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The double sustainability: The link between government debt and renewable energy

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ABSTRACT

This paper innovatively explores the relationship between a country's government debt and the use of renewable energy. Incorporating key socio-economic and financial variables, critical to the United Nations SDG-7, we build a panel dataset for G7 countries from 1990-2021. Using cointegrating regression methods (FMOLS and DOLS), Quantile Regressions (QR) and pairwise panel causality tests, we find bidirectional causality between government debt and renewable energy consumption (REC). The empirical findings emphasize the important policy implications for sustainable economic development. Escalating government debt can hinder investment in renewable energy infrastructure, while increased renewable energy has a positive impact on government debt dynamics. Policymakers are encouraged to prioritize fiscal responsibility to secure resources for renewable energy investments. Moreover, incentivizing renewable energy deployment promotes long-term fiscal benefits and creates a positive feedback loop. In fact, a comprehensive understanding of the relationship between government finances and environmental sustainability is crucial for an optimal balance.

1. Introduction

The adoption of the Sustainable Development Goals (SDGs) by the United Nations General Assembly (UNGA) in 2015 provides a solid framework for international cooperation to realize a sustainable future for our planet. At the heart of the 2030 Agenda are the 17 SDGs and their 169 targets, which point the way to eradicating extreme poverty, fighting injustice and inequality, preserving our planet's environment. The success of the 2030 Agenda depends on the transition to a more sustainable energy system and on improving energy efficiency at a global level (Allen et al., 2016; Bowen et al., 2017; Fuso Nerini et al., 2018; McCollum et al., 2018; Nilsson et al., 2016; Von Stechow et al., 2016).

Over the past few decades, the negative effects of environmental pollution have increasingly affected human life and the biosphere. Environmental protection has therefore moved to the forefront of global policy-making and has led to a sharp increase in demand for renewable energy. Energy consumption accounts for 75.6% (or 37.6 Gigatons) of anthropogenic carbon dioxide (CO_2) emissions (Ge & Friedrich, 2000). To tackle global environmental problems, the United Nations (UN) has declared "affordable and clean energy" as the 7th Sustainable Development Goal (SDG-7) (IPCC, 2023). The transition from conventional energy sources to renewable energy is costly. It requires investment in new technologies and infrastructure development, and the initial operating costs can exceed those of potential competitors. This therefore places an additional burden on the energy industry (Khan et al., 2022).

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External financing through government involvement, especially debt financing, can be an option for the deployment of renewable energy or environmental programs. However, the associated costs can have a potentially negative impact on national economies. Rising government spending can increase government debt, which in turn can hamper investment.

Recent literature examining the relationship between government debt and REC continues to provide contradictory findings. From a public finance sustainability perspective, government debt increases over time without reaching a stable equilibrium when the interest rates paid on government debt exceed the growth rate of the economy and government spending constantly overcomes revenues (Magazzino et al., 2015; Magazzino & Mutascu, 2022). A similar mechanism can be observed in nature, as the melting of ice leads to a reduction in albedo, which causes an increase in the absorption of solar radiation, which in turn has an amplifying effect on the melting of ice. Both processes are subject to a reinforcing non-linear feedback mechanism.

An important characteristic of reinforcing feedback mechanisms is that they amplify changes in speed in any given direction.

Financial crises have a negative impact on production and consumption as well as on public finances. Climate change and extreme weather events increase the infrastructure risks and force insurance companies to increase premiums. One example of the impact of climate change is higher temperatures. Higher temperatures can reduce the productivity of workers and thus hurt the profitability of companies. The deterioration of the corporate balance sheets could trigger a wave of insolvencies, which in turn could undermine the stability of the banking system. The same reasoning can be applied to capital investments that are destroyed by extreme weather events. However, while corporate insolvencies can trigger a crisis in the banking sector, public finances are also affected as bailouts in the banking sector increase government spending. It is therefore possible to identify the indirect impact of climate on economic growth through the financial channel. The strain on public finances just described can lead to an increase in a country's external debt. A high level of external debt forces countries to gear their economic policy towards the global market with its extensive supply chains. This limits the ability to pursue a more sustainable path of economic growth and hinders the strengthening of domestic small and medium-sized enterprises. It also hinders investment in renewable energy and agro-ecological initiatives at home.

