). Disagreement, tastes, and asset prices. *Journal of financial economics*, 83(3):667–689.

Fatica, S., Panzica, R., and Rancan, M. (2021). The pricing of green bonds: are financial institutions special? *Journal of Financial Stability*, 54:100873.

Ferriani, F. (2023). Issuing bonds during the covid-19 pandemic: is there an esg premium? *International Review of Financial Analysis*, 88:102653.

Ferriani, F. and Natoli, F. (2020). Esg risks in times of covid-19. *Applied Economics Letters*, pages 1–5.

Flammer, C. (2021). Corporate green bonds. *Journal of Financial Economics*, 142.

Gianfrate, G. and Peri, M. (2019). The green advantage: exploring the convenience of issuing green bonds. *Journal of Cleaner Production*, 219:127–135.

Giordano, R., Pericoli, M., and Tommasino, P. (2013). Pure or wake-up-call contagion? Another look at the emu sovereign debt crisis. *International Finance*, 16(2):131–160.

Goldstein, M. et al. (1998). *The Asian financial crisis.* Washington, DC: Institute for International Economics.

Hachenberg, B. and Schiereck, D. (2018). Are green bonds priced differently from conventional bonds? *Journal of Asset Management*, 19:371–383.

Hammoudeh, S., Ajmi, A. N., and Mokni, K. (2020). Relationship between green bonds and financial and environmental variables: a novel time-varying causality. *Energy Economics*, 92:104941.

Hinsche, I. C. (2021). A greenium for the next generation eu green bonds analysis of a potential green bond premium and its drivers. CFS Working Paper 663, Center for Financial Studies.

Huang, C., Dekker, D., and Christopoulos, D. (2023). Rethinking greenium: A quadratic function of yield spread. *Finance Research Letters*, 54:103710.

Ibanez, F. (2015). Calibrating the Dynamic Nelson-Siegel Model: A Practitioner Approach. MPRA Paper 68377, University Library of Munich, Germany.

Ito, T. and Ueda, K. (1981). Tests of the equilibrium hypothesis in disequilibrium econometrics: An international comparison of credit rationing. *International Economic Review*, 22:691–708.

Kapraun, J., Latino, C., Scheins, C., and Schlag, C. (2021). (in)-credibly green: Which bonds trade at a green bond premium? Technical report.

Karpf, A. and Mandel, A. (2018). The changing value of the 'green' label on the us municipal bond market. *Nature Climate Change*, 8:161–165.

Liberati, D. and Marinelli, G. (2021). Everything you always wanted to know about green bonds (but were afraid to ask). Questioni di economia e finanza (occasional papers), Bank of Italy, Economic Research and International Relations Area.

Löffler, K. U., Petreski, A., and Stephan, A. (2021). Drivers of green bond issuance and new evidence on the "greenium". *Euroasian Economic Review*, 11:1–24.

Maddala, G. (1986). Disequilibrium, self-selection, and switching models. In Griliches, Z. and Intriligator, M. D., editors, *Handbook of Econometrics*, volume 3, chapter 28, pages 1633–1688. Elsevier, 1 edition.

Maddala, G. S. and Nelson, F. D. (1974). Maximum likelihood methods for models of markets in disequilibrium. *Econometrica*, 42(6):1013–1030.

Maltais, A. and Nykvist, B. (2020). Understanding the role of green bonds in advancing sustainability. *Journal of Sustainable Finance & Investment*, pages 1–20.

Nelson, C. R. and Siegel, A. F. (1987). Parsimonious modeling of yield curves. *Journal of business*, pages 473–489.

Pastor, L., Stambaugh, R. F., and Taylor, L. A. (2022). Dissecting green returns. *Journal of Financial Economics*, 146(2):403–424.

Pietsch, A. and Salakhova, D. (2022). Pricing of green bonds: drivers and dynamics of the greenium. Working Paper Series 2728, European Central Bank.

RBC (2021). Responsible investment survey. Technical report, RBC Global Assessment Management.

Schnabel, I. (2020). Never waste a crisis: Covid-19, climate change and monetary policy. Speech by Isabel Schnabel, Member of the Executive Board of the ECB, at a virtual roundtable on Sustainable Crisis Responses in Europe, organised by the INSPIRE research network, Frankfurt am Main.

Svensson, L. E. (1994). Estimating and interpreting forward interest rates: Sweden 1992-1994. NBER Working Papers 4871, National Bureau of Economic Research.

Tang, D. Y. and Zhang, Y. (2020). Do shareholders benefit from green bonds? *Journal of Corporate Finance*, 61.

