The market price of greenness: A factor pricing approach for Green Bonds*

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Abstract

Fostered by an empirical literature providing disparate evidence on the green premium, we propose a two-factor model to explain returns on green bonds not only as a function of market risk but also of the bond greenness. The second factor can be interpreted as a greenness premium, which can be either positive or negative depending on the product of the price given by the market to greenness and the sensitivity of the specific green bond to the latter. Based on the model proposed and its Fama-Mac Beth estimation on a sample of Euro-denominated bonds over the period 08.10-2014-31.12.2019, we are able to conclude that the market does price greenness, but the price is very small: including Government green bonds is 0.7 bps, and focusing on corporate green bonds only is – 1.3 bps. In all cases the dynamics of the price for greenness has a positive drift as the market reaches a more mature phase, landing to a positive average value (2 bps), which implies greenness being viewed as a small penalty. However, differences emerge when we look at the issuer sector level and at single bonds, thus our model is able to explain the disparate empirical evidence provided by the literature on the greenium. On the whole, results hint to a market where the difference in pricing between conventional and green bonds is, ceteris paribus, shrinking, which is consistent with greenness becoming a new normal. These results are of interest for many economic agents, including market participants and financial intermediaries, whereby the latter are also called by the regulator to manage their portfolio in consideration of climate risk.

Keywords: green bonds, green premium, sustainable finance, factor models, asset pricing.

J.E.L. classification: C21, C22, G11, G12; Q01.

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1. Introduction

Responsible and sustainable investments, along with the integration of ESG dimensions into investment decisions, have gained increasing attention and popularity over the recent years, in particular following the introduction of the Principles for Responsible Investment (PRI, 2017) by the United Nations (Widyawati, 2020).

Within responsible and sustainable finance, a particularly promising field is green finance, also fostered by Government measures after the 2020 Covid pandemic especially in Europe. Green finance deals with financial products aimed to support (transition to) an eco-sustainable economic system. Such products can be equity or debt type, whereby the latter include Green Bonds (GB, henceforth), which have increasingly becoming popular since the first issue by the European Investment Bank in 2007. Since then, many issuer types have chosen green bonds to finance their projects, including national and supranational institutions, and corporations. For example, in June 2017 Apple, the American multinational technology company headquartered in Cupertino, California, issued a $1B green bond in favour of "renewable energy and energy efficiency at its facilities and in its supply chain" (Forbes, 2017). Another important issuer is Orsted, the largest energy company in Denmark that has been defined the most sustainable company in the world, according to the Corporate Knights' 2020 index of the Global 100 most sustainable corporations in the world (Corporate Knights, 2020). Orsted uses green bonds to finance the development of its wind capacity thus positively contributing to Sustainable Development Goals (SDGs) set in the 2030 Agenda by UN (2015).[1] Although there is not yet a universal regulatory or legal framework for the issuance of GB, in order to promote an orderly market development standards have been set by the International Capital Market Association (ICMA) in ICMA (2018) and consistently by the European Commission Technical Group on Sustainable Finance (EU-TEG, 2019a,b).

The development of the GB market has been accompanied by an academic literature investigating their risk-return features, and specifically whether their return profile is higher, lower or equal with respect to that of equivalent conventional bonds (CB, henceforth). In fact, GB do not necessarily have a lower return and the green bond premium, i.e. the difference between the yield on a GB and a CB, is not necessarily negative. A relatively large body of empirical literature has addressed the existence, sign and determinants of green premium, without reaching a consensus. Moreover, as far as we know, the literature has not yet proposed a model for pricing green bonds in

[1] Specifically, it powers people with green energy (SDG 7) and helps combat climate change by decarbonising its energy generation and avoiding emissions (SDG 13).

consideration of a stochastic green premium and this represents the aim of the present piece of research.

Against this backdrop, the aim of this paper is to propose and test a theoretical framework to interpret disparate empirical evidence on the green premium, and specifically to answer a few main research-questions that motivated our work. Does the market price greenness in bonds? If so, can we estimate it as a greenness benefit or a greenness penalty? Has the evaluation of greenness changed over time? To this end we take a factor pricing approach to explain returns on GB not only as a function of market risk but also of the bond greenness.

The paper is organized as follows. Section 2 proposes a literature review focusing on the empirical literature on the green premium and possible explanations for it. Section 3 illustrates the theoretical framework we propose, while Section 4 illustrates the dataset and the methodology used to construct the green factor. Section 5 discusses the estimation results, Section 6 presents a pricing error analysis and Section 7 concludes.

2. Literature review

The literature on green bonds has been growing very fast in the latter few years touching upon many issues. To frame the contribution of this review we focus only on the literature dealing with the existence of a difference in the yield between green and conventional bonds, its determinants and models for green bond pricing.[2]

Overall, green bonds are a mean to attain collaboration between investors and issuers aimed to increase the amount of green investments (Kidney and Oliver, 2014). Investors in sustainable finance are driven by responsible and environmental considerations (e.g. Bauer and Smeets, 2015; Gutsche and Ziegler, 2019; Rossi et al., 2019), but green bonds may also help investors to realize diversification objectives. In this connection, Reboredo (2018) shows that green bonds strongly co-move with corporate and treasury bond markets, while weakly co-move with stocks and energy commodities. A different perspective is taken by Fender et al. (2019) who observe that green bonds might be included in reserve portfolios of central banks, because they allow central banks to meet both environmental sustainability objectives and diversification benefits. Doronzo et al. (2021) take the sovereign issuers' perspective showing that the sovereign green bonds' performance is essentially in line with that of conventional bonds.

Likely to be the most relevant issue, concerning both the issuers' and the investors' viewpoint is the existence of a green premium (generally called "greenium" when negative), defined as the yield

[2] Among topics we do not cover in this review, the by-effect of value creation to shareholders (e.g. Lebelle et al. (2020), Tang and Zhang, 2020)

difference between a green bond and a similar conventional bond. Thus, much of the current literature on green bonds pays particular attention to the empirical identification of the greenium by means of a matching method that consists in matching pairs of securities with the same features except for their greenness, i.e. the feature whose effect we are interested in. The first studies to deal with this issue are published by organizations such as Barclays (Preclaw and Bakshi, 2015) and Climate Bonds (Harrison 2017a,b) and underscore the strong demand for environmentally friendly securities in determining a premium. In fact, Marilyn Ceci, the Head of Green Bonds at JP Morgan, commenting Harrison at al. (2020) paper, argues that in normal conditions green bonds are priced in line with conventional bonds, but a difference in prices can arise when green bonds demand exceeds the supply. Zerbib (2019) analyses 110 green bonds on the secondary market between 2013 and 2017 and, based on matching pairs of a green and a conventional bond, finds an average green bond yield premium of -2 bps. Similarly, Hachenberg and Schiereck (2018) study the secondary market and, analysing 63 matched pairs of bonds for six months between 2015 and 2016, find a negative premium of 1 bp. Higher negative green premium amounting to 17 bps and 7 bps are observed by Preclaw and Bakshi (2015) and Baker et al. (2018) respectively. While Preclaw and Bakshi (2015) concentrate on the secondary market, at international level, in the period between 2014 and 2015; Baker et al (2018) study the primary market, in particular 2083 U.S. municipal bonds issued between 2010 and 2016. Conversely, Karpf and Mandel (2018), focusing on 1880 U.S. municipal bonds on the secondary market in the period from 2010 to 2016, find a positive premium of 7.8 bps. This opposite result can be explained by the fact that Karpf and Mandel (2018) do not base their study on after-tax yields and, as observed by Baker et al. (2018), several U.S. municipal bonds are taxable, so they are issued and traded at higher yields. Löffler et al. (2021) analyse a worldwide bond universe from 2007 to October 2019 and comparing green bonds with their matched conventional bonds find an average greenium of 15-20 bps both on the primary and secondary market. A further analysis on both markets by Kapraun et al. (2021) demonstrates that the greenium is exhibited only by Euro Government or supranational green bonds or by corporate green bonds with a large issue amount. Other works do not find a significant greenium in the primary market (e.g. Harrison, 2017b; Tang and Zhang, 2020; Larcker and Watts, 2020), therefore they argue that the main advantage of green bond issuance is not connected to cheaper debt financing. Harrison et al. (2020) points out that the lack of consensus on the existence and the magnitude of the green premium is due to the dynamics of the green bond market and the need to deal with consistent and reliable prices, whereas it is common to price bonds with theoretical prices or with spread techniques.