An important feature to consider when looking at (external) debt financing is a country's credit rating. This plays an important role in determining the interest rate at which a country can borrow. Nations with a high credit rating can benefit from significantly lower interest rates when borrowing than countries with a weaker financial profile. In addition, countries with a high credit rating generally maintain a low debt-to-GDP ratio.

In this paper, we selected the G7 countries (Canada, France, Germany, Italy, Japan, the United Kingdom, and the United States) to compile our panel dataset for the years 1990 to 2021. We aim to fill a gap in the literature by analyzing the relationship between a country's government debt and the use of renewable energy. To our knowledge, this study is unique in two respects. First, it combines several socio-economic and financial variables that are critical to achieving SDG-7 then analyzes the extent to which they influence REC. Then, it provides insights into cross-sectional dependence, improving the methodological practice of panel data analysis. The choice of the G7 countries is underpinned by several compelling reasons that make them an interesting target for investigation under the proposed theme. The importance of exploring our topic within this group lies in its unique positioning within the global economic and political landscape. First, the G7 countries, composed of the advanced industrialized nations, play a central role in shaping international economic policies. In fact, together, these countries influence global economic trends, trade agreements and financial regulations. The context of the G7 allowed us to examine how the policies and practices of these influential countries have far-reaching effects on the global community as a whole. Furthermore, the G7 countries often serve as trendsetters in the adoption of innovative approaches and policies. This group of countries provides an insightful look at possible future trends and best practices that could be adopted by other nations. This research can also serve as a valuable guidance for policymakers, businesses and researchers worldwide. In short, the G7 countries are a captivating target for an empirical investigation due to their influential role in the global arena, their potential to set international standards, and their ability to offer valuable insights into emerging trends. Through an in-depth analysis within this area, the research aims to contribute nuanced perspectives and practical implications that go beyond the immediate context of these countries and benefit a broader audience interested in the dynamics of the global economy. Financial sustainability and environmental sustainability are intrinsically linked in the context of G7 countries, representing some of the world's largest economies. The pursuit of financial stability often involves resource-intensive practices that can strain the environment, leading to ecological degradation and long-term economic risks. Conversely, neglecting environmental concerns can disrupt ecosystems, exacerbate climate change, and incur significant financial burdens in the form of disaster recovery and adaptation costs. Thus, fostering environmental sustainability through green investments, renewable energy adoption, and stringent regulations not only safeguards ecosystems but also enhances resilience, fosters innovation, and promotes long-term economic prosperity for G7 nations, a crucial area for the world economy. Moreover, G7 countries play an important role in international commodity, financial, and energy markets and use debt financing to boost their economic activity and maintain their high living standards. In addition, this study contributes to the existing literature by using novel empirical approaches. After testing for cross-sectional dependence in the series, panel unit root and cointegration tests are conducted to examine the long-term relationship between the selected variables. Furthermore, the theoretical model is estimated using cointegration regression estimators, Fully Modified Ordinary Least Squares (FMOLS) and Dynamic Ordinary Least Squares (DOLS). To check the robustness, the previous results are compared with Quantile Regressions (QR). Finally, the causality flow is analyzed with recent pairwise panel causality tests (Dumitrescu & Hurlin, 2012).

The remaining paper is organized as follows: Section 2 presents a literature review on the impact of socioeconomic and financial factors affecting REC, and highlights potential gaps in the existing research. Section 3 provides the theoretical background of our analysis and describes the dataset, while Section 4 discusses the empirical findings. Then Section 5 provides some concluding remarks and policy recommendations.

