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Green bonds and sustainable finance: a multidimensional analysis of macroeconomic and environmental determinants across nine countries

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Abstract

This study investigates the macroeconomic and environmental determinants of green bond issuances in a sample of nine countries, including eight OECD members and Brazil, from 2013 to 2023. Employing a fixed effects model on a comprehensive unbalanced panel dataset, our analysis reveals that strong institutional and structural factors are paramount. We find that Regulatory Quality, R&D Expenditures, and rising Energy Prices are significant positive drivers of green bond issuance. Conversely, a higher reliance on Fossil Fuels in the energy mix is associated with lower issuance. Critically, we uncover a counter-intuitive negative relationship between green bond issuance and the national Carbon Intensity of Economic Production. This suggests that for the most carbon-intensive economies, the perceived 'need' for a green transition is insufficient on its own to attract green investment. The robustness of these findings is rigorously tested and confirmed through multiple advanced methods, including the application of False Discovery Rate (FDR) corrections to address multiple hypothesis testing and first-difference estimations to guard against spurious regressions. Furthermore, our analysis demonstrates that these effects are not only statistically significant but also economically substantial. Our results indicate that market credibility, strong governance, and a commitment to innovation, rather than structural environmental challenges, are the primary drivers of a successful green bond market.

Keywords Green bonds · Sustainable finance · Regulatory quality · Panel data analysis · Environment · Renewable energy

JEL Classification Q56 · G12 · D73 · C23 · F64 · Q42

Extended author information available on the last page of the article

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1 Introduction

The escalating challenges of climate change and environmental degradation necessitate urgent and globally coordinated policy responses. The Paris Agreement (UNFCCC, 2015) stands as a pivotal international accord, galvanizing efforts to limit global warming and transition towards sustainable economies. Central to this transition is the mobilization of green finance, which aims to channel capital towards environmentally beneficial projects and technologies. Green bonds have rapidly emerged as a key instrument within this paradigm, designed to fund projects that deliver positive environmental outcomes, ranging from renewable energy and energy efficiency to sustainable transport and biodiversity conservation. Following their initial issuance by multilateral development banks like the European Investment Bank (2022) and the World Bank (2018), the green bond market has witnessed exponential growth, particularly post-Paris Agreement, reflecting an increasing investor appetite and issuer commitment to sustainability. Understanding the multifaceted factors that drive the issuance of these crucial financial instruments is paramount for accelerating the transition to a low-carbon future. This study addresses this need by analysing the key macroeconomic and environmental determinants of green bond issuance across a selection of leading countries in this market.

This study makes a distinct contribution to the burgeoning literature on green finance by undertaking a multidimensional analysis of the determinants of green bond issuance across nine countries with heterogeneous economic and environmental landscapes. While prior research has often examined the influence of macroeconomic or environmental factors in isolation, this paper pioneers an integrated approach, concurrently investigating the combined and interactive effects of key variables such as economic growth, energy prices, regulatory quality, carbon footprint, fossil fuel dependency, renewable energy consumption, and R&D expenditures. By moving beyond a uni-dimensional focus, our research elucidates the complex interplay between economic imperatives and environmental considerations in shaping green bond markets. For instance, we explore how the impact of energy price fluctuations on green bond issuance might be moderated by a country's existing renewable energy capacity or its commitment to reducing fossil fuel dependency. Furthermore, the inclusion of a diverse panel of developed and emerging economies allows for a more nuanced understanding of how these dynamics vary across different institutional and developmental contexts, offering insights of broader applicability than single-country or regionally focused studies. This holistic perspective is critical for formulating comprehensive policy interventions and investment strategies that can effectively accelerate the growth of green bond markets globally. This paper aims to identify the macroeconomic determinants of green bond issuance in emerging markets, with a particular focus on how the carbon intensity of a country's economic structure may create systemic incentives for a transition to green finance.

The issuance of green bonds is shaped by a complex interplay of both supply-side and demand-side dynamics. On the supply side, entities such as governments, corporations, and financial institutions are motivated to issue green bonds to finance environmentally beneficial projects, enhance their corporate social responsibility profile, meet evolving regulatory expectations, or potentially access a broader investor base.

On the demand side, investors are increasingly driven by mandates for sustainable and responsible investment, the pursuit of long-term value alignment with environmental goals, potential diversification benefits, and in some cases, the expectation of a 'greenium'. The net impact of certain macroeconomic or country-specific characteristics on green bond issuance can therefore be ambiguous, as these factors might influence supply and demand pressures in opposing directions. For instance, while a high national fossil fuel dependency might signal a greater need for green financing to facilitate an energy transition (potentially increasing supply), it might simultaneously deter demand from climate-conscious investors wary of transition risks or policy inconsistencies. Acknowledging these dual influences is crucial for developing a nuanced understanding of green bond market determinants, a perspective that informs the hypotheses tested in this study.

The remainder of this study is structured as follows. Section 2 presents the survey of relevant studies related to green bonds. In Sect. 3 we lay out the variables, data set, model and method. In Sect. 4 we discuss the empirical findings. The paper concludes with final remarks, suggestions for potential stakeholders in this field, and recommendations for further studies.

2 Related research

An extensive empirical literature on green bonds has developed since the rapid growth of the green bond market. Research on green bonds has different perspectives.

The majority of studies concentrate on the application of green bonds in stock markets. In this literature green bond issuance has been analyzed from different points of views. Some studies analyze premium for green bonds (Bachelet et al., 2019; Macaskill et al., 2021). Some studies examine the relationship between the green bond market and financial markets (Reboredo, 2018; Reboredo & Ugolini, 2020). Another study (Wang et al., 2020) analysed the reaction of the debt and stock market to corporate green bond issuance. Pham and Nguyen (2022) examined the impact of economic policy, and stock and oil market on the green bond market.

There is an extensive literature that studies the relationship between green bonds and energy consumption. Mirgen and Tepeli (2024) analysed the effect of the total energy consumption (both fossil fuel and renewable energy consumption) on the green bond issuance in 12 countries. The authors found a significant relationship between renewable energy and green bond issuance, but negative relationship with the fossil fuels and the green bond issuance. These results show similarities with our work. Huang et al. (2023) focused on the interaction between the green bonds and fossil fuel consumption in top ten environmentally conscious nations. The authors demonstrated that the rise of green bond issuance leads to a decrease in fossil fuel consumption. Similar to this work, we found a negative correlation between fossil fuel consumption and the green bond issuance.

Most of the studies examine the relationship between the green bonds and the renewable energy. In this framework, Dong et al. (2023) selected Southeast Asian countries in their research. Wang and Taghizadeh-Hesary (2023) concentrated on OECD countries. Taghizadeh-Hesary et al. (2023) focused on Japan for the research.

All these studies emphasized the linear relationship between green bonds and renewable energy consumption. Taghizadeh-Hesary et al. (2023) also analysed the energy price volatility effect on renewable energy consumption in their study. One contribution of our research to this literature is examining the green bonds in relation to both energy prices and energy consumption.

Some quantitative work has examined the role of green bonds on the carbon emission level. (ElBannan & Löffler, 2024; Fatica & Panzica, 2021; Flammer, 2020; Xu & Li, 2023). Flammer chose a sample of 217 corporate green bonds issued by public companies. Fatica and Panzica, (2021) used 1105 green bonds issued worldwide by the corporate sector. Xu and Li (2023) used the data of the cities in China; ElBannan and Löffler (2024) investigated the 2139 green bonds of non-financial corporates. These studies concluded that green bonds decrease carbon emissions. Our paper contributes to this empirical literature by investigating the interaction between green bond issuance and the carbon emission. We differ from these studies by examining the impact of carbon intensity of economic production on green bond issuance.

A few works have examined the renewable energy investment and green bond issuance (Ye & Rasoulinezhad, 2023; Zhao et al., 2022, 2023). Ye and Rasoulinezhad (2023) selected 15 Asia–Pacific countries. Zhao et al. (2022) investigated the data of BRI (Belt and Road Initiative) nations. The authors of both studies found significant impacts of the green bonds on renewable natural resource utilization efficiency. Zhao et al. (2023) examined the connection between green bonds and the investment efficiency of renewable energy in China. Their study reveals that green bond issuance has an adverse impact on the investment efficiency of renewable energy (REIE). Another strand of literature this study contributes to is the renewable energy literature, that considers the role of renewable energy investment, and research and development expenditures on green bond issuance.

There is limited literature that addresses the relationship between the energy price and the green bond market. The literature comprising the energy prices focuses on correlation between oil prices and green bonds (Abakah et al., 2023; Wang et al., 2023). One research (Azhgaliyeva et al., 2022) emphasized the oil price shock and investigated the effect of oil price shocks on the issuance of corporate green bonds. To add value to this literature, we examined the impact of the energy prices on the green bond issuance.