A number of studies analyse which factors influence the green premium. Gianfrate and Peri (2019), while finding that from the issuer's viewpoint green bonds are more convenient than conventional bonds, show that the advantage is greater for non-corporate issuers such as municipalities and other governmental entities, and occurs mostly in the secondary market. Wang et al. (2020) find that the green premium is greater when issuers and underwriters are characterized by strong social reputation and when corporate issuers have a lower ownership concentration held by long-term institutional investors. Long-term horizon is a crucial issue, because green bonds usually refer to projects that are completed in the medium to long term; then those types of investors could carry out significant monitoring activities on the use of green bond proceeds. A research by Fatica et al. (2021) highlights that only supranational institutions and non-financial corporates benefit from a negative green premium, while this is not true for financial institutions, possibly due to the greater difficulty that investors have in directly linking the green bond and the green project being funded. Additionally, green bond certifications play an important role in further lowering the green bond yield for non-financial institutions. The result is in line with other works on green certification: for example, Bachelet et al. (2019), Hyun et al. (2020) Kapraun et al. (2021) show that green certifications reduce asymmetric information and ensure investors against greenwashing strategies leading to a more significant greenium. Dorfleitner et al. (2021) find that green bonds with an external review such as a second party opinion issued by an independent research institution (e.g. CICERO, ISS-Oekom, and Sustainalytics) are traded at lower yields with respect matched conventional bonds.

In contrast to such a large – although not conclusive – literature on the green premium, only a few papers offer a theoretical framework for green bond pricing. Among these, Agliardi and Agliardi (2019) provide a structural model based on Gollier (2018) that aims to explain green bond prices and the green premium and find that the greenium (that they define as the yield difference between a conventional bond and a green bond with the same characteristics) increases with asset volatility, the effectiveness of the green technology and the sustainability advantage, whereas it is negatively correlated with corporate tax rates. A recent study by Baker et al. (2018) deals with a pricing relationship for green bonds in order to use it as a motivation for further empirical research in the US market. They identify the utility function of two groups of investors: investors who are mean-variance utility maximisers and investors who additionally care about environmental issues, i.e. derive utility from the green footprint of investments. They treat the green feature as a deterministic element that is identified in an environmental score. From the maximization of the two utility functions and after the market clearing, the authors show that the CAPM is still a suitable model to explain bond returns (both green bonds and non-green bonds). In fact, the basic CAPM equation is simply shifted by means of a deterministic term due to the environmental score. Based on this underlying theoretical setup, Baker et al. (2018) contribution is eventually an empirical investigation of the green premium. From a pricing viewpoint, the CAPM extension proposed by Baker et al. (2018) remains a one-factor model where only market risk is priced and the green factor is simply a deterministic additive shift.

The aim of this paper is to propose and test a theoretical framework to interpret disparate empirical evidence on the green premium, and specifically to assess whether the market price the green feature of GB as a benefit or as a penalty, and to estimate it. Since, as far as we know, the literature has not yet proposed a model for pricing GB in consideration of a non-deterministic green premium, we adopt a two-factor model in order to include in the green bond pricing a green factor beside a market risk factor.

3. The pricing approach: assumptions and estimation

Although both the CAPM (Sharpe, 1964; Lintner, 1965; Mossin, 1966) and the APT (Ross, 1976, 1977) have been originally proposed for pricing stocks, they can be used for bond pricing as well. In fact, the above-mentioned paper by Baker et al. (2018) uses the CAPM mean-variance utility maximizing approach to provide a one-factor pricing model for green bonds. Similarly, Elton et al. (1995) analyse bond return generating processes and propose the APT approach to derive a description of equilibrium for multifactor models.

Alessi et al. (2019, 2021) provide a pricing model for green stocks, which assumes that stock excess returns satisfy a two-factor model: the market risk factor and the green one, where the former is defined as the excess returns on a value weighted market portfolio, and the latter is the difference between the return of a green portfolio and that of a brown portfolio. To determine the components of the green and the brown portfolios they build a synthetic greenness indicator combining the Bloomberg ESG disclosure score with a quantitative disclosure on emissions (Total Greenhouse Gas, GHG, or, total carbon dioxide, CO2, when the former is not available).[3] As a consequence, stocks in the green portfolio have the highest synthetic greenness indicators and stocks in the brown portfolio have the lowest ones.

In this paper, we assume a two-factor model to explain bond returns, whereby beside a market risk factor we introduce a green factor. This framework draws from the pricing model for green stocks used in Alessi et al. (2019, 2021). Specifically, we assume that excess return of green bond i with respect to the risk-free rate can be represented by the following linear factor model:

[3] Bloomberg ESG disclosure score is a proprietary Bloomberg score based on the extent of a company's Environmental, Social, and Governance (ESG) disclosure. The score ranges from 0.1 for companies that disclose a minimum amount of ESG data to 100 for those that disclose every data point collected by Bloomberg. Each data point is weighted in terms of importance, with data such as Greenhouse Gas Emissions carrying greater weight than other disclosures. The score is also tailored to different industry sectors. In this way, each company is only evaluated in terms of the data that is relevant to its industry sector. This score measures the amount of ESG data a company reports publicly, and does not measure the company's performance on any data point. (*Source: Bloomberg*).

$$R_{i,t} = a_i + \beta_{i,m} r_{m,t} + \beta_{i,g} r_{g,t} + \varepsilon_{i,t} \quad (1)$$

where:

$R_{i,t}$ = excess return of green bond $i = 1, \dots, N$ with at date $t = 1, 2, \dots, T$

a_i = "Jensen's alpha"

$r_{m,t}$ = excess return of the market portfolio at date $t = 1, 2, \dots, T$, i.e. the market factor

$\beta_{i,m}$ = the sensitivity of green bond i return to the market factor

$r_{g,t}$ = the difference between the return on a green portfolio and an equivalent (synthetic) conventional portfolio at date $t = 1, 2, \dots, T$, i.e. the green factor

$\beta_{i,g}$ = the sensitivity of green bond i return to the green factor

$\varepsilon_{i,t}$ = a random error term with mean equal to zero and variance equal to $\sigma^2_{\varepsilon i}$.

Equation (1) corresponds to assuming two main determinants of the excess return on a green bond. The first determinant – in line with CAPM – can be interpreted as the risk premium associated to the (non-green) bond market. In fact, $r_{m,t}$ is meant to capture the bond market systemic risk and $\beta_{i,m}$ the sensitivity of the green bond i to the bond market risk and hence its product quantifies the premium associated to the systemic bond market risk. As for its sign, recall that $r_{m,t}$ being the excess return of the market with respect to the risk-free rate is positive by definition, while the sign of the sensitivity $\beta_{i,m}$ depends on the correlation between the bond i riskiness and the bond market riskiness, and it is generally positive. It follows that in most cases the bond market risk premium is expected to be positive.

The second determinant – the one that we propose as specifically characterizing green bonds – can be interpreted as a greenness premium: in fact, $r_{g,t}$, being the difference between the return of a green portfolio and an equivalent conventional portfolio, is positive and meant to capture a compensation for systemic greenness in the bond market if greenness is considered as a penalty (viceversa it is negative if greenness is considered a benefit); $\beta_{i,g}$ measures the sensitivity of green bond i to such systemic penalty/benefit for greenness and hence their product of the two product quantifies the premium associated to greenness. Unlike $r_{m,t}$, $r_{g,t}$ is not necessarily positive by definition being the difference between the returns of a green bond portfolio and a portfolio consisting of equivalent synthetic conventional bonds. This premium can be either positive or negative.[4] In fact, the sign of the sensitivity $\beta_{i,g}$ depends on the correlation between the bond idiosyncratic greenness and the systemic greenness, and its sign cannot be established a priori, given the specificity of the

[4] In principle the premium associated to greenness may also be zero, but we do not discuss this extreme case which would imply a situation where GB are completely equivalent to CB.

green project connected to the bond, which is likely to be specific to the issuer and /or to the industry. Possible outcomes are summarized in Table 1.

Table 1. Determinants of the sign of the green premium

	SYSTEMIC GREENNESS: Market price	
	Greenness is priced as penalty $\boldsymbol{r_{g,t} > 0}$	**Greenness is priced as benefit** $\boldsymbol{r_{g,t} < 0}$
GB *i* positively correlated with systemic greenness $\boldsymbol{\beta_{i,g} > 0}$	Green premium>0 ➔ return on GB > return on CB	Green premium<0 ➔ return on GB < return on CB *Greenium*
GB *i* negatively correlated with systemic greenness $\boldsymbol{\beta_{i,g} < 0}$	Green premium<0 ➔ return on GB < return on CB *Greenium*	Green premium>0 ➔ return on GB > return on CB

Note: GB = Green Bond, CB = Conventional bond

In what follows we adopt the two-stage regression approach used by Fama and MacBeth (1973) to test the CAPM. This approach has been adopted also by Fama and French (1992) and Carhart (1997) to test multifactor models and by Chen et al. (1986) to identify variables that influence stock returns. Our analysis involves single green bonds issued at different dates for which we have time series of different lengths, so we have an unbalanced panel. The Fama and MacBeth (1973) approach allows us to deal with unbalanced panels (Goyal, 2012), because it considers returns only on green bonds that exist at date t.