2. Literature review

The rise in global temperatures caused by climate change poses a significant threat to the planet's ecosystems and human well-being; it also has a major economic impact. Studies on the macroeconomic impacts of annual weather changes show that developing countries will be disproportionately more affected than industrialized nations. Typically, labor-intensive industries account for a larger share of GDP in low-income countries, while capital-intensive industries are more prevalent in industrialized countries. In addition, infrastructure is better developed in the more advanced and wealthier countries, allowing workers in the manufacturing and service sectors to benefit from more favorable working conditions such as, for example, air conditioning. These factors mitigate, to some extent, the impact of climate change on labor productivity and national economic performance. When temperatures rise above a certain threshold, this has a negative impact on labor productivity in industries affected by climate change (Acevedo et al., 2020; Graff Zivin & Neidell, 2014). Labor productivity peaks at around 13 °C and falls dramatically at higher temperatures (Burke et al., 2015). According to Dell et al. (2012), high temperatures slow down economic growth considerably. The rise in temperatures would be particularly damaging for low-income countries, which are mainly located in warm climate regions (Weil, 2016). Conversely, the impact of temperature on production in wealthier countries appears to be minimal or non-existent (Dell et al., 2012). In addition, industries that are particularly vulnerable to climate change, such as agriculture, construction and other outdoor economic activities such as tourism, are more likely to be affected by a decline in labor availability (Antonelli et al., 2021; Shayegh et al., 2021). These findings are consistent with the studies by Burke et al. (2015) and Dell et al. (2012), revealing a non-linear relationship between economic productivity and temperature. Nevertheless, there is a dearth of literature on the impact of climate change on labor supply, which calls for further investigation. On the contrary, the impact of climate change on agricultural productivity and economic growth has been extensively studied, with research consistently indicating a negative impact on these variables (Graff Zivin & Neidell, 2014; Park, 2016; Shayegh et al., 2021; Somanathan et al., 2021).

Uncertainty in climate policy may lead to asset mispricing and credit vulnerability, which could jeopardize overall financial stability. Battiston et al. (2017), Carney (2015) and Dietz et al. (2016) found that financial contagion further increases economic and financial vulnerability. Although there is a consensus on this causal effect, the literature is ambiguous on the underlying mechanism by which climate risk spreads to the financial system (Zhang et al., 2022). According to Dietz et al. (2016) and Stern (2013), it is a disorderly transition to a low-carbon economy that could lead to a sudden drop in the value of carbon-intensive assets and a stranding risk, which could eventually lead to financial risks (Gros et al., 2016). In addition, high rates of non-performing bank loans could increase due to declining business performance (Carney, 2015). As the transition to renewable energy requires significant investments in infrastructure and technology, government debt could overcome financial constraints if governments get involved.

The impact of government debt on the renewable energy sector has been discussed in the literature, with contradictory results. On the one hand, it appears that government debt can contribute to the financing of national programs for the introduction and promotion of renewable energy. On the other hand, government debt is seen as an obstacle to the promotion of renewable energy because it is associated with increasing payment obligations. The idea that government debt can be used to finance renewable energy projects is supported by Hashemizadeh et al. (2021a). Using a sample of 20 emerging countries from 1990 to 2016, their study shows that there is a positive relationship between government debt and the use of renewable energy. Florea et al. (2021) attempt to determine the impact of public finances on REC. They examine 11 emerging economies in the European Union (EU) from 1995 to 2015 using two measures of public finance, namely budget deficit and government debt, using FMOLS. Their empirical results suggest that both measures of public finances have a positive impact on REC. In contrast, Katircioglu and Celebi (2018) claim that financing energy consumption and income growth through external debt can lead to greater environmental damage. Their argument is that economies, especially those that are highly dependent on energy, tend to consume more energy when national income is increased through higher debt. This conclusion is also shared by Bese et al. (2021), Sun and Liu (2020) and Zhang et al. (2022), who go further and argue that the environment could be negatively affected if government debt is used to finance investments in heavy industrialization and infrastructure scenarios. In a recent study, Wang et al. (2021) demonstrate that an increase in the government debt-to-GDP ratio does not result in an increased consumer preference for renewable energy. In contrast, Akram et al. (2021) reach the opposite conclusion when investigating the relationship between external debt and renewable energy, particularly in the context of environmental quality for 33 highly indebted poor countries. Results show that external debt increases CO_2 emissions and thus harms the environment. Their findings also support a causal relationship in both directions between external debt and CO_2 emissions, but not between external debt and REC.

To date, there is no consensus in the literature on the relationship between renewable energy consumption and government debt. Existing studies find positive, negative, or inexistent relationships between these two variables (Lei et al., 2022; Majeed et al., 2022; Murshed, 2021). The contradictory results can be attributed to the methods of analysis, the relevant factors, the regions chosen, and the different time periods (Hashemizadeh et al., 2021a). This lack of consensus in the empirical literature opens an opportunity for further research.