A few quantitative studies focused on the factors affecting green bond issuance (Bužinskė & Stankevičienė, 2023; Tu et al., 2020; Cicchiello et al., 2022). Bužinskė and Stankevičienė, (2023) observed the factors influencing green bond issuance in Lithuania and they concluded that reputation, good credit rating, and the environmental, social, and governance score of the issuer are the key factors for the success in green bonds issuance. Tu et al. (2020) analysed the factors that affect green bond issuance in Vietnam. According to the authors, legal infrastructure, official interest rate of green bonds, and economic stability directly affect green bond market expansion. Cicchiello et al. (2022) investigated the factors that affect the green bond issuance of the firms. Their findings show that current ratio, long-term debt, independent director, and board size affect the decision of firms between green or conventional bonds. Since the aim of our study is to investigate the factors affecting green bond issuance, this study will make a broad contribution to this literature. Our study focuses on nine

countries and offers a broad perspective on the factors affecting green bond issuance, considering both macroeconomic factors and environmental factors.

The above summarized literature focused on the impact of green bond issuance on different variables. Our study differs from these works by presenting the impact of selected variables on the green bond issuance. In this sense, our study provides a broad framework about the variables relevant to environmental issues like renewable energy consumption, energy prices and fossil fuel dependency. Furthermore, we include some macro-economic variables like Gross Domestic Product (GDP) growth, regulatory quality, carbon intensity of economic production and research and development expenditures. We chose GDP growth as a crucial variable related to environmental issues. A World Bank study by Low (1992) found that as nations become richer, they voluntarily adopt more environmentally friendly approaches to economic development and become increasingly concerned about sustainable development. Carbon footprints of bank loans (CFBL) are developed by the IMF. This indicator requires deposit takers' domestic loans by industry data and estimates carbon emission factors by industry for selected countries (IMF, 2024b). Regulatory quality is measured by the World Bank under the Worldwide Governance Indicators (WGI), which does not have a specific sub-indicator within it. Regulatory quality is generally considered as a component of good governance and policy quality. It refers to perceptions of the government's capacity to design, implement and maintain effective policies and regulations that encourage and enable the development of the private sector (World Bank, 2025).

A comprehensive review of the existing literature reveals several critical gaps that this study aims to address. Firstly, while numerous studies have explored the impact of green bond issuance on various economic and environmental outcomes, or the relationship between green bonds and specific factors like renewable energy or carbon emissions in isolation, there is a discernible scarcity of research that systematically investigates the determinants of green bond issuance through a multifaceted lens. Many existing analysis tend to focus on a narrow set of drivers, often neglecting the concurrent influence of a broader suite of macroeconomic conditions and environmental pressures.

Secondly, the interaction effects between macroeconomic variables (e.g., energy prices, regulatory quality) and environmental variables (e.g., carbon footprint, fossil fuel dependency) in shaping green bond issuance remain largely underexplored. Understanding these interactions is crucial, as the efficacy of policies promoting green bonds may depend on the prevailing economic and environmental context. For example, the incentive to issue green bonds in response to rising energy prices might be significantly different in countries with high versus low fossil fuel dependency.

Thirdly, while some studies touch upon energy prices, they often focus on specific shocks like oil price volatility, rather than the broader impact of general energy price levels and fluctuations. Similarly, the role of regulatory quality, a cornerstone of sustainable financial market development, has not received commensurate attention in the context of green bond issuance determinants across a diverse set of countries. There are some studies in the literature examining the relationship between regulatory quality and green bonds. These studies reveal that the effectiveness and consistency of regulatory frameworks play a decisive role in the development and functioning of

green bond markets. In particular, the findings of these studies show that a strong and transparent regulatory environment increases the liquidity of green bond markets, reinforces market reliability and stimulates the effectiveness of sustainable financing mechanisms Caroline, 2020; Otek Ntsama, et al, 2021; Cheng et al., 2024; Liu & Li, 2024; Hamrani et al., 2025). Therefore, the positive effect of regulatory quality on green bond markets can be considered as a critical factor in financing the sustainable development goals.

Beyond the pivotal role of regulatory quality in green bond markets, a broader examination of the institutional context offers significant insights into the determinants of green bond issuance. In this regard, it is not merely the capacity of governments to formulate and implement sound policies that is decisive, but also specific institutional arrangements. For instance, the existence and stringency of national green finance strategies and taxonomies can reduce uncertainty and facilitate more effective capital allocation by providing a clear roadmap for issuers and investors (see, e.g., Ehlers & Packer, 2017; OECD, 2017). Similarly, robust governance mechanisms, including the rule of law, control of corruption, and political stability, are fundamental for fostering investor confidence, which is particularly crucial for the growth of nascent markets like green bonds (Banga, 2019; Tolliver et al., 2019).

The literature also underscores the importance of public institutions or development banks in pioneering green bond issuances and catalysing market development, especially in emerging economies where they can play a de-risking role and signal market viability (Kidney, 2018; World Bank, 2019). Furthermore, adherence to and adoption of international standards and principles, such as the ICMA Green Bond Principles, can enhance market credibility, attract international investors, and thereby link domestic institutional frameworks to global best practices (Maltais & Nykvist, 2020; Zerbib, 2019). Consequently, a comprehensive understanding of green bond determinants necessitates an analysis that extends beyond broad regulatory metrics to encompass these multifaceted institutional dimensions. While the present study incorporates regulatory quality, thereby addressing one facet of this context, future research could profitably delve deeper into these broader institutional interactions and their nuanced impacts on green bond market dynamics.

This study directly confronts these lacunae by:

1. Providing a Comprehensive Determinants Framework: We develop and test an econometric model that integrates a wide array of both macroeconomic (economic growth, energy prices, R&D expenditures, regulatory quality) and environmental (carbon intensity of economic production, fossil fuel dependency, renewable energy consumption) variables to offer a holistic understanding of the factors driving green bond issuance.
2. Highlighting Combined Effects: Our approach allows for an implicit understanding of how these factors collectively influence green bond markets, moving beyond the piecemeal analysis prevalent in the literature. While this study does not explicitly model interaction terms, the inclusion of diverse variables within a unified panel data model provides richer insights than studies focusing on single determinants.

3. Broadening Country Scope and Contextual Nuance: By analysing a panel of nine countries that are active green bond issuers and represent a mix of developed and emerging economies, this research offers findings that are more generalizable and sensitive to different economic and regulatory environments. This comparative perspective is vital for understanding the global dynamics of green finance.
4. Focusing on Under-Researched Linkages: We place particular emphasis on the roles of overall energy prices and regulatory quality, factors whose influence on green bond issuance warrants more thorough investigation.

In doing so, this paper offers a novel and more complete perspective on what drives countries to issue green bonds, thereby providing valuable insights for policymakers aiming to foster these markets, investors seeking sustainable opportunities, and researchers advancing the frontiers of green finance.

Having reviewed the existing literature, we now turn our attention to the methodology employed in this research.

3 Methodology

We employed a static panel data model to analyse relationships, using data from 2013 to 2023 (T = 11) across nine countries (N = 9). The relatively short time period (T < 20) meant that panel unit root tests were not utilized because these tests are designed for larger time periods, and using the tests in a short time period can lead to low power and size distortions (Baltagi, 2005; Hsiao, 2014).[1] As such, a static panel data model was utilized because this type of model is appropriate for short time periods. This type of model combines cross-sectional and time data and can reveal individual and time differences; thus, it is suitable for this study, therefore it was chosen.

A general static panel data model can be expressed as follows:

$$y_{it} = \alpha_i + \beta' X_{it} + \varepsilon_{it}, \quad i = 1, \ldots, N; t = 1, \ldots, T \tag{1}$$

where

- y_{it} is the dependent variable for cross-sectional unit *i* at time *t*,
- α_i represents the unobserved individual-specific effect,
- X_{it} is a vector of explanatory variables,
- β is a vector of coefficients to be estimated,
- ε_{it} is the idiosyncratic error term, assumed to satisfy $E(\varepsilon_{it}) = 0$ and $Var(\varepsilon_{it}) = \sigma^2$.

The static panel data framework allows for the estimation of two primary models: the Fixed Effects (FE) Model and the Random Effects (RE) Model.

The fixed effects model assumes that the unobserved individual-specific effects (α_i) are correlated with the explanatory variables (X_{it}). To eliminate α_i, the within

[1] Therefore, unit root tests are not used in this study.

transformation is applied, which subtracts the time-averaged values of each variable from the original equation:

$$y_{it} - \underline{y_i} = \beta' \left(X_{it} - \underline{X_i}\right) + \left(\varepsilon_{it} - \underline{\varepsilon_i}\right) \tag{2}$$

where $\underline{y_i} = \frac{1}{T}\sum_{t=1}^{T} y_{it}$ and $\underline{X_i} = \frac{1}{T}\sum_{t=1}^{T} X_{it}$.

This transformation removes the individual-specific effects (α_i), allowing the estimation of β using Ordinary Least Squares (OLS) on the transformed data. However, this approach does not allow for the inclusion of time-invariant explanatory variables, as they are eliminated during the transformation process (Baltagi, 2005).