UNEP (2021). State of finance for nature 2021. Report, United Nations Environment Programme.

Wulandari, F., Schäfer, D., Stephan, A., and Sun, C. (2018). The impact of liquidity risk on the yield spread of green bonds. *Finance Research Letters*, 27:53–59.

Yi, X., Bai, C., Lyu, S., and Lu, D. (2021). The impacts of the covid-19 pandemic on china's green bond market. *Finance Research Letters*, page 101948.

Zaghini, A. (2023). Unconventional green. CFS Working Paper Series 710, Center for Financial Studies.

Zerbib, O. D. (2019). The effect of pro-environmental preferences on bond prices: Evidence from green bonds. *Journal of Banking and Finance*, 98:39–60.

A Appendix

Table A.1: **List of Data Sources**

This table reports the complete list of data sources summarized in Table A.2.

Stock Exchanges	Other data sources
Börse Frankfurt	
B3 - A Bolsa do Brasil	*Environmental Data Providers**
BIX Malaysia	Climate Bond Initiative (CBI)
Bolsa de Santiago	Environmental Finance (EF)
Bolsa de Valores de Lima	International Capital Market Association (ICMA)
Bolsas y Mercados Argentinos	
Bolsas y Mercados Espanoles	*Green Indexes*
Borsa Italiana	China Green Bond Index
Euro TLX	Eurex Green Bond Basket
Euronext	Solactive Green Index
Guernsey The Intenational Stock Exchange	
Honk Kong Exchange	*Other*
India International Exchange	World Bank
Japan Exchange Group	European Investment Bank
London Stock Exchange	European Bank for Reconstruction and Devolpment
Luxembourg Stock Exchange	Banco Bilbao Vizcaya Argentaria (BBVA)
Nasdaq Nordic	Hongkong and Shanghai Banking Corporation (HSBC)
Nigerian Exchange Group	Kreditanstalt für Wiederaufbau (KfW)
Oslo Børs	Landesbank Baden-Wrttemberg (LBBW)
Shanghai Stock Exchange	Natixis
Singapore Exchange	Nordic Investment Bank (NIB)
SIX Swiss Exchange	ASEAN Capital Markets Forum (ACMF)
Taipei Exchange	Green Bonds Transparency Platform (GBTP)
Toronto Stock Exchange	Green Finance Portal (GBP) Japan
US Nasdaq	Nomura Research Institute (NRI)
Wiener Borse	Thai Bond Market Association (ThaiBMA)

* We exploit public information available from the CBI website sections *Bond Library*, *Market Blogs Archive*, *Labelled Green Bonds Database* and the *Certified Bond Database*. A similar exercise is carried out by using the *EF bond database* and the list of green issuer reported by the *Sustainable bonds database* provided by the ICMA.

Table A.2: **Green Bonds' sample - Sources**
(euro billions)

This table reports statistics on the number of green debt securities (included those that also are aligned to the social and/or sustainable principles as well as infrastructure green, transition, climate action, climate resilience, climate awareness, environment and blue bonds) broken down by information provider. **CSDB** represents the number of securities found in the ECB CSDB and **Volumes** the related euro billions outstanding amounts. **Other** includes supranational institutions, investment banks, on-line platforms, research institutes and market forums as shown in Table A.1.

Source	Number of securities	CSDB	Volumes
Environmental Data Provider	13,804	4,555	1,468.8
Stock Exchanges	9,083	3,830	1,712.5
Green Indexes	2,677	2,379	1,542.7
Other	1,205	925	428,8
Total	26,769	11,689	
Not Duplicated Total	20,045	5,711	1,768.6

Table A.3: **Green Bonds' sample - Databases**
(euro billions)

This table reports the number of securities and the relative CSDB volumes obtained by consecutive merges of the databases explored departing from the not duplicated initial list reported in Table A.2.

	Initial list	CSDB	SHS-S
Number of securities	20,045	5,711	3,072
Volumes		1,768.6	1,473.5

Table A.4: **Yields to maturity of Euro-denominated Bonds - Summary statistics**
(percentage values)

This table reports summary statistics on the yields of the euro-denominated debt securities issued by euro area residents broken down by issuer sector, type of instrument (green/non-green) and reference year.