Starting from the model described by equation (1), in the first stage we estimate multiple time-series regressions for each green bond in the sample. Then, in the second stage, we estimate a cross-sectional regression at each time period t:

$$R_{t,i} = \lambda_{0,t} + \lambda_{m,t}\widehat{\beta_{i,m}} + \lambda_{g,t}\widehat{\beta_{i,g}} + \alpha_{t,i} \qquad (2)$$

where:

$R_{t,i}$ = excess return at date $t = 1, 2, \dots, T$ for green bond $i = 1, \dots, N$

$\lambda_{0,t}$ = intercept denoting the zero-beta rate in excess of the risk-free rate

$\lambda_{m,t}$ = market risk excess return at date $t = 1, 2, \dots, T$

$\widehat{\beta_{i,m}}$ = the sensitivity of green bond i return to the market factor estimated in equation (1)

$\widehat{\beta_{i,g}}$ = the sensitivity of green bond i return to the green factor estimated in equation (1)

$\lambda_{g,t}$ = greenness "excess" return at date $t = 1, 2, \dots, T$

$\alpha_{t,i}$ = pricing error at date $t = 1, 2, \dots, T$ for green bond $i = 1, \dots, N$

Market and green risk excess return represent the amount of extra return generated on average from taking on an additional unit of market risk and greenness respectively. However, in line with equation (1), it has to be stressed that what we call greenness "excess" return is not necessarily positive, given that, unlike market risk, greenness is not necessarily a risk.

Instead of adopting a rolling window approach, we run a single time-series regression for each green bond and then a single cross-section regression for each day in which we have returns observations. This choice derives from the fact that we have a relatively short period of observation, so factor loadings and risk excess returns have a lower tendency to vary over time. In addition, according to Goyal (2011), Fama and French (1992) obtain similar results using both a rolling window and a full-sample approach.

After running equations (1) and (2), we estimate λ_m, λ_g and α_i as the average of the cross-sectional regression estimates:

$$\widehat{\lambda_m} = \frac{1}{T}\sum_{t=1}^{T}\widehat{\lambda_{m,t}} \ ; \ \widehat{\lambda_g} = \frac{1}{T}\sum_{t=1}^{T}\widehat{\lambda_{g,t}} \ ; \widehat{\alpha_\iota} = \frac{1}{T}\sum_{t=1}^{T}\widehat{\alpha_{t,\iota}} \tag{3}$$

To generate the standard errors for the estimates of λ_m, λ_g and α_i, standard deviations of the cross-sectional regression estimates are used. The variance of the cross-sectional regression estimates is computed as follow:

$$\sigma^2(\widehat{\lambda_m}) = \frac{1}{T^2}\sum_{t=1}^{T}(\widehat{\lambda_{m,t}} - \widehat{\lambda_m})^2 \ ; \ \sigma^2(\widehat{\lambda_g}) = \frac{1}{T^2}\sum_{t=1}^{T}(\widehat{\lambda_{g,t}} - \widehat{\lambda_m})^2 \ ; \ \sigma^2(\widehat{\alpha_\iota}) = \frac{1}{T^2}\sum_{t=1}^{T}(\widehat{\alpha_{t,\iota}} - \widehat{\alpha_\iota})^2 \tag{4}$$

4. The setup of the dataset

In this section we illustrate the dataset needed for the estimation of the two-factor model. First in Section 4.1 we illustrate the selection of the green bonds and of the market risk factor. The methodology used to construct the green factor is detailed in section 4.2.

We base our analysis on the Bloomberg identification of green bonds, i.e. fixed income instruments complying with the market standards of Green Bond Principle that fund exclusively green projects promoting climate change, adaptation or other environmental sustainability purposes (ICMA, 2018).

4.1 Green bonds and the market risk factor

We start with a sample of 466 Euro-denominated green bonds on December 31, 2019 and we exclude green bonds with missing information regarding ISIN, maturity, amount issued and all green bonds with floating coupon and option clauses. Moreover, in order to control for credit risk, green bonds without a rating or with a rating lower than BBB are excluded. According to other studies on the green bond secondary market (Zerbib, 2019; Hyun et al., 2020; Löffler et al., 2021) we focus on ask yields to maturity.[5] This type of yield, reflecting the return an investor would receive if she/he purchases and holds the green bond until its maturity, is suitable for our study that analyses green bond secondary market and returns available to potential investors. Hence, we select only green bonds for which information about ask yields to maturity are available.

The final sample, satisfying the above requirements, consists of 163 green bonds that represent 35% of the total green bond universe denominated in Euros and 54% of the outstanding green bond debt in Euros. According to the Bloomberg Industry Classification System (BICS) level 1 name, just over three-quarters of green bonds belong to the Government and Financials sector and they count for 80% of the total amount issued of the final sample analysed (see Table 2). The majority of green bonds have a rating equal or higher than A, while the average issued amount and years to maturity of the sample is € 0.96 billion and 6.7 years respectively (see Table 3).

Table 2. Issuers by sector

Sector	Number of Green Bonds	Issue amount (€ bn)
Financials	68	156.75
Government	59	78.27
Utilities	18	16.76
Industrials	8	7.68
Consumer Discretionary	6	3.91
Materials	2	1.13
Communications	1	0.84
Energy	1	0.72
Total	163	156.75

Table 3. Characteristics of green bonds

	Sample					
	Min.	1st Quart.	Median	Mean	3rd Quart.	Max
Rating	1.00	2.00	3.00	2.45	3.00	4.00
Issue amount (€ bn)	0.01	0.56	0.59	0.96	0.97	22.30
Years to Maturity (on December 31, 2019)	0.38	3.77	5.47	6.70	7.86	29.27

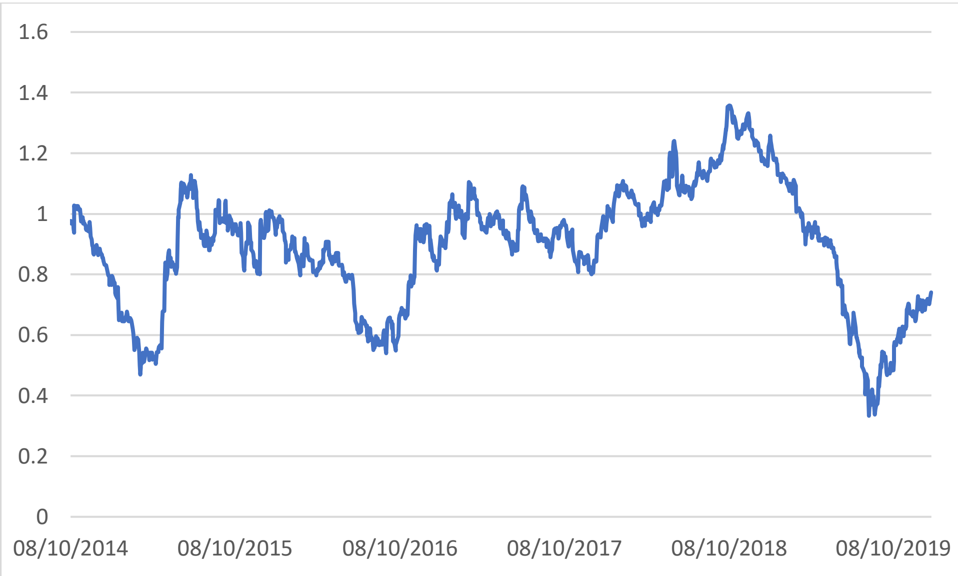
Notes: the distribution for the rating is obtained assigning a score to each rating: 1 to AAA, 2 to AA, 3 to A and 4 to BBB.

[5] We retrieve ask yields to maturity from Bloomberg. The ask yield to maturity is obtained by discounting bond cash flows using the market ask price as a reference and assuming the bond is held up to maturity and coupons are reinvested at the same yield.

To implement the proposed two-factor model, we consider the period from October 8, 2014 to December 31, 2019, because on December 31, 2019 there are very few green bonds that have been issued before October 8, 2014.