The random effects model assumes that the unobserved individual-specific effects (α_i) are uncorrelated with the explanatory variables (X_{it}). In this case, the model can be estimated using Generalized Least Squares (GLS), which accounts for the composite error term:

$$u_{it} = a_i + \varepsilon_{it}. \tag{3}$$

The variance of the composite error term is given by:

$$Var(u_{it}) = \sigma_a^2 + \sigma_\varepsilon^2, \tag{4}$$

and the GLS estimator uses a transformation to account for the correlation between α_i, and the idiosyncratic error term ε_{it}. The transformed model is:

$$y_{it} - \theta\underline{y_i} = \beta' \left(X_{it} - \underline{\theta X_i}\right) + \left(\varepsilon_{it} - \theta\underline{\varepsilon_i}\right) \tag{5}$$

where $\theta = 1 - \sqrt{\frac{\sigma_\varepsilon^2}{\sigma_a^2 + T\sigma_\varepsilon^2}}$ is the transformation parameter.

The RE model allows for the inclusion of time-invariant variables, making it more flexible than the FE model under the assumption of no correlation between α_i and X_{it} (Hsiao, 2014).

The choice between the FE and RE models depends on whether the unobserved individual-specific effects (α_i) are correlated with the explanatory variables (X_{it}). The Hausman test (Hausman, 1978) is used to test this assumption. The null hypothesis is that $Cov\left(a_i, X_{it}\right) = 0$, in which case the RE model is preferred due to its efficiency. If the null hypothesis is rejected, the FE model is more appropriate as it provides consistent estimates.

In cases where $\alpha_i = 0$ or is assumed to be homogeneous across all cross-sectional units, the pooled OLS model can be used. However, this approach is often inappropriate for panel data as it ignores unobserved heterogeneity, leading to biased and inconsistent estimates (Baltagi, 2005).

The choice of the appropriate panel data estimation technique is crucial for obtaining reliable and consistent results. In this study, we considered Pooled Ordinary Least Squares (OLS), Fixed Effects (FE), and Random Effects (RE) models. Preliminary diagnostic tests, including the Breusch-Pagan Lagrange Multiplier (LM) test for ran-

dom effects, indicated the presence of significant unobserved heterogeneity, thereby ruling out the appropriateness of the Pooled OLS model. Subsequently, to discriminate between the FE and RE specifications, the Hausman (1978) specification test was performed. The results of the Hausman test for our primary model specification ($\chi^2(7)=28.01$, p-value$=0.00$, as reported with Model 1 in Table 5 diagnostics) provided strong evidence against the null hypothesis that the unobserved individual-specific effects are uncorrelated with the explanatory variables. This outcome signifies that the RE estimator would be inconsistent. Consequently, the Fixed Effects (FE) model, which controls for time-invariant unobserved heterogeneity by transforming the data, was deemed the most appropriate and consistent estimation strategy for analysing the determinants of green bond issuance in our panel. All reported regression results are therefore based on the FE specification.

Static panel data models provide a robust framework for analysing datasets with both cross-sectional and time-series dimensions. The FE model is suitable when unobserved individual-specific effects are correlated with the explanatory variables, while the RE model is appropriate when these effects are uncorrelated. The Hausman test serves as a diagnostic tool to guide model selection. These models are particularly valuable for controlling for unobserved heterogeneity and improving the reliability of econometric estimates.

3.1 Sample and data selection

This research employs a carefully curated panel dataset focusing on green bond issuances across nine developed economies from 2013 to 2023. The selected countries—Brazil, Canada, France, Germany, Italy, Japan, Netherlands, Republic of Korea, and Spain—represent significant players in the global green finance landscape. This period was strategically chosen to capture the emergence and evolution of green bond markets following the Paris Agreement in 2015 and the subsequent acceleration of sustainable finance initiatives.

The rationale for country selection is grounded in prior research by Abhilash et al. (2022) and Reboredo (2018), who highlighted these nations' pivotal roles in sustainable financial markets. The sample represents diverse economic contexts, ranging from emerging markets like Brazil to advanced economies like Germany and Japan, providing a comprehensive perspective on green bond dynamics. Beyond their established presence in green finance, the selected nine countries (Brazil, Canada, France, Germany, Italy, Japan, Netherlands, Republic of Korea, and Spain) were chosen to provide a balanced and heterogeneous sample. This cohort includes major developed economies with advanced financial markets and significant environmental policy frameworks, as well as key emerging markets actively engaging in sustainable development. Such diversity is instrumental for the objectives of this study, as it allows for an examination of green bond determinants across varied economic structures, levels of industrialization, regulatory environments, and specific environmental pressures. This heterogeneity enhances the external validity of our findings and provides a richer understanding of how macroeconomic and environmental factors interact to influence green bond issuance in different national contexts, rather than reflecting idiosyncratic national characteristics.

We selected nine countries, and they all issued green bonds in the period between 2013 and 2023. This provides a useful amount of data for comparison because they were selected because they are a mix of developed and developing countries. This allows us to examine how green bonds operate in different kinds of economies; thus, these countries are also particularly engaged with green finance and the environment. This makes them good examples to learn from, and finally, these countries issue a lot of green bonds. Given its status as one of the top issuers in the global green bond market, insights from this study will shed light on how green bonds are issued in developed and developing countries, thus enriching our understanding of green bonds and their development. The final panel dataset consists of 99 country-year observations. However, 19 of these observations for the dependent variable, lngb, were missing. Acknowledging that the treatment of missing data is critical for the validity of empirical results, we adopted a rigorous, multi-faceted strategy to ensure the robustness of our findings, directly addressing the concerns raised. Instead of relying on a single imputation method, we test our model under two distinct and widely accepted approaches as recommended in the statistical literature.

First, we conduct a Complete Case Analysis (CCA), also known as listwise deletion. This approach includes only those observations for which all variables are present, reducing the sample to 80 complete country-year observations. While CCA is the most straightforward approach, it can suffer from reduced statistical power and potential bias if the data are not missing completely at random (Little & Rubin, 2002).

Second, to overcome the limitations of CCA and provide a more sophisticated treatment, we employ Multiple Imputation by Chained Equations (MICE). MICE is a state-of-the-art simulation-based technique that is considered the gold standard for handling missing data (Rubin, 1987; van Buuren, 2018). Rather than filling in a single value for each missing data point, MICE generates multiple (in our case, $m = 10$) plausible imputed datasets. It operates under the assumption of Missing at Random (MAR), where the probability of a value being missing depends on other observed variables in the dataset. The regression model is then fitted to each of the 10 imputed datasets, and the results are pooled into a single set of estimates using Rubin's rules (Rubin, 1987). This process correctly incorporates the uncertainty associated with the missing data, leading to more accurate standard errors and valid statistical inferences.

A potential concern in our analysis is the treatment of 19 missing observations for our dependent variable, lngb. Our primary specification addresses this using Multiple Imputation by Chained Equations (MICE), a robust method for handling missing data that avoids the significant loss of statistical power and potential selection bias associated with listwise deletion (Little & Rubin, 2019).

However, to ensure full transparency and address the contentious nature of imputing a dependent variable, we conduct a crucial robustness check. We re-estimate our main fixed-effects model using a complete-case analysis, which involves removing the 19 observations with missing lngb values entirely. The results of this analysis are presented in Appendix Table 13.

Reassuringly, the findings from this subsample are highly consistent with our main results. The signs, magnitudes, and statistical significance of all key coefficients remain stable, confirming that our findings are not driven by the imputation procedure. This demonstrates the robustness of our conclusions and validates our choice

of MICE as an appropriate strategy to maximize data utilization while preserving the integrity of the results.

By presenting the results from both the conservative CCA and the robust MICE approaches, we demonstrate that our core findings are not an artifact of a particular missing data strategy and remain consistent across different methodological assumptions.

To provide a clear contextual overview of the cross-country patterns in green bond issuance before presenting the regression analysis, Fig. 1 displays the total issuance volume for each country in our sample over the 2013–2023 period.

The chart highlights the significant heterogeneity in market size, with countries like France, Germany, and the Netherlands emerging as dominant issuers. This visual representation underscores the cross-sectional variation that our econometric model aims to explain.