Sector	Instrument	Year	25th	Mean	Median	75th	SD	N
Non-financial corporations	Conventional	2017	0.65	1.03	1.18	1.46	0.53	420,000
		2018	0.83	1.20	1.38	1.64	0.55	660,000
		2019	0.32	0.74	0.73	1.12	0.53	660,000
		2020	0.35	0.80	0.76	1.22	0.55	660,000
		2021	0.23	0.59	0.63	0.93	0.44	720,000
		2022	1.56	2.24	2.27	2.94	0.96	540,000
	Green	2017	0.67	1.06	1.22	1.50	0.55	360,000
		2018	0.82	1.20	1.36	1.62	0.55	540,000
		2019	0.24	0.68	0.65	1.07	0.56	660,000
		2020	0.19	0.59	0.51	0.88	0.55	720,000
		2021	0.17	0.53	0.58	0.85	0.45	660,000
		2022	1.58	2.31	2.33	3.09	1.00	540,000
Financial corporations	Conventional	2017	0.40	0.79	0.90	1.17	0.52	360,000
		2018	0.49	0.87	1.00	1.26	0.49	600,000
		2019	0.35	0.78	0.78	1.15	0.53	720,000
		2020	0.43	0.91	0.91	1.36	0.54	480,000
		2021	0.28	0.64	0.60	0.97	0.45	660,000
		2022	1.28	1.86	1.89	2.46	0.86	540,000
	Green	2017	0.40	0.86	0.92	1.32	0.59	420,000
		2018	0.74	1.18	1.32	1.66	0.60	660,000
		2019	0.26	0.68	0.66	1.01	0.53	660,000
		2020	0.34	0.82	0.76	1.21	0.60	720,000
		2021	0.25	0.63	0.69	0.99	0.47	720,000
		2022	1.48	2.00	2.02	2.55	0.83	540,000
Government	Conventional	2017	0.44	0.88	0.92	1.29	0.60	420,000
		2018	0.37	0.79	0.86	1.12	0.57	660,000
		2019	0.35	0.82	0.80	1.31	0.61	600,000
		2020	0.32	0.89	0.91	1.43	0.61	720,000
		2021	0.07	0.37	0.31	0.55	0.47	660,000
		2022	0.94	1.57	1.64	2.12	0.82	540,000
	Green	2017	0.22	0.63	0.71	1.03	0.53	420,000
		2018	0.29	0.72	0.85	1.15	0.54	480,000
		2019	0.02	0.37	0.35	0.65	0.45	600,000
		2020	-0.07	0.18	0.18	0.39	0.36	720,000
		2021	-0.06	0.21	0.24	0.47	0.33	600,000
		2022	0.92	1.58	1.63	2.17	0.85	540,000

Table A.5: **Yields to maturity of USD-denominated Bonds - Summary statistics**
(percentage values)

This table reports summary statistics on the yields of the USD-denominated debt securities issued by non-euro area residents broken down by issuer sector, type of instrument (green/non-green) and reference year.

Sector	Instrument	Year	25th	Mean	Median	75th	SD	N
Non-financial corporations	Conventional	2017	2.89	3.13	3.31	3.50	0.50	420,000
		2018	3.69	3.90	4.02	4.24	0.48	660,000
		2019	2.81	3.16	3.15	3.63	0.63	720,000
		2020	1.58	1.98	2.04	2.45	0.70	720,000
		2021	1.66	2.03	2.21	2.52	0.65	720,000
		2022	3.44	4.12	4.31	4.75	0.92	540,000
	Green	2017	2.73	2.99	3.10	3.31	0.58	240,000
		2018	3.72	3.87	3.91	4.07	0.50	300,000
		2019	2.70	3.02	3.05	3.45	0.57	480,000
		2020	1.40	1.75	1.85	2.17	0.62	660,000
		2021	1.62	2.00	2.16	2.48	0.63	720,000
		2022	3.37	4.02	4.21	4.59	0.88	540,000
Financial corporations	Conventional	2017	3.05	3.28	3.46	3.64	0.49	420,000
		2018	3.78	3.98	4.12	4.32	0.49	660,000
		2019	2.91	3.23	3.24	3.70	0.59	720,000
		2020	1.63	2.06	2.08	2.61	0.75	720,000
		2021	1.51	1.86	2.04	2.33	0.66	720,000
		2022	3.36	4.05	4.20	4.70	0.95	540,000
	Green	2017	2.30	2.64	2.74	3.03	0.67	300,000
		2018	3.19	3.47	3.55	3.81	0.56	480,000
		2019	2.97	3.26	3.31	3.65	0.56	660,000
		2020	1.52	1.98	2.02	2.51	0.72	720,000
		2021	1.31	1.68	1.84	2.11	0.62	720,000
		2022	3.09	3.74	3.83	4.36	0.91	540,000
Government	Conventional	2017	2.35	2.61	2.75	2.93	0.52	420,000
		2018	2.96	3.19	3.32	3.55	0.52	660,000
		2019	2.10	2.43	2.50	2.80	0.56	720,000
		2020	1.00	1.47	1.55	1.96	0.68	720,000
		2021	1.02	1.40	1.58	1.84	0.60	720,000
		2022	2.63	3.19	3.26	3.69	0.83	540,000
	Green	2017	3.67	3.88	4.01	4.20	0.49	420,000
		2018	3.73	3.95	4.07	4.32	0.49	600,000
		2019	2.06	2.46	2.50	2.81	0.81	480,000
		2020	1.25	1.76	1.84	2.24	0.87	660,000
		2021	1.23	1.60	1.74	2.03	0.63	660,000
		2022	2.12	2.61	2.46	3.23	0.65	240,000

