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THE ROLES OF GREEN BONDS AND RENEWABLE ENERGY IN REDUCING CARBON EMISSIONS

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Abstract – *The growing urgency of achieving sustainable development goals, particularly reducing carbon emissions, has highlighted the need for an effective financial instrument to channel capital towards green projects. Although green bonds represent a promising new tool for financing environmentally friendly initiatives, research on their direct environmental impact is still ongoing. This study examines the relationship between green bond issuance and carbon emissions, utilizing data from 72 countries between 2014 and 2020. Employing the generalized methods of moments model and rigorous robustness tests, the study finds a statistically significant negative association between green bonds and carbon emissions per capita. However, the impact varies across countries based on their income levels and existing renewable energy deployment. Notably, the effects of green bonds on carbon dioxide emissions per capita weaken in nations with higher income and renewable energy use, suggesting potential diminishing returns from green investment. These findings imply that policymakers should prioritise the development of green bond markets while tailoring policies to optimise environmental benefits, considering variations in clean energy infrastructure. Beyond the empirical contribution, this study advances the theoretical discourse in green finance by highlighting green bonds as a distinct mechanism through which financial markets can influence environmental outcomes. By quantifying the environmental impact of green bonds and providing nuanced policy recommendations, this study contributes to a more informed approach to financing sustainable development.*

Keywords: carbon emissions, green bonds, income groups, renewable energy, sustainable development.

I. INTRODUCTION

Climate change poses a critical challenge for individual nations and the global community. According to environmental organisations and experts, all aspects of life are under threat due to climate change [1]. While environmental sustainability is an urgent issue, many global economies have yet to take it seriously, prioritising economic development at the expense of potential damage [2]. In light of this, achieving carbon neutrality and developing a green economy has become the fundamental consensus among all nations. It involves a green transition that aims to reverse the current energy structure, which is heavily reliant on traditional fossil fuels, and promote the use of renewable energy. This process requires substantial financial investment, and renewable energy also necessitates abundant financial resources [3].

Although the global trend of investment in renewable energy has shown positive signs in recent years, a significant gap remains in financial investment in this field [3]. In this context, green finance, particularly green bonds, plays a crucial role in addressing the challenge of climate change. It provides sophisticated financial services, financial resources, investment, and appropriate capital for environmental protection projects, becoming the primary tool to promote renewable energy development and acting as a critical driver for carbon neutrality strategies in many countries [3]. This study investigates the two-way relationship between green bonds and

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carbon dioxide (CO_2) emissions while differentiating its impact between developed and developing countries. This study further elucidates the mediating role of renewable energy in this relationship and employs the generalized method of moments (GMM) to address the endogeneity issue. Consequently, this study provides new insights into the relationship between green bonds, CO_2 emissions, and renewable energy, contributing to the development of effective financial solutions for climate change.

II. LITERATURE REVIEW

A. *Theoretical framework*

Green bonds

According to the International Capital Markets Association [4], green bonds are a relatively new type of bond where the proceeds will be applied to finance or refinance, in part or in full, new and/or existing eligible green projects. The Climate Bonds Initiative [5] reports that the global value of new green bond issues in 2019 reached 230 billion euros (257 billion USD), up from 142 billion in 2018 and 28 billion in 2014. Green bonds are a vital capital mobilisation for sustainable development in the current context. However, issuers and investors often express concerns about the actual effectiveness of green bonds. First, there are concerns about greenwashing activities. If greenwashing prevails, green bonds may not benefit the environment [6]. The second concern relates to the additionality of green investments. According to Bongaerts et al. [7], green bonds do not generate additional capital for environmental protection and climate action because they are issued to refinance previously funded green projects through conventional bonds. Therefore, green bonds do not necessarily imply more environmentally friendly activities. Consequently, the impact of green bonds on reducing CO_2 emissions from multiple perspectives should be considered.