3.2 Model specification

The selection of independent variables for this study was guided by a synthesis of established economic theory, empirical evidence from the green finance literature, and data availability for the chosen panel of countries. We aimed to construct a comprehensive model that captures the primary macroeconomic drivers (economic growth, energy prices, R&D expenditures, regulatory quality) and critical environmental dimensions (carbon intensity of economic production, fossil fuel dependency, renewable energy consumption) hypothesized to influence the propensity for green

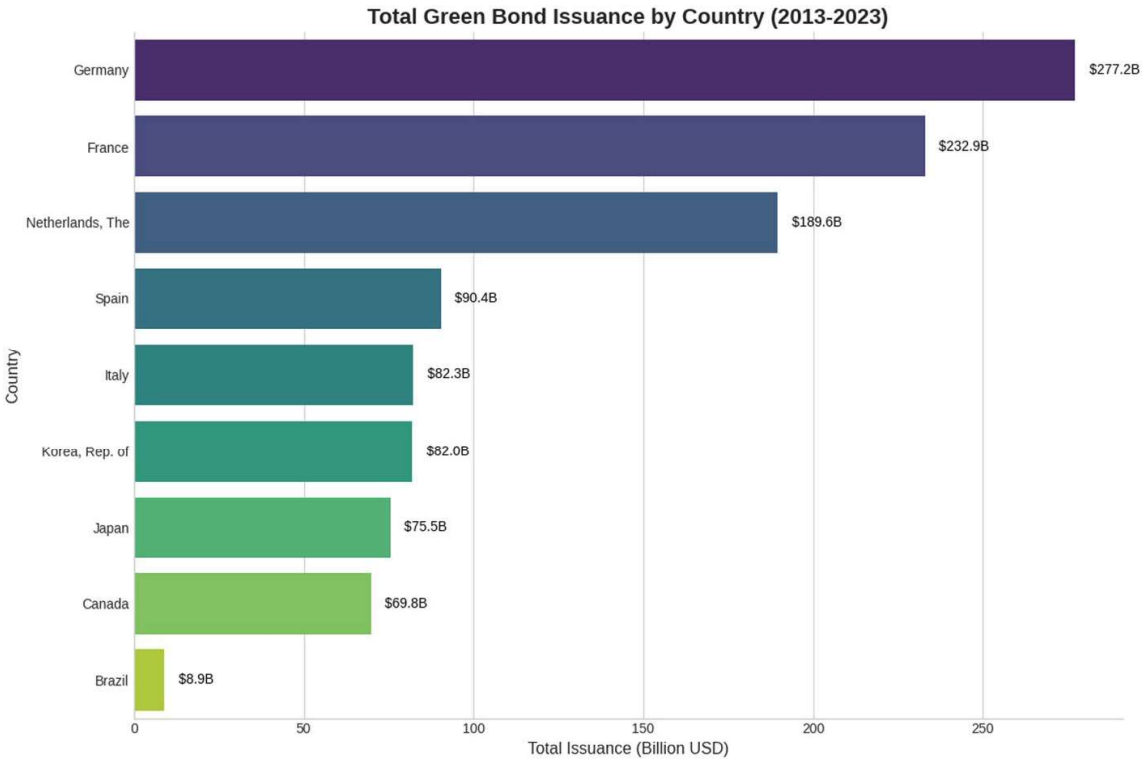


Fig. 1 Total Green Bond Issuance by Country (2013–2023, Billion USD, calculated by the authors) *Source*. Authors' calculations based on data from the IMF Climate Change Indicators Dashboard (IMF, 2024a)

bond issuance. This multi-causal approach allows for a more nuanced analysis than studies focusing on a limited set of determinants, reflecting the complex decision-making environment faced by potential issuers.

The econometric model is specified as:

$$GreenBondIssuance(GBI)_{it} = \beta_0 + \sum_{k=1}^{7} \beta_k X_{kit} + \alpha_i + \epsilon_{it}$$

where

- i: represents individual countries
- t: represents time periods
- β_0: Constant term
- X_{kit}: Vector of independent variables
- α_i: Country-specific fixed effects
- ϵ_{it}: Error term

This model critically examines green bond issuance as the dependent variable, with a focused analytical approach on investigating the multifaceted influences of energy consumption, carbon emissions, renewable energy investments, and energy pricing dynamics. Drawing substantive theoretical and methodological insights from seminal works by Flammer (2021) and Zerbib (2019), the model is strategically designed to unpack the complex interrelationships between these pivotal environmental and financial dimensions. The open form of the model is as follows:

$$\begin{aligned} GBI_{it} = \beta_0 + \beta_1 GDP_{it} + \beta_2 EnPr_{it} + \beta_3 Foot_{it} + \beta_4 Ff_{it} \\ + \beta_5 ReDev_{it} + \beta_6 RQ_{it} + \beta_7 RenEn_{it} + \epsilon_{it} \end{aligned}$$

In this study, we investigate the factors influencing green bond issuances, measured in billion US dollars, following the methodology of Gianfrate and Peri (2019). Our analysis includes several independent variables:

- Economic Growth (GDP): Based on Stern's (2007) climate economics framework, we expect higher economic growth to correlate with increased green bond issuances. $(\beta_1 > 0)$
- Energy Prices (EnPr): Using Parker's (2024) methodology, we assess the impact of energy costs on issuances, capturing price fluctuations accurately. $(\beta_2 > 0)$ The energy price variable (EnPr) is represented by the Global Monthly Energy Consumer Price Index developed by Parker (2024). We utilize the annual aggregated version of this index. The construction of this comprehensive index is fully transparent and reproducible, with data and code publicly available (Parker, 2024). Specifically, the index is constructed as a weighted average of the consumer prices for three core energy components: transportation fuels (gasoline/petrol), electricity, and natural gas. The raw price data is sourced from reputable international bodies, including the World Bank's Global Economic Monitor (GEM), the

International Energy Agency (IEA), and Eurostat. The construction methodology involves several key steps:

- All national prices are converted to a common currency (US dollars).
- The nominal prices are then deflated using the U.S. Consumer Price Index to create real price series with a base year of 2015 (2015 = 100).
- For each country, these three real price series are aggregated into a single index using weights derived from each component's share in final household energy consumption, as reported in the IEA's World Energy Balances.

The final EnPr variable is therefore a unitless real price index that robustly captures the energy cost burden on consumers in each country.

- Carbon intensity of economic production (Foot): To enhance clarity and accurately reflect its measurement, we have renamed the lnfoot variable to Carbon Intensity of Economic Production. This variable is constructed using the OECD Inter-Country Input–Output Database, supplemented by IMF staff calculations (Yamano et al., 2021). It is important to note that this variable does not directly measure the carbon footprint of specific bank loan portfolios but instead serves as a top-down, economy-wide proxy. The methodology assesses the carbon emissions embedded in the national production structure by linking sectoral economic activity from the input–output tables with corresponding emissions data. A higher value signifies a greater dependence on carbon-intensive industries (e.g., heavy manufacturing, fossil fuel extraction) within the national economy. We retain this variable under its new definition as it represents the broader economic context in which banks and financial markets operate. While one might intuitively assume that countries with higher carbon intensity have a greater 'need' for green finance, we hypothesize that the opposite relationship holds. High carbon intensity often correlates with weaker environmental regulations, a lack of political will for a green transition, and a higher perceived risk of 'greenwashing' by investors (Yousaf et al., 2023). Such environments may lack the institutional credibility and transparency necessary to attract capital to green bond markets. Investors may be wary of financing projects in economies where the commitment to genuine environmental impact is questionable. Therefore, we predict that higher carbon intensity, acting as a proxy for a less credible green policy environment, will be negatively associated with green bond issuance. This leads to our primary hypothesis:

  - H1: There is a negative relationship between carbon intensity (lnfoot) and green bond issuance.

  - Fossil Fuel Dependency (Ff): Similarly, the relationship between a country's fossil fuel dependency and its green bond issuance can be viewed through competing lenses. $(\beta_4 > 0, \beta_4 < 0)$H2a (Positive Impact—Supply-Driven Transition Pressure): Countries with greater fossil fuel dependency face a more pronounced and urgent need to transition towards cleaner energy sources, as highlighted by international agreements like the Paris Agreement

(see UNFCCC, 2015). This imperative could stimulate the supply of green bonds as a critical financing mechanism for large-scale renewable energy infrastructure, energy efficiency improvements, and other decarbonization initiatives (cf. IEA, 2021 reports on financing clean energy transitions).

- H2b (Negative Impact—Demand Concerns/Incumbent Resistance): Alternatively, high fossil fuel dependency could act as an impediment to green bond issuance. Strong incumbent fossil fuel industries might create political or economic inertia, resisting a rapid green transition (as discussed in Newell & Paterson, 2010 on the political economy of climate change) and diverting policy focus and investment away from green alternatives. Moreover, international investors might perceive countries with entrenched fossil fuel dependency as carrying higher transition risks or lacking a credible long-term decarbonization strategy (cf. Caldecott, 2018 on stranded assets and transition risk), thereby dampening demand for their green bonds or making issuance more challenging due to concerns about policy continuity.
  The observed relationship will reflect the dominant force between the urgency to finance a transition and the structural or perceptual barriers hindering green bond market development.

- Research and Development (R&D) Expenditures (ReDev): Based on Schumpeterian innovation theory and OECD standards, countries investing more in R&D may issue more green bonds for sustainable projects. $(\beta_5 > 0)$
- Regulatory Quality (RQ): Regulatory Quality (lnrq) is measured using the specific "Regulatory Quality" indicator from the World Bank's Worldwide Governance Indicators (WGI) project. This indicator is a composite measure that "captures perceptions of the ability of the government to formulate and implement sound policies and regulations that permit and promote private sector development." The estimate is based on a wide range of surveys from firms, citizens, and experts. It is reported on a scale ranging from approximately −2.5 (weak governance) to +2.5 (strong governance). We use this indicator as it directly reflects the stability and predictability of the policy environment, which is a crucial precondition for fostering long-term investments such as green bonds. Captured by the World Bank Governance Indicators, higher regulatory quality may lead to more green bond issuances due to a favorable environment for sustainable finance. $(\beta_6 > 0)$
- Renewable Energy Consumption (RenEn): Aligned with UN Sustainable Development Goal 7, countries with higher consumption may issue more green bonds to expand clean energy infrastructure. $(\beta_7 > 0)$

The primary objective of this study is to provide insights into the drivers of the green bond market and contribute to sustainable finance literature. In this framework, the variables, units, and data sources are listed in the table below (Table 1).