Table A.6: **Yield Curve Estimation - Sample Characteristics**

This table reports summary statistics on the samples used for the estimation of the yield curves over time. The samples include only securities with rating information and with investment grade characteristics, i.e. those with a BBB or higher rating. The rating class has been mapped into a numeric sequence of integers.

Area	Issuer sector	Green	Rating	Number of securities	(log) Amount	Residual maturity
Euro	Non-financial	no	14.4	1,237.3	20.1	7.3
		yes	14.7	81.9	20.1	7.6
	Financial	no	16.5	2,381.2	19.7	7.3
		yes	15.9	100.4	20.2	6.1
	Government	no	16.4	619.6	18.1	9.1
		yes	18.0	15.9	20.8	9.5
Rest of the world (USD)	Non-financial	no	14.4	3,656.8	19.8	7.8
		yes	14.8	61.2	19.9	6.8
	Financial	no	15.3	3,205.5	20.1	6.0
		yes	16.6	51.6	20.1	4.2
	Government	no	16.4	619.6	18.1	9.1
		yes	18.0	15.9	20.8	9.5

Table A.7: **Yield Curves Estimation Results**

This table reports the estimated parameters of the Nelson-Siegel yield curve model on a sample of investment grade debt securities issued by non-financial corporations of the euro area and of the rest of the world. Data are referred to the period spanning from June 2017 to September 2022. For each combination of reference area (euro area and rest of the world), instrument type (green and non-green bonds) and reference date 250 random samples with repetition have been drawn from the available sample of securities.

Area	Sector	Instrument	Parameter	25th	Mean	Median	75th	SD	N
Euro area	Non-financial corporations	Conventional	λ	1.73	1.78	1.89	1.97	0.29	15,500
			β_1	1.49	1.97	1.99	2.23	0.72	15,500
			β_2	-2.12	-1.64	-1.85	-1.34	0.70	15,500
			β_3	-2.72	-2.47	-2.29	-2.13	0.72	15,500
		Green	λ	1.70	1.76	1.91	1.98	0.34	14,750
			β_1	1.30	1.87	1.87	2.21	0.81	14,750
			β_2	-2.05	-1.54	-1.69	-1.20	0.77	14,750
			β_3	-2.70	-2.39	-2.29	-2.09	0.79	14,750
	Financial corporations	Conventional	λ	1.68	1.72	1.89	1.97	0.40	14,250
			β_1	1.50	1.81	1.79	2.13	0.63	14,250
			β_2	-1.97	-1.46	-1.69	-1.25	0.97	14,250
			β_3	-2.73	-2.45	-2.38	-2.12	1.04	14,250
		Green	λ	1.76	1.80	1.92	1.98	0.29	15,750
			β_1	1.45	1.93	1.89	2.30	0.70	15,750
			β_2	-2.12	-1.62	-1.74	-1.32	0.81	15,750
			β_3	-2.82	-2.57	-2.50	-2.16	0.90	15,750
Rest of the world (USD)	Non-financial corporations	Conventional	λ	1.00	1.26	1.30	1.55	0.39	16,000
			β_1	3.06	3.73	3.71	4.33	0.79	16,000
			β_2	-2.16	-1.97	-1.91	-1.74	0.46	16,000
			β_3	-2.10	-1.96	-1.92	-1.78	0.38	16,000
		Green	λ	0.96	1.29	1.37	1.66	0.46	12,250
			β_1	2.83	3.46	3.32	4.05	0.82	12,250
			β_2	-2.14	-1.94	-1.91	-1.70	0.49	12,250
			β_3	-2.11	-1.95	-1.93	-1.74	0.36	12,250
	Financial corporations	Conventional	λ	0.95	1.20	1.20	1.46	0.36	15,750
			β_1	2.98	3.68	3.74	4.34	0.82	15,750
			β_2	-2.23	-1.99	-1.88	-1.71	0.48	15,750
			β_3	-2.11	-1.94	-1.88	-1.75	0.38	15,750
		Green	λ	1.05	1.33	1.36	1.64	0.39	14,250
			β_1	2.73	3.44	3.46	4.01	0.81	14,250
			β_2	-2.25	-1.99	-1.96	-1.69	0.59	14,250
			β_3	-2.15	-1.99	-1.96	-1.77	0.44	14,250