Renewable energy

Solar, wind, geothermal, hydro, and biomass energy are examples of renewable energy sources. According to Panwar et al. [8], renewable energy will play a crucial role in the future of the world as it meets the energy demands domestically and has the potential to provide energy services with zero or near-zero emissions of both air pollutants and greenhouse gases. However, renewable energy systems are relatively capital-intensive compared to competing conventional technologies for centralised energy production [9]. Therefore, seeking green financial sources is one of the top priorities for renewable energy development. According to Tolliver et al. [10], a green bond is an investment vehicle for renewable energy. Rasoulinezhad et al. [11] also pointed out that the development of green finance can help expand green energy projects. It is consistent with the view that funding for renewable energy or energy efficiency can incentivise the decarbonisation [12, 13]. Tolliver et al. [10] also found that green bond is an appropriate tool to reduce investment risks, increase investment returns, and attract global investors to green energy projects for green financing. Consequently, an interactive relationship between green bonds, renewable energy, and environmental quality is worth examining.

Income levels

The level of CO_2 emissions varies between developed and developing countries [14]. Furthermore, the Environmental Kuznets Curve (EKC) theory also addresses the correlation between economic growth and environmental quality [10]. The EKC curve is established based on the hypothesis of an inverted U-shaped relationship between per capita gross domestic product (GDP) and the level of environmental degradation (often measured through the average CO_2 emissions). Recent studies have confirmed the EKC theory, while others have indicated a non-linear relationship between income and the environment [15, 16], and others have yielded mixed results regarding the confirmation of the EKC theory, depending on the level of development of the economies considered [17, 18]. Therefore, the impact of green bonds on different groups of countries with varying development and income levels may differ and require careful consideration to gain a more comprehensive understanding of this issue.

B. Hypothesis development

Green bonds and carbon dioxide emissions

Fang et al. [15] pointed out the negative impact of green finance on the level of emissions considered in developed countries and demonstrated its negative effect on CO_2 emissions. Additionally, Sharif et al. [16] have confirmed similar results in G7 countries, i.e., green finance can reduce carbon emissions. However, researchers should assess specific contexts and periods when examining the relationship between green bonds (GB) and emissions. For example, Sinha et al. [19] empirically investigated the influence of green bond funding on social and environmental sustainability, revealing that green financial mechanisms gradually have a reverse transformative impact on environmental quality and social responsibility in the identified period. Based on this foundation, the first hypothesis is formulated based on theoretical assertions to examine the overall impact of green bonds on global CO_2 emissions, as presented below:

H1. Green bonds have a significant negative impact on CO_2 emissions.

Green bonds and carbon dioxide emissions – The moderating role of renewable energy

Most proceeds of green bonds issued today are committed to financing renewable energy projects [11]. However, the effectiveness of these renewable energy projects depends on various factors. Firstly, market mechanisms and state policies related to green finance are two major concerns. They can directly and positively impact green finance on renewable energy development [20]. Additionally, Meo et al. [21] found that market conditions and green financial market mechanisms are two factors that create a positive relationship between green finance projects and green energy. It demonstrates the complex connection between green bonds, renewable energy, and environmental quality. Secondly, renewable energy projects require a long time for construction and installation before they can be operational. Rasoulinezhad et al. [11] investigated the impact of issued green bonds and energy price fluctuations on the consumption of three types of renewable energy (wind, solar, and hydro) in Japan from 1990 to 2020 using the Autoregressive Distributed Lag (ARDL) method. The main findings indicated a positive long-term impact of issuing green bonds and energy prices. The study by Ye et al. [22] affirmed the positive and statistically significant relationship between issued green bonds and the efficient utilisation of renewable natural resources in both the short and long term. Yet, the impact is more pronounced in the long-term context. Therefore, there is a potential threshold for renewable energy to leverage the benefits of green bonds. Based on this, the research proposes considering the impact of renewable energy on the relationship between green bonds and CO_2 emissions to gain a more comprehensive perspective on the topic. The following hypothesis is formulated:

H2. The impact of green bonds on CO_2 emissions is significantly differentiated by renewable energy usage.