As in the CAPM, the market factor consists in the excess return of the market portfolio with respect to the risk-free rate.[6] Concerning the market portfolio, we consider the Bloomberg Barclays Euro Aggregate Bond Index which we retrieve from Factset. Among different definitions of return, we use the yield to maturity given that ask yields to maturity are not available. The Bloomberg Barclays Euro Aggregate Bond Index includes fixed-rate, investment-grade Euro-denominated bonds and the principal sectors in the index are the Treasury, corporate, Government-related and securitised. Since the market portfolio includes only investment grade bonds, it is consistent with our sample of 163 green bonds and allows us to control for credit risk. Market factor is represented in Figure 1.

Figure 1. **Market factor (%) over time**



4.2 The Green Factor: dataset and methodology

We build the green factor in eq. (1), i.e. the difference between the return of a green bond portfolio and a portfolio consisting of equivalent synthetic conventional bonds, from matched pairs of green and synthetic conventional bonds with identical properties except for their greenness. Most studies on the existence of the green premium adopt matching methods: we follow the approach in Zerbib (2019) that consists of two stages.

[6] We use the 1-Month London Interbank Offered Rate (LIBOR), based on Euro, Percent, Daily, Not Seasonally Adjusted (source: Federal Reserve Economic Data https://fred.stlouisfed.org/series/EUR1MTD156N)

In the first stage we start from the sample of 466 Euro-denominated green bonds on December 31, 2019 (as in Section 4.1). Then we exclude only green bonds with missing information regarding ISIN, maturity, amount issued, ask yield to maturity and all green bonds with floating coupon and option clauses. Specifically, in this stage we allow for green bonds without a rating or with a rating lower than BBB, because in the matching process we look for conventional bonds with the same credit quality as the green bonds selected. As a consequence, the yield difference we are interested in depends only on the greenness and not on credit risk. The sample reduces to 225 green bonds and for each of them we search for the two most similar conventional bonds. Conventional bonds must have the same issuer, currency, rating, bond structure, seniority, collateral and coupon type.[7] To limit the difference in maturities we collect conventional bonds with a maturity that is neither 2 years shorter nor 2 years longer than the green bond's maturity. Moreover, we control for the difference in liquidity between green and conventional bonds, restricting the range of conventional bonds to those (i) with an issue amount between 1/4 and 4 times the green bond's issued amount and (ii) with an issue date that is within a 6-year interval with respect the green bond's issue date. However, Wulandari et al. (2018) study the impact of liquidity risk on the yield difference between green and conventional bonds and find that it has become negligible in the recent years, suggesting that green bond market is becoming more mature. All the restrictions adopted are summarised in Table 4. When multiple conventional bonds meet the above criteria, in line with Hyun et al. (2020) we choose the conventional bond with the closest issue date to the green bond issue date. On the other hand, in the case where fewer than two conventional bonds respect the requirements, we exclude that green bond from the construction of the green factor.

Table 4. Matching method restrictions

Green bond properties	Two closest conventional bonds properties
issuer	the same
currency	the same
rating	the same
bond structure	the same
seniority	the same
collateral type	the same
coupon type	the same
maturity	neither 2 years shorter nor 2 years longer
issue amount	between 1/4 and 4 times the green bond's issued amount
issue date	neither 6 years shorter nor 6 years longer

[7] Concerning the rating, we collect rating information from the three main agencies: S&P, Moody's and Fitch, then the rating is rounded off by removing potential + and -, so that all the rating in our sample can be AAA, AA, A, BBB, BB or Non-rated (NR). To assess an overall rating to each bond, we take the majority rating among the available ones; when only two different ratings are available, we select the highest one. Concerning the bond structure, since we exclude green bonds with option clauses, we consider only bullet structure.

In the second stage, for each triplet of one green bond and two conventional bonds, the maturity bias is eliminated by constructing a synthetic conventional bond with the exact maturity of the green bond. To do so, we retrieve the ask yields of each triplet from the issue date up to December 31, 2019 and we build an unbalanced panel. Whenever, on a specific date, at least one of the three ask yields is not available, we remove that line from the panel. We then identify the synthetic conventional bond through a linear interpolation (or extrapolation) of the two conventional bonds at the green bond time to maturity. The ask yield $\tilde{y}_{i,t}^{CB}$ of the synthetic conventional bond of triplet i at time t is:

$$\tilde{y}_{i,t}^{CB} = a^{*} Maturity_{i,t}^{GB} + b^{*} \tag{7}$$

where:

$a^{*} =$ the slope of the linear function passing through ($Maturity_{i,t}^{CB1}, y_{i,t}^{CB1}$) and ($Maturity_{i,t}^{CB2}, y_{i,t}^{CB2}$)

$Maturity_{i,t}^{GB} =$ the time to maturity of the green bond of triplet i at time t

$b^{*} =$ the intercept of the linear function passing through ($Maturity_{i,t}^{CB1}, y_{i,t}^{CB1}$) and ($Maturity_{i,t}^{CB2}, y_{i,t}^{CB2}$).

Hence the yield spread between the green bond *i* and the equivalent synthetic conventional bond is:

$$\Delta\tilde{y}_{i,t} = y_{i,t}^{GB} - \tilde{y}_{i,t}^{CB}. \tag{8}$$

This process leaves us with 92 triplets and, consequently, with 92 green bonds and their respective equivalent synthetic conventional bonds, accounting for 36% of the starting sample of 255 green bonds and 34% of the associated outstanding green bond debt. On the other hand, if we consider the total sample of 466 Euro-denominated green bonds, the 92 green bonds for which a matching is found represent 20% of the sample and 22% of the associated outstanding green bond debt. Zerbib (2019) matched 10% of the international green bond market and 17% of the associated outstanding green bond debt as of December 31, 2017. This increase, with respect to Zerbib (2019), can be attributed to the fact that two years later, on December 31, 2019, the number of companies and institutions that have issued green bonds besides conventional bonds increased. In addition, our study focuses on green bonds denominated in Euros, which are the second largest market in the world for the number of green bonds after the U.S. dollar-denominated one.

The average ask yield to maturity of the sample of 92 green bonds decreases when there are some forms of collateral (especially when they are guaranteed by the Government) and increases with credit risk (see Table 5). In the sample there are 16 green bonds that are not rated, but their yield to maturity is in line with the other investment grade bonds, so those green bonds without a rating do not seem to incorporate high credit risk.

Table 5. **Green bonds for the green factor: breakdown by sector, rating, and collateral type**

		AAA	AA	A	BBB	NR	Total
Financials							
SR Unsecured	Average yield (%)		0.10	0.34	0.75	0.68	0.36
	Average maturity (years)		3.26	3.76	4.18	8.16	4.07
	Nb. of GB		14	19	7	4	44
Covered	Average yield (%)	-0.03				1.13	0.26
	Average maturity (years)	8.32				5.09	7.51
	Nb. of GB	3				1	4
Pfandbriefe	Average yield (%)					-0.07	-0.07
	Average maturity (years)					4.48	4.48
	Nb. of GB					8	8
Unsecured	Average yield (%)					0.40	0.40
	Average maturity (years)					4.76	4.76
	Nb. of GB					1	1
Government							
SR Unsecured	Average yield (%)	0.13	0.18	0.37		0.26	0.23
	Average maturity (years)	8.58	6.46	4.61		7.84	6.73
	Nb. of GB	4	4	4		2	14
Covered	Average yield (%)	0.09					0.09
	Average maturity (years)	9.88					9.88
	Nb. of GB	1					1
Govt Guaranteed	Average yield (%)	-0.20	0.21	-0.14			0.01
	Average maturity (years)	4.52	7.61	4.09			6.02
	Nb. of GB	4	5	1			10
Utilities							
SR Unsecured	Average yield (%)			0.24	0.72		0.56
	Average maturity (years)			1.32	6.03		4.46
	Nb. of GB			1	2		3
Company Guarantee	Average yield (%)				0.69		0.69
	Average maturity (years)				4.41		4.41
	Nb. of GB				3		3
Consumer Discretionary							
SR Unsecured	Average yield (%)			-0.06	1.03		0.49
	Average maturity (years)			1.56	3.94		2.75
	Nb. of GB			1	1		2
Communications							
SR Unsecured	Average yield (%)				0.42		0.42
	Average maturity (years)				6.90		6.90
	Nb. of GB				1		1
Industrials							
SR Unsecured	Average yield (%)		0.37				0.37
	Average maturity (years)		9.07				9.07
	Nb. of GB		1				1
Average yield		-0.02	0.15	0.30	0.73	0.26	

Notes: average maturity is expressed in years with reference to December 31, 2019.