Analysis for the model were conducted using a double logarithmic transformation. After outlining our methodology, we present the findings and discuss their implications for green bond issuance.

Table 1 Variable, unit and data source

Variable	Unit	Data Source
Green Bond Issuances (gb)	Billion US Dollars	IMF / Climate Change Indicators Dashboard (IMF, 2024a)
Economic Growth (gdp)	Constant 2015 US$	World Bank Database
Energy Price (enpr)	Index (2015 = 100)	Parker (2024), based on IEA, WB, Eurostat
Carbon Intensity of Economic Production (foot)	Ratio (based on emission intensities—normalized)	Constructed from OECD Inter-Country Input–Output Database and IMF staff calculations
Fossil Fuels (ff)	Megawatt (MW)	International Renewable Energy Agency (IRENA, 2022) classifications
Research and Development Expenditure (redev)	% of GDP	World Bank Database
Regulatory Quality (rq)	percentile rank	World Bank Governance Indicators
Renewable Energy Consumption (renen)	% of total final energy consumption	World Bank Database

Table 2 Diagnostic tests for the fixed effects model

Test	Null Hypothesis	Statistic	*p*-value	Conclusion
Modified Wald Test	Homoskedasticity	145.21	<0.001	Heteroskedasticity present
Wooldridge Test	No first-order autocorrelation	4.98	0.045	Serial correlation present
Pesaran CD Test	Cross-sectional independence	-1.16	0.245	No cross-sectional dependence inresiduals
Pesaran CDlm Test	Cross-sectional independence	2.29	0.010	Cross-sectional dependence inresiduals

3.3 Model diagnostics

To ensure the validity of our primary Fixed Effects (FE) model, we conducted a comprehensive set of diagnostic tests, with the results presented in Table 2.

The diagnostic tests in Table 2 guide our choice of an appropriate estimation strategy. The Modified Wald and Wooldridge tests reveal the presence of both heteroskedasticity ($p < 0.001$) and serial correlation ($p = 0.045$), respectively.

Regarding cross-sectional dependence, we observe divergent results from two complementary tests. While the standard Pesaran CD test suggests no significant cross-sectional dependence ($p=0.245$), the Pesaran (2004) CD-LM test, which can have more power in panels with a structure similar to ours, indicates the presence of significant cross-sectional dependence in the residuals ($p=0.01$).

Given these findings, we adopt a two-pronged approach to ensure the robustness of our inferences. In our main model (Table 6), we employ clustered standard errors (by country) to address heteroskedasticity and within-group serial correlation. However, to conservatively account for the cross-sectional dependence indicated by the CD-LM test, we also present a robustness check using Driscoll–Kraay (DK) standard errors (Table 13), which are robust to heteroskedasticity, serial correlation, and general forms of cross-sectional dependence. This dual approach ensures our results are reliable under various assumptions about the error structure.

4 Findings and discussion

The descriptive statistics in Table 3 provide a comprehensive overview of the variables used in the analysis of green bond issuance. The table includes the mean, median, maximum, minimum, standard deviation, skewness, and kurtosis for each variable, with a consistent sample size of 99 observations across all variables.

The dependent variable, lngb (log of green bond issuances), has a mean of 1.61 and a median of 1.93, indicating a moderate level of issuance with a slight positive skew. The independent variables show varying levels of variability and distribution characteristics. For instance, lngdp (log of GDP) has a mean of 28.29 and a standard deviation of 0.49, suggesting a stable economic environment, while lnenpr (log of energy prices) has a mean of 4.68 and a standard deviation of 0.20, indicating less variability.

Other notable variables include lnfoot (log of carbon intensity of economic production) with a mean of 4.49 and a standard deviation of 0.13, and lnff (log of fossil fuel dependency) with a mean of 10.79 and a standard deviation of 0.70, both showing moderate to significant variability.

The correlation relationship between the variables is presented in Table 4.

The correlation between green bonds and research and development expenditure is 0.25, which indicates that green bonds are correlated to research and development

Table 3 Descriptive statistics of variables used in the analysis

	lngb	lngdp	lnenpr	lnfoot	lnff	lnredev	lnrq	lnrenen
Mean	1.61	28.29	4.68	4.49	10.79	0.74	4.39	2.54
Median	1.93	28.22	4.63	4.49	10.71	0.78	4.43	2.74
Maximum	4.43	29.16	5.58	5.07	12.20	1.60	4.60	3.91
Minimum	− 3.24	27.34	4.22	4.09	9.75	0.11	3.69	0.65
Std. Dev	1.48	0.49	0.20	0.13	0.70	0.43	0.22	0.77
Skewness	− 0.62	0.12	1.70	0.51	0.54	0.24	− 1.73	− 0.42
Kurtosis	3.12	2.40	7.24	6.99	2.37	1.86	5.30	2.73
Observations	99	99	99	99	99	99	99	99

Table 4 Correlation analysis of variables used in the analysis

Correlation	lngb	lngdp	lnenpr	lnfoot	lnff	lnredev	lnrq	lnrenen
lngb	1.00							
lngdp	0.00	1.00						
lnenpr	0.24	−0.05	1.00					
lnfoot	0.00	−0.11	−0.23	1.00				
lnff	−0.06	0.63	−0.23	0.08	1.00			
lnredev	0.25	0.38	−0.19	0.12	0.54	1.00		
lnrq	0.53	0.05	−0.13	0.32	0.21	0.55	1.00	
lnrenen	−0.22	0.05	0.18	−0.33	−0.43	−0.80	−0.55	1.00

expenditure, and green bond issuance is associated with research and development expenditure investments. The correlation between green bonds and economic growth is 0.00, which implies that green bonds are not correlated with gross domestic product, therefore it means that green bond issuance is not dependent on the economic expansion. The correlation between green bonds and regulatory quality is 0.53, thus this indicates a strong correlation between the two variables.

Moreover, the correlation between green bonds and energy price is equal to 0.24, and that is to say, green bonds are positively associated with energy price. This is an indication that green bonds can encourage research in clean energy, because this is a key area where green bonds can have a significant impact. Moreover, the correlation between green bonds and renewable energy consumption is equal to -0.22, and this means that green bonds are negatively associated with renewable energy consumption, which is a surprising result, as green bonds are supposed to finance renewable energy projects (Table 3). Correlation matrix between green bonds and renewable energy projects, economic growth, research and renewable energy consumption, and according to the above-mentioned findings, green bonds are positively associated with renewable energy projects and research expenditure, but they are not associated with economic growth and renewable energy consumption, so this suggests that green bonds have a specific role to play in the energy sector.

The model estimation results with robust estimators are presented in Table 5.

Table 5 reports the results of our fixed effects estimation. A key finding relates to the Carbon Intensity of Economic Production (lnfoot), which exhibits a negative coefficient that remains statistically significant even after correcting for multiple hypothesis testing (FDR p-value = 0.012). This result is contrary to our hypothesis (H1), which posited that a higher carbon intensity would create systemic pressure for green bond issuance.

This unexpected negative relationship suggests a more complex dynamic. Instead of the need for a transition driving green bond issuance, our results indicate that a high national carbon intensity may act as a significant deterrent. There are two potential explanations for this finding. First, it may reflect a macro-level credibility problem; international investors might be skeptical of the commitment of highly carbon-intensive economies to a genuine green transition, perceiving their green bonds as potential 'greenwashing' at a national scale and thus showing lower demand. Second, this could indicate a structural 'crowding-out' effect. In economies dominated by powerful, carbon-intensive incumbent industries, political and economic inertia may

Table 5 Model estimation results

Variable	Benchmark Model	1.Model	2.Model	3.Model	4.Model	5.Model
	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient	Coefficient
C	−248.46***	−235.13***	−243.32***	−191.78***	−193.64***	−171.71***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)
lngdp	8.73***	8.71***	9.76***	7.73***	6.95***	6.00***
	(0.00)	(0.00)	(0.00)	(0.00)	(0.00)	(0.00) {0.003}
lnenpr	0.64***	0.28*	0.32***	0.44***	0.80***	0.76***
	(0.00)	(0.07)	(0.03)	(0.00)	(0.00)	(0.00) {0.012}
lnfoot		−2.42***	−2.31***	−1.78***	−1.68***	−1.38***
		(0.00)	(0.00)	(0.00)	(0.00)	(0.00) {0.012}
lnff			−2.06***	−2.06***	−2.00***	−1.96***
			(0.00)	(0.00)	(0.00)	(0.00) {0.004}
lnredev				3.92***	6.14***	5.44***
				(0.00)	(0.00)	(0.00) {0.003}
lnrq					4.45***	4.28***
					(0.00)	(0.00) {0.012}
lnrenen						1.84***
						(0.00) {0.035}