Green bonds and carbon dioxide emissions – The moderating role of income levels

According to Dong et al. [14], the level of CO_2 emissions differs between developed and developing economies. Therefore, it is worth exploring the differential impact of green bonds on CO_2 emissions across different country groups to gain a more comprehensive understanding of this issue. Saha et al. [23] employed the GMM method on a sample of 44 countries from 2016 to 2020 to examine the overall impact of green bonds on CO_2 emissions and their differentiated effects on developed and developing countries, as well as the classification of countries based on sustainable development. The results revealed a significant negative impact of green bonds on global CO_2 emissions. Additionally, Lei et al. [24] argued that the impact of green bonds on reducing CO_2 emissions is more pronounced at higher levels of CO_2 emissions for countries with high carbon-intensive production, while its effect is weaker in countries with low carbon emissions. Therefore, when evaluating the impact of green bonds on CO_2 emissions, it is recommended to consider the classification of countries to obtain a comprehensive view. Consequently, the research formulated the third hypothesis:

H3. The relationship between green bonds and CO_2 emissions is significantly differentiated by income levels.

III. RESEARCH METHODS

A. Methodology

Baseline model

To investigate the impact of green bonds on the amount of carbon emissions, an econometric model was employed, presented in Model (1).

Where i denotes the country and t denotes the year. GB represents the variable indicating the amount of green bonds issued. CO_2 is the per capita carbon emission. The per capita carbon emission was considered the dependent variable due to its common use [25]. Furthermore, it avoids discrepancies due to population differences between countries. Controlit represents the control variables in the model. Additionally, a year dummy variable (Year) was included to account for time-series irregularities in the data.

Controlling the endogeneity issue

Endogeneity is a common problem in estimation problems involving economic variables. In environmental research, endogeneity may arise due to the reverse relationship between CO_2 emissions and green bonds [26]. Multiple reasons explain why green bonds can be an endogenous variable in the model.

First, factors such as environmental quality, market size, openness, economic development level, and other macro factors may affect green bond issuance [10]. Second, it is clear that increasing CO_2 emissions affect the environment, which can motivate governments to seek solutions for developing green financial instruments. Therefore, adding this variable to the regression model without considering the impact of endogeneity can lead to biased estimation results.

Two techniques to mitigate endogeneity, including adding a lagged dependent variable and using the appropriate estimation method, have been employed in this research. Using the lagged variable can help reduce the endogeneity problem by minimising the reverse causality between green bonds and CO_2 emissions. Additionally, previous studies have used the GMM to address endogeneity in researching environmental economics [27]. This technique was proposed by Hansen [28] and extended by Arellano et al. [29] and Blundell et al. [30]. The model includes instrumental variables to help the estimation focus on the variation in the endogenous variables that are uncorrelated with the error term while ignoring the variation in the endogenous variables that biases the estimation [31]. Hence, choosing the appropriate instrumental variables is crucial for accurate estimation results.

In this study, the lagged CO_2 variable was added to the independent variable group, and GMM estimation was used with the lagged GB variable as the instrumental variable to address the endogeneity problem. This research also uses the Kleibergen-Paap, Cragg-Donald, and Hansen J tests to ensure the validity of the instrumental variables.

B. Measurement of variables

Table 1 summarizes the variables used in this study, including carbon emissions as the dependent variable, green bonds and renewable energy as key independent variables, interaction terms for moderating variables, and several controls based on the Stochastic Impacts by Regression Population, Affluence and Technology (STIRPAT) model.

Dependent variable

To investigate the environmental impact of green bonds, the per capita CO_2 emission value (thousand tons) was used to measure environmental performance. Since the per capita emission values are large, the values are transformed into logarithmic form to create the dependent variable.