Descriptive statistics of the green bonds, conventional bonds and synthetic conventional bonds are presented in Table 6. The panel is strongly unbalanced since green bonds were issued at different dates and, consistently with the recent success of this market, in 2019 the number of new issuances increased. The distribution of the maturity and issued amount of the two conventional bonds do not significantly differ to the one of the green bonds because of the restrictions we imposed in the matching process. The difference in yield between the green bonds and the equivalent synthetic conventional bonds are on average negative and small (2 bps), which is very much in line with results by Zerbib (2919). The distribution is skewed to the left, suggesting that green bonds are characterised by a lower yield to maturity than the corresponding synthetic ones, keeping everything else constant.

Table 6. **Descriptive statistics of the green factor determinants**

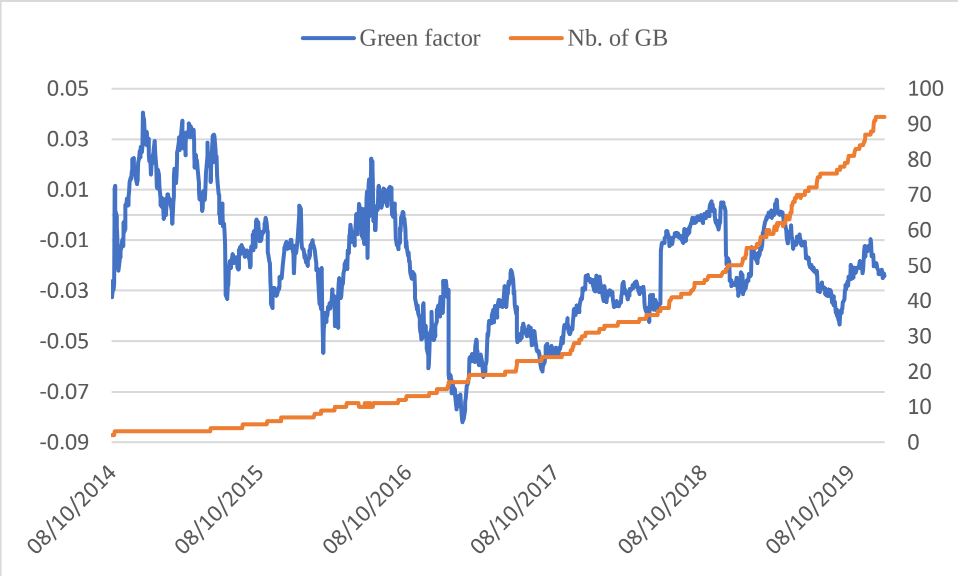
	Sample					
	Min.	1st Quart.	Median	Mean	3rd Quart.	Max
Number of days per bond	14	156	302	409	603	1347
Ask yield of the GB (%)	-0.81	-0.07	0.12	0.25	0.49	2.27
Ask yield of the equivalent synthetic CB (%)	-1.02	-0.08	0.21	0.27	0.53	2.62
Ask yield of CB1 (%)	-0.76	-0.09	0.23	0.28	0.55	2.88
Ask yield of CB2 (%)	-0.76	-0.03	0.24	0.29	0.51	2.19
Yield difference (%)	-2.01	-0.04	-0.01	-0.02	0.01	1.12
GB maturity	0.44	3.39	4.54	5.02	5.85	19.44
CB1 maturity	0.42	3.12	4.19	4.97	6.41	19.21
CB2 maturity	0.91	3.02	4.46	4.90	5.49	20.96
GB issue amount (€ bn)	0.003	0.500	0.500	0.707	0.750	4.000
CB1 issue amount (€ bn)	0.010	0.500	0.937	1.112	1.250	6.000
CB2 issue amount (€ bn)	0.003	0.500	1.000	1.114	1.250	6.000

Notes: GB = Green Bond; CB = Conventional Bond. Determinants of the green factor are 92 triplets (one green bond and two conventional bonds) and the resulting synthetic conventional bonds. The number of days represents the length of the time series of each triplet. The difference in yield is the difference between the green bond ask yield and the interpolated (or extrapolated) equivalent synthetic conventional bond ask yield. The table provides also distributions of time to maturity expressed in years (with reference to December 31, 2019) and the issue amount in billions of Euros.

Figure 2 shows the green factor, defined by the difference of the returns on the green portfolio and the synthetic portfolios, over time. The ask yield of the green and the synthetic portfolios is calculated as the simple arithmetic mean of the ask yields of their 92 components.[8] For most of the time, the green factor is negative, consistently with the distribution emerging from Table 6. To be noted that the number of bonds included in the green portfolio increased considerably: until June 2017, bonds in both the green and the conventional portfolio are less than 20, but the number of bonds in the portfolios increases over time in line with the development of green bond market.

[8] When, for a certain date, the ask yield of one of the components is not available, zero weight is attributed to that component.

Figure 2. Green factor (%) over time



Notes: the left scale refers to the green factor in %; the right scale refers to the cumulative number of bonds, both green and synthetic, composing the green factor at each date.

Over the sample period from October 8, 2014 to December 31, 2019, the green factor and the market factor show low correlation, as highlighted by the scatter plot represented in Figure 3. The correlation is equal to -0.18, a value which is in line with the literature adopting a multifactor approach (e.g. Fama and French, 1993; Alessi et al., 2019, 2021).

Figure 3. Scatter plot of the green factor and the market factor

08/10/2014 - 31/12/2019

correlation r = -0.18 (p-value < .001)

5. Results

In this section we present the results from the estimation of the two-factor model for pricing green bonds following the methodology presented in Section 3, i.e. the Fama and MacBeth (1973) two-stage regressions. The results provide a test for the theoretical framework proposed and allow to discuss whether the green premium is positive or negative, disentangling its components.

We start by estimating the model over the whole sample (Section 5.1), and then on a subsample excluding Government bonds (Section 5.2) that in principle could be different in nature from the corporate ones.

5.1 The whole sample

In the first stage, for each green bond we estimate a time-series regression according to equation (1), i.e. we obtain 163 estimates for the sensitivities ($\beta_{i,m}$ and $\beta_{i,g}$) of both the market and the green factor. In the second stage, at each day in the dataset (from October 8, 2014 to December 31, 2019) we estimate a cross-sectional regression according to equation (2), i.e. we obtain 1347 estimates for the excess returns ($\lambda_{m,t}$ and $\lambda_{g,t}$) of both the market and the green factor.

Table 7 reports the estimated sensitivities to the two factors, $\beta_{i,m}$ and $\beta_{i,g}$, excluding green bonds with sensitivity to the green factor not statistically significant at a 10% level.[9] This implies that the bonds considered amount to 124 and the Communication and Materials sectors disappear. The sensitivity of green bond returns to the market factor confirms expectations: it is positive for all the sectors analysed and on average equal to 1.15. By contrast, the sensitivity to the green factor is on average negative and equal to -2.90, but the magnitude of the mean varies considerably across sectors. At no surprise sectors with more green bonds display higher variability in the distribution of the estimated sensitivities.

From Table 8, reporting the adjusted R^2 of equation (1), we can conclude that overall the two-factor model based on a market and a green factor well explains green bond yields. In fact, the average R^2 is 0.77 with little variation across sectors, whereby the sectors with greater number of green bonds, Financials and Government, have a very good R^2 (75% and 81% respectively).

[9] Results keeping also bonds that are not significantly sensitive to the green factor are qualitatively similar and are available upon request.

Table 7. Distribution of $\boldsymbol{\beta_{i,m}}$ and $\boldsymbol{\beta_{i,g}}$: full sample and by issuer sector

	Min	1st Quart.	Median	Mean	3rd Quart.	Max	St. Dev.
Full sample (124 GB)							
Market factor ($\beta_{i.m}$)	-1.28	0.86	1.22	1.15	1.49	2.31	0.51
Green factor ($\beta_{i.g}$)	-13.46	-5.75	-3.20	-2.90	-1.12	24.37	5.37
Financials (50 GB)							
Market factor ($\beta_{i.m}$)	-1.28	0.66	0.96	0.98	1.30	2.31	0.58
Green factor ($\beta_{i.g}$)	-8.35	-5.08	-2.23	-1.18	0.87	24.37	6.25
Government (45 GB)							
Market factor ($\beta_{i.m}$)	0.20	0.99	1.22	1.19	1.46	1.73	0.36
Green factor ($\beta_{i.g}$)	-11.41	-6.21	-3.30	-3.80	-1.79	2.50	3.39
Utilities (16 GB)							
Market factor ($\beta_{i.m}$)	0.32	0.87	1.50	1.29	1.65	2.16	0.57
Green factor ($\beta_{i.g}$)	-10.53	-6.00	-4.49	-2.88	1.95	6.16	4.88
Industrials (7 GB)							
Market factor ($\beta_{i.m}$)	1.34	1.48	1.52	1.49	1.54	1.56	0.07
Green factor ($\beta_{i.g}$)	-13.46	-11.36	-10.26	-7.85	-3.27	-2.01	4.83
Consumer Discretionary (5 GB)							
Market factor ($\beta_{i.m}$)	0.38	1.42	1.43	1.37	1.69	1.93	0.59
Green factor ($\beta_{i.g}$)	-13.21	-11.01	-4.14	-4.74	-2.43	7.11	8.02
Energy (1 GB)							
Market factor ($\beta_{i.m}$)	-	-	-	1.55	-	-	-
Green factor ($\beta_{i.g}$)	-	-	-	-5.21	-	-	-

Notes: The number of green bonds in each sector is reported in brackets. In the Energy sector there is only one green bond, hence only the mean is reported.