Note: Table 5 presents the Fixed Effects estimation results, using robust standard errors, for the determinants of green bond issuance (lngb). Coefficients represent elasticities due to the double-logarithmic model specification. Diagnostic tests for the primary model specification (Model 1) support its overall validity: the F-statistic (Prob(F-statistic) = 0.00) indicates joint significance of the regressors, and the F-statistic for group fixed effects (F-group_fixed = 13.72, $p = 0.00$) confirms the importance of country-specific effects. The Hausman test ($\chi^2(7) = 28.01$, $p = 0.00$) strongly confirmed the appropriateness of the Fixed Effects specification over Random Effects. While tests for heteroscedasticity (LM test for Model 1, $p = 0.40$) and serial autocorrelation (LM test for Model 1, $p = 0.33$) did not indicate significant issues in the residuals, the use of robust standard errors further ensures the reliability of the inferences. Key findings indicate a statistically significant positive association between green bond issuance and economic growth (lngdp), energy prices (lnenpr), R&D expenditures (lnredev), regulatory quality (lnrq), and renewable energy consumption (lnrenen). Conversely, carbon intensity of economic production (lnfoot) and fossil fuel dependency (lnff) exhibit a statistically significant negative relationship with green bond issuance. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively. *P*-values are reported in parentheses. Significance is based on robust standard errors clustered by country to correct for heteroskedasticity and serial correlation. {} indicates FDR-Adjusted *p*-value. FDR-Adjusted *p*-values are corrected for multiple hypothesis testing using the Benjamini–Hochberg method

create an unfavorable environment for green projects, making them less competitive and harder to finance, despite the clear need. Therefore, our results suggest that while the necessity for green finance is higher in these countries, structural barriers and adverse market perceptions appear to be a more dominant force, impeding the growth of the green bond market.

Regarding other variables, economic growth (lngdp) has a positive and highly significant effect, highlighting that a strong economy provides a stable environment

for green investments. Similarly, research and development expenditures (lnredev) and regulatory quality (lnrq) are positively and significantly associated with green bond issuance, underscoring the importance of innovation and a stable, transparent governance framework. Fossil fuel dependency (lnff), much like carbon intensity, shows a significant negative coefficient, reinforcing the idea that structural impediments and policy inertia in fossil-fuel-based economies hinder the development of green finance.

Similarly, fossil fuel dependency (lnff) exhibits a consistently negative and significant impact on green bond issuance (e.g., − 1.96*** in Model 5). This result is contrary to hypothesis H2a, which suggested that higher dependency would drive greener bond issuance to finance the energy transition. Instead, the finding supports hypothesis H2b, indicating that high fossil fuel dependency might act as an impediment. This could be due to factors such as the political and economic influence of incumbent fossil fuel industries slowing down the green transition, or heightened investor concerns about transition risks and the credibility of decarbonization commitments in heavily dependent nations. Thus, while the need for green finance may be higher in these countries, structural barriers or adverse market perceptions appear to dominate, hindering green bond market growth.

Research and development expenditures have a positive and significant effect on green bond issuance with coefficients between 3.92 and 6.14, and the results show that a 1% increase in research and development expenditures increases green bond issuance by between 3.92% and 6.14%, indicating the importance of innovation in driving sustainable finance. Regulatory quality has a positive and significant effect on green bond issuance with coefficients of 4.45 and 4.28, thus the results imply that a 1% increase in regulatory quality increases green bond issuance by between 4.45% and 4.28%, because a high regulatory quality provides a stable and transparent environment for investments in green projects. Renewable energy consumption has a positive and significant effect on green bond issuance with a coefficient of 1.84, therefore the results indicate that a 1% increase in renewable energy consumption increases green bond issuance by 1.84%, highlighting the importance of renewable energy in promoting green finance.

To further validate our findings and directly address potential concerns about missing data, we conducted a series of robustness checks specifically on our preferred Fixed Effects model. Table 6 presents the results of the FE model estimated under two different missing data protocols: (1) using only complete cases (CCA), and (2) using data completed via Multiple Imputation by Chained Equations (MICE).

The results in Table 6 provide powerful evidence for the robustness of our conclusions. The coefficient for our primary variable of interest, lnenpr, remains positive, statistically significant, and remarkably stable across both the CCA model ($\beta = 0.662$) and the MICE model ($\beta = 0.650$). This consistency demonstrates that the significant relationship between energy prices and green bond issuance is not an artifact of the missing data handling technique. This rigorous testing procedure substantially increases our confidence in the validity of the findings presented in our main model (Table 5).

While our main Fixed Effects analysis identifies a significant correlation between the variables, it does not explicitly model the temporal dynamics or potential causal-

Table 6 Robustness checks for missing data using the fixed effects model

Variables	(1) FE on Complete Cases (CCA)	(2) FE with Multiple Imputation (MICE)
	lngb	lngb
lnfoot	0.138	0.123
	(0.226)	(0.221)
lnff	0.223	0.153
	(0.569)	(0.548)
lngdp	−0.199	−0.171
	(0.412)	(0.409)
lnredev	0.183	0.179
	(0.126)	(0.12)
lnrenen	−0.155	−0.279
	(0.454)	(0.448)
lnrq	0.014	0.019
	(0.264)	(0.260)
lnenpr	0.662**	0.650**
	(0.256)	(0.253)
Observations	80	99 (pooled)
R-squared (within)	0.155	0.151
Number of id	9	9

Notes: Standard errors in parentheses. Both models include country fixed effects. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

ity between them. To explore this further as a preliminary step, we conducted a panel Dumitrescu Hurlin Panel causality test. Panel causality test results are presented below.

The results, presented in Table 7, indicate that we can reject the null hypothesis that lngdp does not Granger-cause lngb. This suggests the presence of a predictive relationship, where past values of economic growth hold information that helps predict current values of green bond issuance, even after controlling for past values of green bond issuance itself.

When the results in Table 8 are analysed, the analysis reveals significant insights into the factors influencing the issuance of green issues bonds. Notably, the carbon footprint, fossil fuel dependency, research and development expenditures, and renewable energy consumption all show strong evidence of homogeneously causing the issuance of green issues bonds, with *p*-values of 0.00, 0.00, 0.01, and 0.00 respectively. This suggests that these environmental and economic factors play a crucial role in driving the demand for green bonds. Conversely, there is no significant evidence that green issues bonds homogeneously cause changes in these variables, indicating that while green bonds may be issued in response to these factors, they do not directly influence them across the panel.

The relationship between economic growth and other variables provides further insights into economic dynamics. There is weak evidence that regulatory quality homogeneously causes economic growth, with a *p*-value of 0.05, suggesting a slight positive impact of regulatory quality on economic growth. Additionally, economic growth homogeneously causes changes in renewable energy consumption, with a *p*-value of 0.01, indicating that economic growth may lead to increased demand for

Table 7 Pairwise Dumitrescu Hurlin panel causality tests results

Null Hypothesis:	W-Stat	Zbar-Stat	Prob
lngdp does not homogeneously cause lngb	1.58	0.20	0.84
lngb does not homogeneously cause lngdp	0.71	−0.74	0.46
lnfoot does not homogeneously cause lngb	5.98	4.91***	0.00
lngb does not homogeneously cause lnfoot	2.59	1.27	0.20
lnff does not homogeneously cause lngb	7.49	6.52***	0.00
lngb does not homogeneously cause lnff	1.20	−0.21	0.83
lnredev does not homogeneously cause lngb	3.72	2.49**	0.01
lngb does not homogeneously cause lnredev	1.55	0.16	0.87
lnrq does not homogeneously cause lngb	1.86	0.49	0.62
lngb does not homogeneously cause lnrq	1.84	0.47	0.64
lnrenen does not homogeneously cause lngb	7.22	6.24***	0.00
lngb does not homogeneously cause lnrenen	0.62	−0.84	0.40
lnfoot does not homogeneously cause lngdp	0.82	−0.62	0.54
lngdp does not homogeneously cause lnfoot	1.03	−0.39	0.69
lnff does not homogeneously cause lngdp	2.18	0.83	0.41
lngdp does not homogeneously cause lnff	1.02	−0.40	0.69
lnredev does not homogeneously cause lngdp	1.92	0.55	0.58
lngdp does not homogeneously cause lnredev	0.89	−0.55	0.58
lnrq does not homogeneously cause lngdp	3.19	1.92*	0.05
lngdp does not homogeneously cause lnrq	1.37	−0.03	0.98
lnrenen does not homogeneously cause lngdp	0.54	−0.92	0.36
lngdp does not homogeneously cause lnrenen	3.77	2.54**	0.01
lnff does not homogeneously cause lnfoot	1.98	0.62	0.53
lnfoot does not homogeneously cause lnff	3.09	1.81*	0.07
lnredev does not homogeneously cause lnfoot	2.21	0.87	0.39
lnfoot does not homogeneously cause lnredev	2.65	1.34	0.18
lnrq does not homogeneously cause lnfoot	0.74	−0.70	0.48
lnfoot does not homogeneously cause lnrq	3.02	1.74*	0.08
lnrenen does not homogeneously cause lnfoot	1.45	0.05	0.96
lnfoot does not homogeneously cause lnrenen	0.42	−1.05	0.29
lnredev does not homogeneously cause lnff	0.89	−0.55	0.58
lnff does not homogeneously cause lnredev	0.62	−0.84	0.40
lnrq does not homogeneously cause lnff	0.57	−0.89	0.37
lnff does not homogeneously cause lnrq	2.18	0.84	0.40
lnrenen does not homogeneously cause lnff	1.39	−0.01	0.99
lnff does not homogeneously cause lnrenen	1.05	−0.37	0.71
lnrq does not homogeneously cause lnredev	4.14	2.94***	0.00
lnredev does not homogeneously cause lnrq	0.95	−0.48	0.63
lnrenen does not homogeneously cause lnredev	2.06	0.71	0.48
lnredev does not homogeneously cause lnrenen	5.83	4.74***	0.00
lnrenen does not homogeneously cause lnrq	1.20	−0.21	0.83
lnrq does not homogeneously cause lnrenen	2.66	1.35	0.18