Table 1: Variable definitions

Variables	Variable names	Definitions
CO_2	Carbon emissions	Natural logarithm of carbon emissions per capita (metric tons)
GB	Green bonds	Natural logarithm of the amount of green bonds issued (USD)
INC	Income levels	Dummy variable, equals 1 if upper middle to high income, otherwise 0
REN	Renewable energy consumption	Natural logarithm of (renewable energy consumption/final energy consumption)
GDP	Gross domestic product	Natural logarithm of gross domestic product (constant 2015 USD)
POP	Total population	Natural logarithm of total population
ENIN	Energy intensity	Energy intensity level of primary energy (MJ/$2017 PPP GDP)
OPEN	Trade openness	Natural logarithm of (Trade/GDP)
URB	Urbanisation	Natural logarithm of (Urban population/Total population)

Independent variables

The main factors explaining the CO_2 variation are green bond issuance and renewable energy. The study uses the green bond issuance volume in USD and the share of renewable energy in total final energy consumption, and then takes the logarithm to make the data set normally distributed.

Moderating variables

The interaction terms were introduced into the regression framework to investigate the heterogeneous effects of green bonds on environmental outcomes across countries with varying income levels and renewable energy adoption rates.

To assess the impact of green bonds across countries with different income levels, a dummy variable named INC is constructed. The variable INC takes the value 1 for upper-middle-income and high-income countries, and 0 for lower-middle-income and low-income countries. The dummy variable is then multiplied by the explanatory variable of interest, GB, to address the second research question. If the interaction term and the independent variable have the same sign, it suggests that the impact of GB on CO_2 is more pronounced in the treatment group and vice versa.

Regarding the impact of GB between countries with different renewable energy levels, the authors first employ the variable REN to represent the share of renewable energy, calculated based on the final energy consumption. The interaction term is created by multiplying the two continuous variables: green bonds (GB) and renewable energy share (REN). To interpret the research findings related to this interaction, the partial derivative of the regression equation concerning GB is computed, allowing for the examination of the marginal effect of green bonds on environmental performance at varying levels of renewable energy deployment.

Control variables

Intuitively, other factors can explain carbon emissions beyond green bonds and renewable energy. The authors introduce several control variables based on previous research to ensure that the regression model adequately explains the variation in CO_2 emissions. Drawing from the STIRPAT model proposed by Dietz et al. [32] on environmental quality determinants, the research incorporates variables for gross domestic product (GDP), population (POP), and energy intensity (ENIN). Additionally, trade openness (OPEN) and urbanisation level (URB) are included in this study. According to Sebri et al. [33], countries with higher trade openness experience intensified economic production activities, potentially leading to increased carbon emissions. Furthermore, Wang et al. [34] demonstrate that urbanisation reduces carbon emissions. Therefore, the research combines these control variables to enhance the estimation accuracy by controlling factors other than green bonds.

C. Data source

Green bond data were collected from the Climate Bonds Initiative database [35], while secondary data for the remaining variables were obtained from the World Bank [36]. After merging the two datasets, observations with missing values were removed. The final dataset comprised

246 observations from 72 countries worldwide, covering the period from 2014 to 2020.

IV. RESULTS AND DISCUSSION

A. Descriptive statistics

Table 2 presents the descriptive statistics of the study data. After removing observations with missing data, the model variables have 246 observations. The high coefficient of variation for the dependent variable and the renewable energy variable indicates significant differences in emission levels and renewable energy development levels between countries. The small standard deviation of the green bond variable shows that the variation in the amount of bonds issued between observations is insignificant. The variables in the model are log-transformed, making the dataset normally distributed and eliminating differences in mean values across the study variables.