Table 8. Average adjusted R^2: full sample and by issuer sector

	Full sample	Financials	Government	
Nb. Of GB.	124	50	45	
Adj. R^2	0.77	0.75	0.81	
	Utilities	**Industrials**	**Consumer Discretionary**	**Energy**
Nb. Of GB.	16	7	5	1
Adj. R^2	0.64	0.91	0.83	0.91

Notes: Adjusted R^2 is calculated from time-series regressions according to equation (1) and in the table the average value for the full sample and for each subsample is reported.

In the second stage, we use the estimated sensitivities to run a cross-sectional regression according to equation (2) for each day thus obtaining 1347 estimates for the excess returns ($\lambda_{m,t}$ and $\lambda_{g,t}$) of both the market and the green factor. We then average across time according to equation (3) to obtain λ_m and λ_g, i.e. average market and green risk excess returns reported in Table 9. Both market risk and green risk excess return are significant at 1% significance level, suggesting the ability of both market and green factor to explain green bond returns. Over the sample, the market risk excess return λ_m is positive and equal to 0.738 % (73.8 bps), showing a positive relation between the bond return and its market systemic riskiness as captured by the bond market index. The greenness excess return λ_g is very small and positive: the coefficient estimate is 0.007 % (0.7 bps), and the positive sign suggests that, over the whole market and the whole period, on average taking an additional unit of greenness requires a compensation with an excess return, pointing to greenness being priced as a slight penalty.

Table 9. Average excess returns

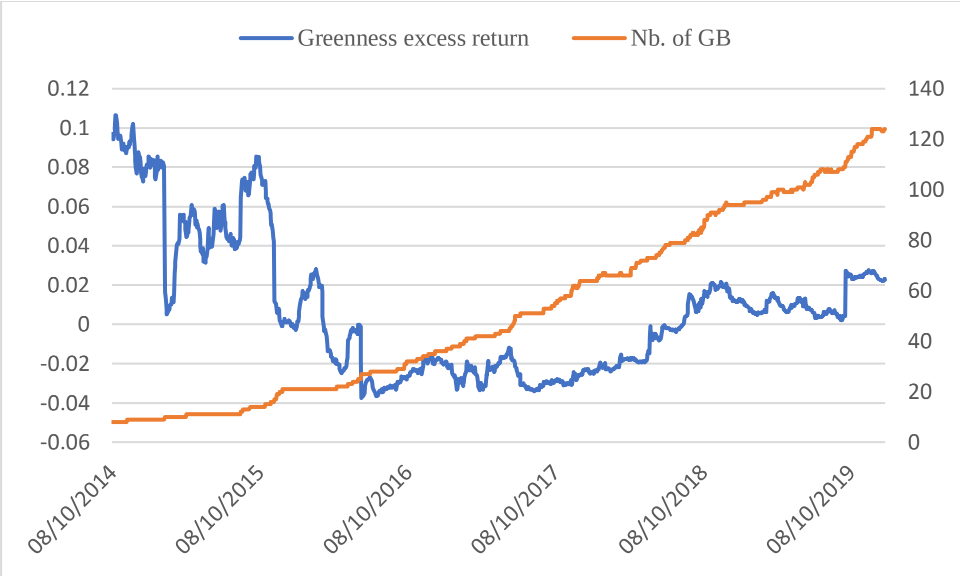
Intercept (%)			λ_m (%)			λ_g (%)		
mean	std err	t-value	mean	std err	t-value	mean	std err	t-value
0.150	0.006	26.797	0.738	0.006	122.844	0.007	0.001	7.585

Notes: the intercept represents the average intercept of equation (2); λ_m e λ_g are the time-series average of market and green risk excess returns calculated from equation (2).

What is the implication of our results for the sign of the green premium? To answer recall that, according to equation (2), the green risk premium is represented by the product of the sensitivity to systemic greenness of bond *i* and the green risk excess return at time *t*. Over the sample period, the sensitivity to the green factor is on average negative (-2.90, see Table 7), the green excess return is on average positive (0.007%, see Table 9). Thus, the product is negative on average for the full sample analysed and amounts to – 0.0203% (-2.03 bps). The analysis on single sectors provides different magnitudes of it due to differences in the sensitivities to the green factor $\beta_{i,g}$ emerging from Table 7. For the two sectors issuing more green bonds, i.e. Financials and Government sectors, the green risk premium is on average -0.826 bps and -2.66 bps respectively. However, there are differences also within a specific sector as represented by the relatively wide range of sensitivities to the green factor reported in Table 7.

To get more insight into these results on the whole period, and given the growth of the green bond market in the latter years, which is also reflected in our database, we look at the dynamics of the estimated green risk excess return over time. Figure 4 plots it together with the number of green bonds used in the estimation. While the latter significantly increases from about 5 at the beginning of our sample to about 120 at the end, the green risk excess dynamics shows two distinct phases. In a first period, up to mid-2016, when the number of green bonds is low (below 20), the excess return is extremely volatile and most of the time positive. In a second period, until end of sample, the greenness excess return shows a positive drift that takes it from the lowest value of about -0.04% to the highest of about 0.02%. Disregarding the first period with the green bond market in its initial phase, and focusing on this latter trend, we may conclude that, as the market becomes more mature with an increasing number of bonds, the excess return becomes positive, but very small. This may be pointing to a convergence between green and non-green bonds in terms of risk and pricing.

Figure 4. Greenness excess return over time



Notes: the left scale refers to the green risk excess return (λ_g) in %; the right scale refers to the cumulative number of green bonds that are in the sample.

5.2 Excluding Government bonds

Although results on the whole sample do not highlight differences for the Government green bonds, since the latter are in principle different in nature from the corporate ones, we repeat the whole estimation excluding the Government bond from the analysis.

By comparative inspection of Tables 9 and 10, we can see that results on the market risk excess return are quite robust, while the average green risk excess return remains very small but becomes negative. This has implications on the sign of the green risk premium that, over the whole period and the whole sample, becomes positive and equal to 0.0311 (3.11 bps), resulting from the product of the average sensitivity to the green factor (-2.39, see Table 7) and the green excess return (-0.013%, see Table 10). As in the previous case, the analysis on single sectors provides different magnitudes remaining however negative. Specifically, for the sector issuing more green bonds, i.e. the Financials one, the green risk premium becomes positive and equal on average to 1.534 bps.

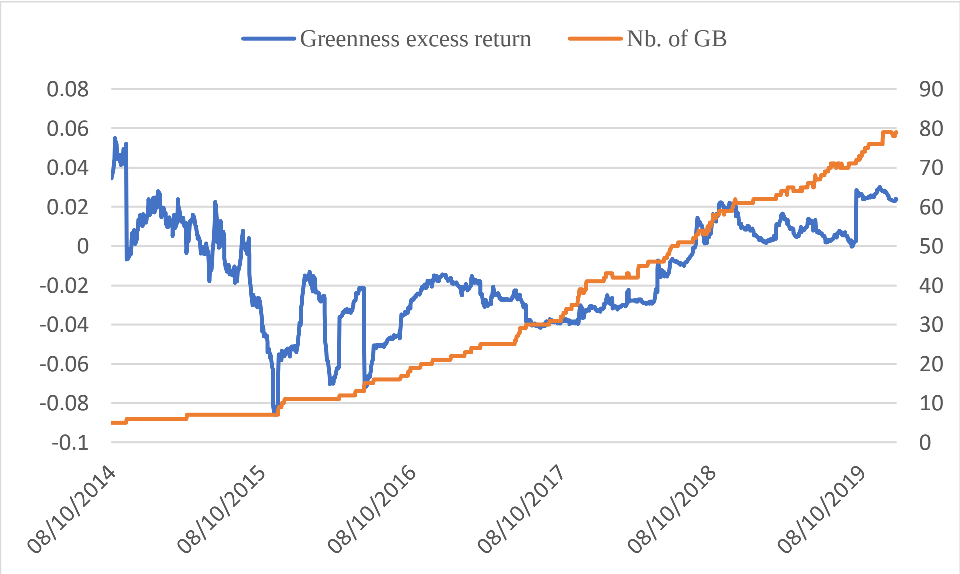
Table 10. Average excess returns without Government green bonds

Intercept (%)			λ_m (%)			λ_g (%)		
mean	std err	t-value	mean	std err	t-value	mean	std err	t-value
0.339	0.007	50.505	0.702	0.006	122.132	-0.013	0.001	-18.975

Notes: the intercept represents the average intercept of equation (2); λ_m e λ_g are the time-series average of market and green risk excess returns calculated from equation (2).