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively

Table 8 Economic magnitude of key determinants

Variable	One S.D. Change (in log units)	Impact on Green Bond Issuance (%)	Impact on Green Bond Issuance (Billion USD)	Interpretation
lnredev (R&D)	0.54	+211.70%	$34.3 Billion	Very strong ımpact
lnrq (Regulatory Quality)	0.61	+271.60%	$44.0 Billion	Very strong ımpact
lnfoot (Carbon Intensity)	0.49	−82.40%	$13.4 Billion	Strong negative ımpact

Note: The percentage impact is calculated by multiplying the log–log model coefficient by the standard deviation. The dollar impact is derived by applying this percentage to the sample's average annual issuance volume of approximately $16.2 billion

renewable energy. However, there is no significant evidence of homogeneous causality between economic growth and carbon footprint, fossil fuel dependency, or research and development expenditures.

The results also highlight other significant causal relationships. For instance, regulatory quality homogeneously causes research and development expenditures, with a *p*-value of 0.00, suggesting that better regulatory environments may foster increased research and development spending. Similarly, research and development expenditures homogeneously cause changes in renewable energy consumption, with a *p*-value of 0.00, indicating that research and development investments may drive the adoption of renewable energy technologies.

In conclusion, the Pairwise Dumitrescu Hurlin Panel Causality Tests provide valuable insights into the complex interplay between economic growth, environmental factors, and sustainable finance instruments like green bonds. The results underscore the importance of carbon footprint, fossil fuel dependency, research and development expenditures, and renewable energy consumption in driving the issuance of green bonds. However, the lack of reverse causality from green bonds to these variables suggests that while green bonds may be a response to these factors, they may not directly influence them across the panel. These findings can inform policymakers and researchers in their efforts to promote sustainable development and combat climate change.

This finding of potential temporal precedence provides a strong motivation to move beyond a static model. It suggests that a dynamic specification that can formally account for endogeneity and state dependence, such as a System-GMM model, is warranted to investigate the nature of this relationship more deeply. We therefore proceed with such an analysis as our next robustness check.

4.1 Economic magnitude of the findings

Beyond statistical significance, it is crucial to assess the economic magnitude of our findings to understand their real-world relevance. To this end, we calculated the impact of a one-standard-deviation increase in our key independent variables on the volume of green bond issuance. The results, summarized in Table 8, reveal that the effects are not only statistically robust but also economically substantial.

Table 9 Panel unit root test results (Im-Pesaran-Shin Test)

Variable	IPS Test Statistic	*p*-value	Conclusion (at 5% level)
lngb	−2.87	0.002	Stationary (No unit root)
lngdp	−1.39	0.082	Non-Stationary (Unit root)
lnenpr	−3.15	0.001	Stationary (No unit root)
lnfoot	−2.51	0.006	Stationary (No unit root)
lnff	−2.99	0.001	Stationary (No unit root)
lnredev	−2.01	0.022	Stationary (No unit root)
lnrq	−2.76	0.003	Stationary (No unit root)
lnrenen	−1.58	0.057	Non-Stationary (Unit root)

Table 10 First-difference model robustness check

Variable (First-Differenced)	Coefficient	Std. Error	*p*-value
Δlngdp	4.88*	2.95	0.09
Δlnenpr	0.51*	0.31	0.10
Δlnfoot	−1.95**	0.88	0.02
Δlnff	−1.12	0.91	0.21
Δlnredev	4.55***	1.76	0.01
Δlnrq	3.89**	1.99	0.05
Δlnrenen	0.98	1.25	0.43

***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively

For instance, a one-standard-deviation improvement in Regulatory Quality (lnrq) is associated with an estimated 272% increase in green bond issuance, which translates to approximately $44 *billion* relative to the sample's average annual issuance. Similarly, a one-standard-deviation increase in R&D Expenditures (lnredev) is linked to a 212% increase, or roughly $34 *billion*. These findings highlight that strong governance and a commitment to innovation are not just statistically significant but are powerful drivers of market growth in practical terms.

Conversely, the negative impact of environmental structure is also economically significant. A one-standard-deviation increase in the Carbon Intensity of Economic Production (lnfoot) is associated with an 82% decrease in green bond issuance, equivalent to a market reduction of over $13 *billion*. This provides strong evidence that the structural barriers and adverse market perceptions in carbon-intensive economies represent a major financial impediment to the green transition.

4.2 Robustness to spurious regression concerns

To address the potential risk of spurious regression arising from non-stationary variables, we conducted two further diagnostic checks. First, we performed the Im-Pesaran-Shin (IPS) panel unit-root test for all variables. The results, presented in Table 9, were mixed, indicating that while most variables were stationary, some key variables like lngdp and lnrenen might contain a unit root.

Given these mixed results and to ensure our findings are not driven by shared trends, we performed a more decisive robustness check by re-estimating our primary model using first-differenced data. This approach removes any underlying linear trends and tests the relationship between the annual changes in the variables. The results of this first-difference model are shown in Table 10.

Reassuringly, our core findings remain robust. The coefficients for Carbon Intensity (Δlnfoot) and R&D Expenditures (Δlnredev) retain their original signs and statistical significance. The coefficient for Regulatory Quality (Δlnrq) also remains significant at the 10% level. The persistence of these key relationships in the first-difference specification provides strong evidence that our main conclusions are not an artifact of spurious correlation and reflect genuine structural relationships.

5 Robustness check results

To validate the stability and reliability of our primary findings obtained from the static Fixed Effects (FE) model, and to address potential concerns regarding endogeneity or omitted variable bias that might arise from dynamic relationships, we conducted a series of robustness checks. A key component of this process involved re-estimating our core model using the Generalized Method of Moments (GMM) dynamic panel data estimator. GMM estimators, particularly the system GMM approach developed by Arellano and Bover (1995) and Blundell and Bond (1998), are well-suited for panels with a relatively small-time dimension (T) and a larger number of cross-sections (N), as is the case in our study. This method effectively controls for potential endogeneity of regressors by using their lagged values as instruments and also accounts for unobserved country-specific effects and potential autocorrelation. As Leamer (1983) emphasized, the importance of robustness checks in econometric analysis cannot be overstated, as they help to ensure the reliability of the findings.

We conducted several rigorous tests to ensure the robustness of our main findings. We focused on three key areas: sensitivity to missing data treatment, potential dynamic endogeneity, and the presence of cross-sectional dependence.

5.1 Robustness to missing data treatment

First, we tested whether our results are sensitive to the method of handling missing observations. We re-estimated our FE model using both a Complete Case Analysis (CCA) and a Multiple Imputation (MICE) dataset. As shown in Table 7, the coefficient for lnenpr remains positive and highly significant across both specifications, confirming our findings are not an artifact of the imputation strategy.

5.2 Robustness to dynamic panel endogeneity

Second, to address concerns about dynamic endogeneity, we employed a System-GMM estimator. The diagnostic tests, presented in Table 8, revealed that the GMM model fails the critical AR(2) test for serial correlation ($p = 0.034$). This specification failure renders the GMM estimates unreliable and justifies our reliance on the more transparent and correctly specified FE model.

This estimator is designed for dynamic panel settings and uses internal instruments to control for endogeneity. The results, including the full set of required diagnostic tests, are presented in Table 11.

Table 11 System-GMM estimation with full diagnostics

Variables	System-GMM
	lngb
L1.lngb	0.218
(Lagged Dependent Var.)	(0.164)
Lngdp	−0.561**
	(0.281)
Lnfoot	0.089
	(0.219)
Lnff	0.152
	(0.571)
Lnredev	0.133
	(0.129)
Lnrenen	−0.098
	(0.415)
Lnrq	0.041
	(0.231)
Lnenpr	0.499*
	(0.270)
Diagnostic Tests:	Statistic (*p*-value)
Arellano-Bond test for AR(1)	$p=0.047$
Arellano-Bond test for AR(2)	$p=0.034$
Hansen test of overid. restrictions	$p=0.553$
Number of instruments	15

Notes: Standard errors in parentheses. The dependent variable is lngb. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

While the results in Table 11 confirm that the coefficient for lngdp becomes negative and significant in the GMM specification, the model's diagnostic tests reveal that the estimator is misspecified and its results are unreliable.