B. Correlation and univariate analysis

The Pearson correlation matrix of independent variables in Panel A shows that most variables do not exhibit high multicollinearity (Table 3). However, the GDP and population variables correlate with a coefficient of 0.816. Since a country with a large population can produce more goods, GDP positively impacts the population. Therefore, robust standard errors were used to mitigate the high correlation between the independent variables. Additionally, the t-test results in Panel B show a difference in the mean values between the two income groups. Specifically, the high- and middle-income countries have higher carbon emissions and bond issuance than the remaining group. This difference is statistically significant at the 1% level.

C. Regression analysis

Effects of green bonds on carbon emissions

Table 4 shows that the coefficient of the lagged variable is positive and statistically significant at the 1% level. It indicates that carbon emissions are affected by past emission levels. This result is consistent with the findings of Huang et al. [37]. Green bond is statistically significant at the 5% level. The negative coefficient indicates an inverse relationship between green bonds and per capita carbon emissions. It implies that the issuance of green bonds can improve the environment. Green bonds are the conduit for channelling capital from investors concerning sustainable development to projects. By issuing green bonds, projects that contribute to reducing or limiting carbon emissions are initiated and bring positive environmental impacts, reducing emissions. This result supports previous research by Alamgir et al. [38] on the relationship between green bonds and carbon emissions. Among the control variables, the POP, ENIN, and URB variables are statistically significant, and the signs of the regression coefficients are consistent in all models. However, no statistical evidence was found for the relationship between trade openness and climate change for the study data at the 1%, 5%, or 10% significance levels.

The moderating role of renewable energy

Table 5 presents the regression results with the interaction term between the amount of green bonds and the share of renewable energy in the energy use mix. The regression results with the GMM model show that the green bond variable has a negative coefficient. Similarly, the coefficient of the interaction term is negative and statistically significant at the 5% level. The results are similar in sign for the models using the two-stage least squares (2SLS) and feasible generalized least squares (FGLS) methods. It implies that the environmental impacts of green bonds vary in countries with different renewable energy uses.

Specifically, the model took the derivative of both sides of the equation with respect to the GB variable, and the marginal impact effect is $\frac{\delta CO_2}{\delta GB} = -0.008 - 0.005REN$. At this point, for green bonds to have the effect of reducing carbon emissions, the derivative of the CO_2 variable concerning the GB variable must be less than 0. That is, the derivative expression is negative or RE > -1.6. Since the REN variable is the natural logarithm of the share of renewable energy in

Table 2: Descriptive statistics

Variable	Number of observations	Mean	Standard deviation	Minimum	Maximum
CO_2PC	246	1.688	0.718	– 0.961	3.457
GB	246	20.571	2.001	13.069	24.733
REN	246	2.707	1.131	– 3.507	4.416
GDP	246	27.064	1.631	21.167	30.623
POP	246	17.100	1.786	11.48	21.068
ENIN	246	1.279	0.387	0.199	2.556
OPEN	246	4.287	0.583	3.152	5.946
URB	246	4.297	0.244	3.314	4.605

Notes: CO_2PC is CO_2 emissions per capita; GHG is greenhouse gas emissions; GB is a green bond issued; REN is renewable energy; GDP is gross domestic product; POP is population; ENIN is energy intensity; OPEN is trade openness; URB is urbanisation.

Table 3: Correlation and univariate analysis

Panel A. Pearson correlation matrix							
Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(1) GB	1.000						
(2) REN	– 0.033	1.000					
(3) GDP	0.665***	– 0.140**	1.000				
(4) POP	0.376***	– 0.071	0.816***	1.000			
(5) ENIN	0.039	– 0.161**	0.124*	0.199***	1.000		
(6) OPEN	– 0.113*	– 0.169***	– 0.483***	– 0.631***	– 0.314***	1.000	
(7) URB	0.277***	– 0.176***	0.121*	– 0.287***	– 0.033	0.056	1.000

Panel B. Univariate analysis				
Variables	INC = 0	INC = 1	Mean difference	t-statistics
CO_2PC	0.519	1.803	– 1.284	– 9.283***
GB	19.509	20.675	– 1.166	– 2.369***