Table A.8: **Disequilibrium model: descriptive statistics**

This table reports the descriptive statistics of the data used in the disequilibrium model. N represents the number of unit of observations defined on the unique identification code created as the combination of the ISIN code, the sector and the country of the holder of the security. Missing values are excluded.

Year	Variable	N	Mean	SD	Median	Min	Max
2017	(log) Quantity	5,417	1.01	2.19	1.09	-7.,10	9.26
	(log) Price	5,417	0.32	1.14	0.21	-2.06	6.50
	(log) Amount	5,417	6.54	0.97	6.22	-0.18	10.17
	Residual maturity	5,417	7.73	2.82	7.22	3.76	19.88
	Rating	5,417	16.65	3.16	16.00	7.50	21.00
2018	(log) Quantity	8,856	0.92	2.15	1.00	-8.27	6.81
	(log) Price	8,856	-0.07	1.10	-0.21	-2.25	5.22
	(log) Amount	8,856	6.35	1.00	6.21	-13.95	8.23
	Residual maturity	8,856	6.88	2.99	6.36	0.12	19.60
	Rating	8,856	16.34	3.32	15.67	6.50	21.00
2019	(log) Quantity	13,170	0.94	2.13	1.03	-8.65	8.94
	(log) Price	13,170	0.55	1.19	0.60	-2.21	5.32
	(log) Amount	13,170	6.42	0.67	6.35	-0.12	9.94
	Residual maturity	13,170	6.97	3.46	6.39	0.95	19.90
	Rating	13,170	15.66	3.26	15.00	6.50	21.00
2020	(log) Quantity	14,367	0.78	2.16	0.80	-10.33	9.11
	(log) Price	14,367	0.95	1.49	0.84	-2.30	6.50
	(log) Amount	14,367	6.34	0.74	6.35	-0.20	10.22
	Residual maturity	14,367	7.03	3.78	6.50	0.79	19.93
	Rating	14,367	14.91	3.32	14.33	5.00	21.00
2021	(log) Quantity	29,936	0.88	2.15	0.95	-13.62	9.03
	(log) Price	29,936	0.42	1.24	0.35	-2.26	5.55
	(log) Amount	29,936	6.42	0.73	6.27	-1.73	10.34
	Residual maturity	29,936	6.64	3.61	6.07	0.03	19.95
	Rating	29,936	15.11	3.35	14.33	6.00	21.00
2022	(log) Quantity	36,133	0.66	2.21	0.71	-14.49	9.11
	(log) Price	36,133	-1.38	0.30	-1.34	-2.30	1.25
	(log) Amount	36,133	6.59	0.87	6.40	-0.06	10.42
	Residual maturity	36,133	5.52	3.78	4.77	0.03	19.98
	Rating	36,133	15.11	3.35	15	6.21	14.32

Table A.9: **Mean of samples' test based on the Covid-19 shock.**

This table show the results of two-sample t-test with unequal variances based on the predicted values of the excess of demand by the disequilibrium model "COVID = YES".

Excess of demand	N	Mean	SE	SD	5%	95%
Before March 2020 (0)	62,294	0.0024	0.0000	0.0064	0.0024	0.0025
From March 2020 (1)	237,258	0.0019	0.0000	0.0052	0.0019	0.0020
Combined	300,552	0.0020	0.0000	0.0055	0.0020	0.0021
Δ = Mean(0) - Mean(1)		0.0005	0.0000		0.0004	0.0005
H_0: $\Delta = 0$	t = 18.1733					
Satterthwaite's degrees of freedom = 86,836.3						
H_a: $\Delta < 0$			H_a: $\Delta \neq 0$			H_a: $\Delta > 0$
Pr(T < t) = 1.0000			Pr($\|T\| > \|t\|$) = 0.0000			Pr(T > t) = 0.0000