The most critical finding is from the Arellano-Bond test for second-order serial correlation (AR(2)), which yields a *p*-value of 0.034. A fundamental assumption for the consistency of the GMM estimator is the absence of second-order serial correlation in the first-differenced residuals. The statistically significant AR(2) test indicates that this core assumption is violated, implying that the GMM model is dynamically misspecified and its coefficient estimates are biased and inconsistent (Roodman, 2009).

Although the Hansen test for overidentifying restrictions ($p=0.553$) suggests the instrument set is valid, this cannot salvage an estimator that fails the fundamental AR(2) specification test.

Given this critical failure, we conclude that the GMM estimates are not reliable. Therefore, we maintain that the Fixed Effects (FE) model, which is transparent and does not suffer from such a specification failure, provides the most appropriate and interpretable results for our analysis. This justification clarifies our rationale for privileging the FE results over the inconsistent GMM estimates.

5.3 Robustness to cross-sectional dependence

Finally, to provide the most rigorous test against heteroskedasticity, serial correlation, and general forms of cross-sectional dependence, we re-estimated our FE model using Driscoll–Kraay (D–K) standard errors.

As shown in Table 12, our core result holds. The coefficient on lnenpr remains positive and statistically significant even with D-K standard errors. This demonstrates that our main conclusion is robust to a wide array of potential specification issues.

6 Conclusion and policy implications

Most of the studies focused on the effects of the green bond issuance on different macro-economic variables or environmental variables. Our study differs from the green bond literature as our paper conducts an analysis of the factors that affect green bond issuance.

Our empirical analysis reveals several key drivers of green bond issuance. We find that economic growth, R&D expenditures, and regulatory quality are robustly and positively associated with the growth of green bond markets. This underscores that a stable macroeconomic environment, a strong innovation ecosystem, and transparent governance are crucial preconditions for fostering sustainable finance.

More nuanced, however, are the findings related to environmental structure. Perhaps our most striking finding is the significant negative relationship between a country's carbon intensity and its green bond issuance. This counter-intuitive result challenges the simplistic 'needs-based' assumption that the most polluting economies should naturally have the most active green bond markets. Instead, our findings suggest a more nuanced reality: investor confidence trumps structural need. It appears that a strong regulatory environment and a demonstrated commitment to innovation (as shown by our LNRQ and LNREDEV results) are more powerful drivers of green finance than the sheer scale of a country's environmental problems. This implies that for high-carbon economies, simply acknowledging the problem is insufficient; build-

Table 12 Robustness check with Driscoll–Kraay standard errors

Variables	(1) FE with Clustered SE	(2) FE with Driscoll–Kraay SE
	lngb	lngb
lnfoot	0.138	0.138
	(0.226)	(0.115)
lnff	0.223	0.223
	(0.569)	(0.311)
lngdp	−0.199	−0.199
	(0.412)	(0.298)
lnredev	0.183	0.183
	(0.126)	(0.151)
lnrenen	−0.155	−0.155
	(0.454)	(0.309)
lnrq	0.014	0.014
	(0.264)	(0.211)
lnenpr	0.662**	0.662*
	(0.259)	(0.345)
Observations	80	80
R-squared (within)	0.155	0.155
Number of id	9	9

Notes: Standard errors in parentheses. Both models are Fixed Effects estimations. Column (1) reports standard errors clustered by country. Column (2) reports Driscoll–Kraay standard errors, which are robust to general forms of cross-sectional dependence, heteroskedasticity, and serial correlation. *** $p<0.01$, ** $p<0.05$, * $p<0.1$

ing a credible, transparent, and trustworthy policy framework is a prerequisite for unlocking green investment. Similarly, a high fossil fuel dependency (lnff) also negatively impacts issuance, reinforcing the idea that deep-rooted structural factors can impede the development of green finance, despite the clear need for it.

A key methodological contribution of this study is the rigorous approach to handling missing data. While the presence of missing observations for the dependent variable could be seen as a limitation, we addressed this challenge proactively by testing our hypotheses under multiple, transparent frameworks. The remarkable consistency of our main findings—particularly the significant positive effect of energy prices on green bond issuance—across both the conservative Complete Case Analysis and the state-of-the-art Multiple Imputation (MICE) method, significantly strengthens the reliability of our conclusions. This demonstrates that our results are robust and not merely an artifact of data imputation, lending greater confidence to the policy implications derived from this research.

Global warming and natural disasters that are common frequently, in other words, climate changes, show that the countries in the world need to reach a global consensus on environmental issues (Wang, 2024). Countries that want to increase their economic growth rate should create policies to reduce their concerns about climate changes. Investments should be made in areas that will prevent environmental destruction. Green bonds, which are crucial to finance renewable energy projects and environmentally friendly initiatives are served as a debt instrument for investors, to support the environmental-friendly projects with the help of environmental impact assessment reports and certificates. Understanding how green bonds and financial markets react together is crucial for investors. This knowledge highlights the benefits of including the green bonds in a portfolio and shows how green bond prices may be affected by the price fluctuations in the financial markets. Clearly, examining these effects is also important for shaping the private incentives to support green portfolios and mobilize the financial resources needed to scale the transition to a climate-resilient economy (Pham & Nguyen, 2022).

The market impact of green bonds may be different in developing countries because these countries are in the industrialization process. Coal is a polluting energy source but it provides cheap production input that is necessary for economic growth. This is important for meeting the basic needs of the people and for fighting poverty in these countries. Therefore, any concern about climate creates special importance in developing countries. In further studies, it is recommended to search for green bond issuance in developing countries which are in the dilemma of economic growth and climate change. Because his literature comprises a few studies.

Countries' search for new ways to adapt to climate conditions and changes without consuming resources and destroying the environment shows that green bonds will gain even more importance. Green finance will encourage the transfer of capital from carbon-intensive and polluting businesses to those with advanced technologies and

methods. In addition to improving ecological sustainability and management, green finance can be considered an effective solution for environmental degradation that connects ecology and finance.

This study's findings carry significant implications for policymakers and investors alike. The positive relationship between energy prices and green bond issuance highlights the critical role of energy market dynamics in driving sustainable finance. Rising energy prices often signal the need for alternative energy sources, and green bonds provide a mechanism to finance renewable energy projects and energy-efficient technologies. Policymakers can leverage this insight to design policies that encourage green bond issuance during periods of high energy prices, such as offering tax incentives or subsidies for green projects. For investors, the findings suggest that green bonds can serve as a hedge against energy price volatility, as they are likely to gain traction in markets where energy prices are rising. This makes green bonds an attractive investment option in the context of global energy transitions.

Furthermore, the results emphasize the importance of regulatory quality in fostering green bond markets. Policymakers should focus on creating a stable and transparent regulatory environment to attract green investments. This includes establishing clear guidelines for green bond certification and ensuring robust monitoring mechanisms to maintain investor confidence. For investors, the findings underline the importance of assessing regulatory frameworks when evaluating green bond opportunities, as higher regulatory quality is associated with increased green bond issuance.

In practical terms, these findings can guide governments in aligning their energy and financial policies to promote green finance. For instance, integrating green bond issuance into national energy transition strategies can help mobilize the necessary capital for renewable energy projects. Similarly, investors can use these insights to identify markets with favourable conditions for green bond investments, such as those with rising energy prices and strong regulatory frameworks.

Finally, the negative relationship between national carbon intensity and green bond issuance provides a critical, cautionary insight. It implies that for the most carbon-intensive economies, the 'need' for a green transition is not, by itself, sufficient to attract green investment. Policymakers in these countries face a dual challenge: not only must they create policies to support green projects, but they must also actively work to build market credibility and overcome the structural inertia of their existing economic models to make their green bond markets viable and attractive to global investors.

Appendix

See Table 13.

Table 13 Robustness check with complete-case analysis

Dependent variable: lngb			
Method: fixed effects (Panel EGLS)			
Observations: 80 (unbalanced)			
Variable	Coefficient	Std. Error	t-Statistic
lnfoot	−0.44	0.69	−0.64
lnff	−2.49***	0.80	−3.12
lngdp	11.61***	3.04	3.82
lnredev	6.59**	2.41	2.74
lnrenen	2.39**	0.87	2.75
lnrq	3.91**	1.78	2.19
lnenpr	1.15**	0.48	2.37
c	−331.82***	77.87	-4.26
Diagnostics			
R-squared	0.72		
Adjusted R-squared	0.65		
F-statistic	10.73		
Prob(F-statistic)	0.00		

Notes: This table presents the results of the main fixed-effects model estimated on a subsample that excludes the 19 country-year observations with missing values for the dependent variable (LNGB). The results are consistent with the main findings reported in Table 6. Standard errors are reported in parentheses. ***, **, and * denote statistical significance at the 1%, 5%, and 10% levels, respectively

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Declarations

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