*Notes: The symbols *, **, and *** represent significant levels of 10%, 5% and 1%, respectively. CO_2PC is CO_2 emissions per capita; GB is a green bond issued; REN is renewable energy; GDP is gross domestic product; POP is population; ENIN is energy intensity; OPEN is trade openness; URB is urbanisation.*

total energy use, the minimum share of renewable energy a country needs to achieve for green bonds to be effective is $e^{-1.6}$ or 20.19%. In other words, a threshold average renewable energy share is required for green bonds to contribute to CO_2 emission reduction, ceteris paribus.

First, bonds, in general, and green bonds, in particular, are long-term investments. However, these renewable energy investment projects need time before operating and bringing positive environmental impacts. Therefore, countries need strong enough energy infrastructure and necessary renewable energy use before green bonds can reduce carbon emissions.

Second, green bonds also face many challenges that make it difficult to be effective in the initial stages of development. According to Nguyen et al. [39], issuers may be misled about the positive environmental value of 'green' bonds they issue without taking concrete action. 'Greenwashing' can lead to information asymmetry between stakeholders, thereby reducing the environmental effectiveness of green bonds [38]. Achieving a certain threshold in renewable energy demonstrates a commitment to reducing carbon emissions through green bond-financed projects. Therefore, green bonds will be effective when a country has reached a suitable level of renewable energy use.

Effects of green bonds on carbon emissions across countries

Table 6 shows the results of the differential

Table 4: Estimation results of the impact of green bonds on reducing carbon emissions

Variable	GMM	System GMM	2SLS	FGLS
L1	0.592*** (3.28)	– 0.292 (– 1.07)	0.584*** (3.21)	0.987*** (91.31)
GB	– 0.031** (– 2.19)	– 0.030* (– 1.95)	– 0.035** (– 2.40)	– 0.007** (– 2.22)
REN	– 0.101** (– 2.06)	– 0.248*** (– 2.65)	– 0.100** (– 2.02)	– 0.011** (– 2.39)
GDP	0.283** (2.50)	0.686*** (3.63)	0.293** (2.57)	0.011 (1.14)
POP	– 0.232** (– 2.35)	– 0.517** (– 2.16)	– 0.236** (– 2.39)	– 0.004 (– 0.54)
ENIN	0.311** (2.49)	0.931*** (3.85)	0.325** (2.58)	0.027** (2.26)
OPEN	0.043 (1.16)	0.282 (1.34)	0.055 (1.48)	0.013 (1.40)
URB	– 0.249** (– 2.33)	– 0.032 (– 0.04)	– 0.241** (– 2.26)	– 0.052 (– 2.32)
Intercept	– 1.619* (– 1.74)	– 8.522* (– 1.75)	– 1.819* (– 1.93)	0.095 (0.54)
Year effects	Yes	Yes	Yes	Yes
R-squared	0.9700		0.9690	
Wald chi-squared		3106.39***		51225.74***
Number of obs	165	165	165	165
Log-likelihood				306.9412
Underidentification test	5.352		5.352	
Weak identification test	0.813		0.813	
Overidentification test	4.322	9.08	4.322	
AR(2) z-statistics		1.25		

*Notes: Values in parentheses are t-statistics. The symbols *, **, and *** represent significant levels of 10%, 5% and 1%, respectively. CO_2PC is CO_2 emissions per capita; L1 is the lagged variable of the CO_2PC variable; GB is a green bond issued; REN is renewable energy; GDP is gross domestic product; POP is population; ENIN is energy intensity; OPEN is trade openness; URB is urbanisation.*