In order to explain this change in results, it is useful to look also in this case at the green risk excess return dynamics against the increase in the number of green bonds (Figure 5). By comparative inspection of Figures 4 and 5, we can see that in the absence of Government green bonds, the market stay more volatile for longer with a positive drift starting later (about mid-2017). However, the two increasing dynamics are quite similar and the green risk excess return ends up at the same level of about 0.02%.

Figure 5. Greenness excess return over time without Government green bonds



Notes: the left scale refers to the green risk excess return (λ_g) in %; the right scale refers to the cumulative number of green bonds that are in the sample.

In other words, by not considering Government green bonds, the market appears to reach a more mature phase later, although the landing point for the green risk excess return is the same. Overall, our model is able to explain the disparate empirical evidence recalled in Section 2, both across sectors and across time.

6. Pricing error analysis

In order to see whether the two-factor model estimated in Section 5 is able to predict green bond returns, in this section we analyse pricing error measures. We compute an in-sample analysis based on the same sample of 124 green bonds used to implement the pricing model. We do it first on the whole sample and then excluding Government bonds.

Pricing errors $a_{i,t}$ for green bond i at time t are retrieved from equation (2) and represent the difference between the market return (indicated by $R_{i,t}$) and the corresponding return predicted by the model equation (2) (indicated by $\widehat{R_{i,t}}$):

$$a_{i,t} = R_{i,t} - \widehat{R_{i,t}} \tag{9}$$

We focus on the mean absolute error (MAE) computed as follow:

$$MAE = \frac{1}{N \times T} \sum_{i=1}^{N} \sum_{t=1}^{T} |a_{i,t}| \tag{10}$$

where T is the total number of days and N is the total number of green bonds.[10]

For the full sample the absolute distance of the predicted yield from its market value is on average 0.23 percentage points (see Table 11) and differences among industries are not very pronounced: on average it varies from 0.20 percentage points of the Financials sector, to 0.34 percentage points for the Industrials sector. The MAE distribution is not significantly skewed since the mean is quite close to the median.

Table 11. Mean absolute error (MAE)

Industry	**Range (min - max)**	**Median**	**Mean**
Full sample (124 GB)	0.01 – 1.81	0.18	0.23
Financials (50 GB)	0.01 – 1.81	0.14	0.20
Government (45 GB)	0.03 – 0.58	0.26	0.25
Utilities (16 GB)	0.09 – 0.61	0.21	0.27
Industrials (7 GB)	0.08 – 0.9	0.27	0.34
Consumer Discretionary (5 GB)	0.04 – 0.20	0.19	0.15
Energy (1 GB)	-	-	0.17

[10] Results based on the mean absolute percentage error (MAPE) are qualitatively the same and are available upon request. We do not consider root mean squared error (RMSE) and mean squared error (MSE), because squaring the pricing error, they give more importance to errors whose absolute value is greater than one and are less suitable when analysing yields to maturity.

Notes: MAE is calculated from pricing errors retrieved from equation (2) and is expressed in percentage points. MAE is reported for the full sample and by issuer's sector. The number of green bonds in each sector is reported in brackets and when there is only a green bond in a sector only the mean is reported.

Table 12. Mean absolute error (MAE) without Government green bonds

Industry	Range (min - max)	Median	Mean
Full sample (79 GB)	0.03 – 1.52	0.15	0.20
Financials (50 GB)	0.03 – 1.52	0.11	0.17
Utilities (16 GB)	0.07 – 0.55	0.20	0.25
Industrials (7 GB)	0.05 – 0.82	0.23	0.30
Consumer Discretionary (5 GB)	0.09 – 0.28	0.18	0.18
Energy (1 GB)	-	-	0.12

Notes: MAE is calculated from pricing errors retrieved from equation (2) and is expressed in percentage points. MAE is reported for the full sample and by issuer's sector. The number of green bonds in each sector is reported in brackets and when there is only a green bond in a sector only the mean is reported.

Excluding Government bonds, the pricing performance slightly improves (Table 11), but overall we can conclude that the model has a good pricing performance over both samples, and hence it appears to be appropriate also for Government bonds

7. Conclusions

Fostered by an empirical literature providing disparate evidence on the green premium, we propose a theoretical framework based on a two-factor model whereby returns on green bonds are explained not only as a function of market risk but also of the bond greenness. Specifically, beside the risk premium associated to a conventional bond market, the second determinant that we propose as specifically characterizing green bonds can be interpreted as a greenness premium. Such premium can be either positive or negative depending on the product of the price given by the market to systemic greenness (greenness excess return) and the sensitivity of the specific GB to the latter (the GB idiosyncratic greenness).

We estimate the two-factor model following the approach originally proposed by Fama and MacBeth (1973) on a sample of 163 Euro-denominated green bonds over the period 8.10.2014 – 31.12.2019. The market factor used in our study is the excess return of the market portfolio, represented by the Bloomberg Barclays Euro Aggregate Bond Index. The second factor of our model, the green factor, was constructed as the difference between the return of a green bond portfolio and a portfolio consisting of equivalent synthetic conventional bonds. To this end we adopted the most popular matching method (e.g. Zerbib, 2019), which requires matching pairs of green and synthetic conventional bonds with identical properties except for their greenness.

The main results are as follows. First, from time-series estimate on the whole sample we find that all green bonds have, as expected, a positive sensitivity to the market risk factor (on average equal to 1.15) and the great majority of them (124 over 163) have a significant sensitivity to the green risk factor. The latter is on average negative and equal to -2.90, but its magnitude varies across sectors.

Second, cross section estimates on the 124 green bonds whose returns are also significantly explained by the green factor, provide estimates of the market excess return and the greenness excess return. While the former is, as expected, significant and positive (73.8 bps), the latter is significant and positive, but very small (0.7 bps). This suggests that on average taking an additional unit of greenness requires a return compensation, pointing to greenness being evaluated, on average over the full sample and the whole period, as a penalty. However, since the average sensitivity to the green factor is positive, the greenness risk premium is negative although quite small (-2.03 bps), with some variability in magnitude between sectors: e.g. for the two sectors issuing more green bonds, i.e. Financials and Government sectors, the green risk premium is on average -0.826 bps and -2.66 bps respectively.

Third, when excluding Government green bonds, which might be considered different from corporate ones, we can see that results on the market risk excess return are quite robust, while the average green risk excess return remains very small but becomes negative (-1.3 bps). Hence, when we consider the market of corporate bonds only, greenness is associated, on average over the sample and the whole period, to a small benefit and as such the market price for greenness is negative. However, accounting for the negative average sensitivity to the green factor, the green risk premium becomes positive (3.11 bps).

Fourth, in order to explain these average results, we look at the dynamics of the estimated green factor in relation to the growth of the green bond market, i.e the number of green bonds available for our estimates. While the latter significantly increases over the sample period, the green risk excess dynamics shows two distinct phases. In a first period (up to mid-2016) when the number of green bonds is low (below 20), the excess return is extremely volatile and most of the time positive. In a second period, up to the end of sample, the greenness excess return shows a positive drift that takes it from the lowest value of about -0.04% to the highest of about 0.02%. Focusing on this latter trend, we may conclude that, as the market becomes more mature with an increasing number of bonds, the greenness excess return, although still very small, becomes positive. By not considering Government green bonds, the market appears to reach a more mature phase later, although the landing point for the greenness excess return is the same. These results may be pointing to a convergence between green and conventional bonds in terms of risk and pricing.

Finally, the pricing performance of our two-factor model on the full sample is good in terms of MAE (in mean 23%). When excluding Government bonds, the pricing performance improves but slightly (20%), and overall we can conclude that the model has a good pricing performance over both samples. Thus the model appears to be appropriate also for Government green bonds, pointing to a sort of single market for greenness in bonds.