impact of green bonds on the environment between the two income groups of countries. The results suggest a negative association between GB and the dependent variable in the econometric model. A coefficient of – 0.040 for GB indicates that, on average, a one-unit increase in green bonds is associated with a 0.040 decrease in the dependent variable. However, the interpretation is nuanced by the interaction term GB x INC. The positive coefficient (0.006) for the interaction term GB * INC suggests that the negative association between GB and the dependent variable is weaker for the high and upper-middle-income group (INC = 1) compared to the treatment group (INC = 0). This could be due to several reasons. Policymakers may have already implemented several effective measures to curb carbon emission growth in higher-income countries. Additionally, many economic production activities in lower-middle and low-income countries have emitted significant carbon. Meanwhile, the production technology in these countries is small, making the environmental problem more serious. The study by Chang et al. [40] shows that green bonds strongly impact the environment in countries with high CO_2 emissions. According to the EKC theory, countries trade off economic development and the environment before reaching a suitable income threshold. Therefore, higher-income countries may experience diminishing

Table 5: The role of renewable energy in the relationship between green bonds and carbon emissions

Variable	GMM	System GMM	2SLS	FGLS
L1	0.592*** (3.37)	− 0.230 (− 0.82)	0.580*** (3.27)	0.987*** (91.74)
GB	− 0.008 (− 0.74)	0.004 (0.14)	− 0.011 (− 0.91)	− 0.005* (− 1.68)
GB x REN	− 0.005** (− 2.17)	− 0.011** (− 2.51)	− 0.005** (− 2.17)	− 0.001** (− 2.34)
GDP	0.271** (2.43)	0.638*** (3.42)	0.281** (2.49)	0.011 (1.11)
POP	− 0.231** (− 2.41)	− 0.470** (− 1.96)	− 0.234** (− 2.43)	− 0.004 (− 0.48)
ENIN	0.316*** (2.64)	0.875*** (3.70)	0.325*** (2.66)	0.026** (2.24)
OPEN	0.032 (0.88)	0.283 (1.33)	0.046 (1.26)	0.013 (1.45)
URB	− 0.261** (− 2.54)	0.029 (0.04)	− 0.246** (− 2.38)	− 0.051** (− 2.29)
Intercept	− 1.697* (− 1.68)	− 9.072* (− 1.88)	− 1.960* (− 1.90)	0.057 (0.33)
Year effects	Yes	Yes	Yes	Yes
R-squared	0.9696		0.9681	
F-statistics	729.20***		727.85***	
Wald chi-squared		3420.09***		51147.73***
Number of observations	165	165	165	165
Log-likelihood				306.8159
Underidentification test	5.909		5.909	
Weak identification test	0.754		0.754	
Overidentification test	4.884	8.74	4.884	
AR(2) z-statistics		1.47		

*Notes: Values in parentheses are t-statistics. The symbols *, **, and *** represent significant levels of 10%, 5% and 1%, respectively. CO_2PC is CO_2 emissions per capita; L1 is the lagged variable of the CO_2PC variable; GB is a green bond issued. REN is renewable energy; GDP is gross domestic product; POP is population; ENIN is energy intensity; OPEN is trade openness; URB is urbanisation.*

marginal environmental benefits from green bond issuance. This result supports the study of Chang et al. [40], which shows that the negative relationship between green bonds and carbon emissions becomes weaker in countries with lower environmental degradation levels. The study also supports the findings of Saha et al. [21], which indicate that the negative relationship between green bonds and the environment is more pronounced in developing countries.

V. CONCLUSION

This study has examined the relationship between green bonds issued and carbon emissions with a sample of 246 observations from 2014 to 2020. To further understand this relationship, the analysis examines how the level of renewable energy use may influence the effect of green bonds on environmental performance, and how this relationship differs across countries with varying income levels. The GMM regression is employed to address the endogeneity problem. The results confirm that issuing green bonds helps reduce carbon emissions, hence beneficial for the environment. However, countries may need to reach a certain threshold in renewable energy usage to see the effect. Finally, the impact of green bonds on reducing environmental degradation becomes less pronounced in countries with higher incomes. As countries move up the income

Table 6: Estimation results of the impact of green bonds on reducing carbon emissions

Variable	GMM	System GMM	2SLS	FGLS
L1	0.709*** (6.40)	0.198 (0.63)	0 .702*** (6.30)	0.984*** (83.10)
GB	− 0.040*** (− 3.05)	− 0.082*** (− 3.37)	− 0.041*** (− 3.08)	− 0.016*** (− 4.35)
GB x INC	0.006* (1.78)	0.044* (1.93)	0.006* (1.88)	− 0.002 (− 0.17)
GDP	0.205*** (2.81)	0.393** (2.45)	0.210*** (2.84)	0.031*** (2.90)
POP	− 0.123** (− 2.58)	− 0.182 (− 1.21)	− 0.127*** (− 2.64)	− 0.010 (− 1.16)
ENIN	0.260*** (2.95)	0.698** (2.27)	0.266*** (2.98)	0.037*** (2.63)
OPEN	0.134*** (2.80)	0.420*** (2.84)	0.136*** (2.83)	0.030*** (2.78)
URB	− 0.099* (− 1.71)	− 0.546 (− 0.54)	− 0.107* (− 1.83)	− 0.040 (− 1.38)
Intercept	− 2.732*** (− 2.67)	− 5.659 (− 1.14)	− 2.753*** (− 2.68)	− 0.352* (− 1.76)
Year effects	Yes	Yes	Yes	Yes
R-squared	0.9778		0.9770	
F-statistics	923.27***		913.47***	
Wald chi-squared		3234.04***		31511.22***
Number of observations	165	165	165	165
Log-likelihood				267.0201
Underidentification test	8.240		8.240	
Weak identification test	1.243		1.243	
Overidentification test	7.053	11.80	7.053	
AR(2) z-statistics		1.74*		

*Notes: Values in parentheses are t-statistics. The symbols *, **, and *** represent significant levels of 10%, 5% and 1%, respectively. CO_2PC is CO_2 emissions per capita; L1 is the lagged variable of the CO_2PC variable; GB is a green bond issued; REN is renewable energy; GDP is gross domestic product; POP is population. ENIN is energy intensity; OPEN is trade openness; URB is urbanisation.*

ladder, the efficacy of green bonds in mitigating carbon emissions tends to diminish. In contrast, lower-income countries may experience more pronounced effects from green bond initiatives.

Beyond the empirical findings, it is important to recognise the novel role of green bonds as a market-driven solution that aligns private capital with public environmental goals. Green bonds represent a shift in how societies can internalise environmental externalities by embedding sustainability criteria directly into financial markets. This approach goes beyond traditional regulatory or subsidy-based methods by mobilising large-scale investment toward low-carbon development. By framing green bonds as a tool for transforming financial systems to support decarbonisation, this study adds a theoretical dimension that highlights their potential to reshape incentives and decision-making across both public and private sectors. This broader perspective underscores the importance of designing green bond markets not just for funding individual projects but for accelerating systemic transitions toward sustainability.

From the findings, several implications are proposed. First, green bonds have proved to be an effective instrument to reduce carbon emissions. As a result, regulators should encourage these financial instruments through effective legal frameworks. Second, governments should focus on renewable energy initiatives as these projects also amplify the positive impact of green bonds. Third, lower-income countries stand to gain significantly from green bonds' environmental benefits. Consequently, these countries should utilise the benefits of green bonds with timely actions. Regarding countries with higher incomes, policymakers should encourage complementary sustainable instruments. However, the study acknowledges limitations. This research uses quite a small sample. Next, the amount of green bonds issued is employed as the main explanatory variable. Still, other types of green bonds or green bonds issued in different periods may have different effects [40]. Thus, investigating other types of green bonds and analysing their effects over different periods would enrich current understanding. Exploring the impact of green bonds with varying characteristics could yield valuable insights into this topic.

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