In sum, based on the two-factor model proposed and its estimation, we are able to answer a few main research questions that motivated our work. Does the market price greenness in bonds? If so, does it price it as a greenness penalty, requiring an extra return, or as a benefit, accepting lower return? Has the evaluation of greenness changed over time? We can conclude that the market does price greenness, but the price is very small: its dynamics over the sample shows that as the market becomes more mature, the market price for greenness in bonds has a positive drift landing to about 2 bps, which means greenness is priced as a penalty. On the whole, our results hint to a market where on average the difference in pricing between conventional and green bonds is, ceteris paribus, shrinking, which is consistent with the green bond market approaching a more mature phase. Overall, our model is able to explain the disparate empirical evidence provided by the literature on the greenium, both across sectors and across time.

Against a generally increased and increasing interest for sustainable finance, our results are relevant for many economic agents, including market participants and financial intermediaries, whereby the latter are also called by the regulator to manage their portfolio in consideration of climate risk.

Bibliography

Agliardi, E., & Agliardi, R. (2019). Financing environmentally sustainable projects with green bonds. *Environment and Development Economics*, *24*(6), 608-623.

Alessi, L., Ossola, E., & Panzica, R. (2019). *The Greenium matters: evidence on the pricing of climate risk* (No. 2019/12). JRC Working Papers in Economics and Finance.

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

Bachelet, M. J., Becchetti, L., & Manfredonia, S. (2019). The green bonds premium puzzle: The role of issuer characteristics and third-party verification. *Sustainability*, *11*(4), 1-22.

Baker, M., Bergstresser, D., Serafeim, G., & Wurgler, J. (2018). *Financing the response to climate change: The pricing and ownership of US green bonds* (No. w25194). National Bureau of Economic Research.

Bauer, R., & Smeets, P. (2015). Social identification and investment decisions. *Journal of Economic Behavior & Organization*, *117*(C), 121-134.

Carhart, M. M. (1997). On persistence in mutual fund performance. *The Journal of Finance*, *52*(1), 57-82.

Chen, N. F., Roll, R., & Ross, S. A. (1986). Economic forces and the stock market. *The Journal of Business*, *59*(3), 383-403.

Corporate Knights. (2020). 2020 Global 100 Issue. *Corporate Knights*, winter 2020.

Dorfleitner, G., Utz, S., & Zhang, R. (2021). The pricing of green bonds: external reviews and the shades of green. *Review of Managerial Science*, forthcoming.

Doronzo, R., Siracusa, V., & Antonelli, S. (2021). *Green Bonds: the Sovereign Issuers' Perspective* (No. 3). Bank of Italy, Directorate General for Markets and Payment System.

Elton, E. J., Gruber, M. J., & Blake, C. R. (1995). Fundamental economic variables, expected returns, and bond fund performance. *The Journal of Finance*, *50*(4), 1229-1256.

EU Technical Expert Group on Sustainable Finance (EU-TEG), (2019a), Financing a Sustainable European Economy, Report on EU Green Bond Standard, TEG report proposal for an EU Green Bond Standard, June.

EU Technical Expert Group on Sustainable Finance (EU-TEG), (2019b), Financing a Sustainable European Economy, Using the Taxonomy, Supplementary Report 2019 by the Technical Expert Group on Sustainable Finance, June.

Fama, E. F., & French, K. R. (1992). The cross-section of expected stock returns. *The Journal of Finance*, *47*(2), 427-465.

Fama, E. F., & MacBeth, J. D. (1973). Risk, return, and equilibrium: Empirical tests. *Journal of Political Economy*, *81*(3), 607-636.

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

Fender, I., McMorrow, M., Sahakyan, V., & Zulaica, O. (2019). *Green bonds: the reserve management perspective*. BIS Quarterly Review. Bank for International Settlements, September 2019.

Forbes. (2017). *Should you invest in green bonds?.* Forbes, June 29.

Gianfrate, G., & Peri, M. (2019). The green advantage: Exploring the convenience of issuing green bonds. *Journal of Cleaner Production*, *219*(3), 127-135.

Gollier, C. (2018). *Ethical Asset Valuation and the Good Society*. Columbia University Press.

Goyal, A. (2012). Empirical cross-sectional asset pricing: a survey. *Financial Markets and Portfolio Management*, *26*(1), 3-38.

Gutsche, G., & Ziegler, A. (2019). Which private investors are willing to pay for sustainable investments? Empirical evidence from stated choice experiments. *Journal of Banking & Finance*, *102*(C), 193-214.

Hachenberg, B., & Schiereck, D. (2018). Are green bonds priced differently from conventional bonds?. *Journal of Asset Management*, *19*(6), 371-383.

Harrison, C. (2017a). *Green Bond Pricing in the Primary Market: Q4 2016 Snapshot*. London: Climate Bonds Initiative.

Harrison, C. (2017b). *Green Bond Pricing in the Primary Market: Jan 2016–March 2017*. London: Climate Bonds Initiative and IFC.

Harrison, C., Partridge, C., & Tripathy, A. (2020). What's in a Greenium: An Analysis of Pricing Methodologies and Discourse in the Green Bond Market. *The Journal of Environmental Investing*, *10*(1), 64–75.

Hyun, S., Park, D., & Tian, S. (2020). The price of going green: the role of greenness in green bond markets. *Accounting & Finance*, *60*(1), 73-95.

International Capital Market Association (ICMA). (2018). *Green Bond Principles, Voluntary Process Guidelines for Issuing Green Bonds*. ICMA, June 2018. Available at https://www.icmagroup.org/sustainable-finance/the-principles-guidelines-and-handbooks/green-bond-principles-gbp/

Kapraun, J., Latino, C., Scheins, C., & Schlag, C. (2021). (In)-Credibly Green: Which Bonds Trade at a Green Bond Premium?. *Proceedings of Paris December 2019 Finance Meeting EUROFIDAI - ESSEC*, Available at SSRN: https://ssrn.com/abstract=3347337

Karpf, A., & Mandel, A. (2018). The changing value of the 'green' label on the US municipal bond market. *Nature Climate Change*, *8*(2), 161-165.

Kidney, S., & Oliver, P. (2014). *Growing a green bonds market in China: reducing costs and increasing capacity for green investment while promoting greater transparency and stability in financial markets.* International Institute for Sustainable Development.

Lebelle, M., Lajili Jarjir, S., & Sassi, S. (2020). Corporate green bond issuances: An international evidence. *Journal of Risk and Financial Management*, *13*(2), 1-21.

Larcker, D. F., & Watts, E. M. (2020). Where's the greenium?. *Journal of Accounting and Economics 69*(2-3), forthcoming.

Lintner, J. (1965). The Valuation of Risky Assets and the Selection of Risky Investments in Stock Portfolios and Capital Budget. *Review of Economics and Statistics*, *47*(1), 13-37.

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

Mossin, J. (1966). Equilibrium in a Capital Asset Market. *Econometrica*, *34*(4), 768-783.

Preclaw, R., & Bakshi, A. (2015). *The cost of being green.* Report, Barclays Credit Research.

Principles for Responsible Investment (PRI). (2017). *The SDG investment case*. Available at https://www.unpri.org/sustainable-development-goals/the-sdg-investment-case/303.article

Reboredo, J. C. (2018). Green bond and financial markets: Co-movement, diversification and price spillover effects. *Energy Economics*, *74*(C), 38-50.

Ross, S. A. (1976). The arbitrage theory of capital asset pricing. *Journal of Economic Theory*, *13*(3), 341-360.

Ross S. A. (1977). Return, risk and arbitrage. In: Irwin Friend and James L. Bicksler (eds.). Risk and Return in Finance. *Cambridge, Mass: Ballinger*, Vol. 1.

Rossi, M., Sansone, D., Van Soest, A., & Torricelli, C. (2019). Household preferences for socially responsible investments. *Journal of Banking & Finance*, *105*(C), 107-120.

Sharpe, W. F. (1964). Capital asset prices: A theory of market equilibrium under conditions of risk. *The Journal of Finance*, *19*(3), 425-442.

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

United Nations (UN) (2015), *Transforming our world: the 2030 Agenda for Sustainable Development.* Available at https://sdgs.un.org/2030agenda

Wang, J., Chen, X., Li, X., Yu, J., & Zhong, R. (2020). The market reaction to green bond issuance: Evidence from China. *Pacific-Basin Finance Journal*, *60*(C), forthcoming.

Widyawati, L. (2020). A systematic literature review of socially responsible investment and environmental social governance metrics. *Business Strategy and the Environment*, *29*(2), 619-637.

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

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