Other studies have isolated various variables and examined their impacts separately on renewable energy consumption. For instance, Ziaei (2012) establishes a link between the Consumer Price Index (CPI) and energy consumption, while Akintande et al. (2020) emphasize the importance of the urban population and human capital. Anton and Nucu (2020) conclude that financial development could facilitate the adoption of green technologies. Ike et al. (2020) emphasize the impact of a fiscal policy index on CO_2 emissions, while (Przychodzen & Przychodzen, 2020) find that an increased unemployment rate may positively affect the use of renewable energies. Florea et al. (2021) find a one-way causal relationship leading from budget deficit and government debt to REC. Hashemizadeh et al. (2021a) show a strong statistical correlation between trade openness, urbanization and REC. Wang et al. (2021) add the role of the Human Development Index (HDI) to their equation, while Raouf (2022) analyzes how the impact of trade

Table 1
Existing literature on renewable energy and public finance indicators.

Author(s)	Region	Period	Variables	Methodology
Akintande et al. (2020)	5 African countries	1996–2016	RE consumption, population growth, electricity power consumption, energy use, oil demand, GDP, CO_2 emission growth, Government effectiveness, natural gas, external debt	BMA
Florea et al. (2021)	11 EU emerging countries	1995–2015	RE consumption, GDP, public debt, net lending, trade openness	FMOLS, GC
Hashemizadeh et al. (2021b)	20 emerging countries	1990–2016	RE consumption, GDP, public debt, trade openness, urbanization	Regression with Driscoll–Kraay S.E., FGLS, PCSE, FMOLS, DHC
Ike et al. (2020)	Thailand	1972–2014	CO_2 emissions, GDP, energy use, fiscal policy index	DOLS, TYC
Przychodzen and Przychodzen (2020)	27 transition economies	1990–2014	Electricity production from renewable sources, GDP, unemployment, inflation, government debt, domestic credit, FDI, current account balance, R&D expenditures, CO_2 emissions	Panel regressions
Raouf (2022)	17 OECD countries	1980–2020	RE consumption, non-RE consumption, GDP, public debt, inflation, trade openness, population growth	PQR
Tugcu et al. (2020)	33 net energy importing countries	2000–2012	RE consumption, non-RE consumption, budget deficit, GDP, exchange rate, interest rate	DOLS, FMOLS, DHC
Wang et al. (2021)	BRICS countries	1990–2016	RE use, HDI, GDP, public debt, industrialization	Regression with Driscoll–Kraay S.E., Regression with Newey–West S.E., DHC

Notes: BMA: Bayesian Model Averaging; DHC: Dumitrescu-Hulin Causality; DOLS: Dynamic Ordinary Least Squares; FGLS: Feasible Generalized Least Squares; FMOLS: Fully Modified Ordinary Least Squares; GC: Granger Causality; PCSE: Panel-Corrected Standard Errors; PQR: Panel Quantile Regression; TYC: Toda–Yamamoto Causality.

openness, population growth, and inflation on renewable and conventional energy consumption vary in different quantiles of the population. Furthermore, Magazzino et al. (2019) analyze the sustainability of fiscal policy in a panel framework for the G7 countries in the 1980–2015 years. The results evidence the presence of a long-term relationship between government debt and primary deficit, while a bidirectional causality flow emerges both between government revenues and expenditures as well as between government primary deficit and debt.

In this context, our paper extends the empirical literature on the determinants of REC, encompassing a broad set of variables. While existing literature has introduced each of these factors separately, to the best of our knowledge, there is no study that concurrently examines the collective impact of all previously analyzed variables and their interactions on REC (see Table 1).

3. Theoretical background and data description

Our study builds on the existing literature, yet it is innovative in that it empirically examines the dynamic relationship between government debt and REC for seven major players in international markets and global finance. We consider the G7 economies as an appropriate sample for our empirical analysis, as these countries account for a significant share of global emissions and exert a substantial influence on global energy demand and consumption as well as on the global ecological balance. Secondly, the impact of government debt on REC is examined using updated panel data techniques.

The methodology proposed involves estimating the theoretical model using cointegration regression estimators such as FMOLS and DOLS (Kao & Chiang, 2000). These estimators are used to check the robustness of the results, and they are compared with QR findings (Machado & Silva, 2019). The use of cointegrating estimators such as FMOLS and DOLS is supported by various studies that applied these techniques to check the consistency and validity of long-run dynamics (Bhardwaj et al., 2021; Janpolat et al., 2021; Moolio & Kong, 2016). Additionally, the causality flow is analyzed using the recent panel causality approach proposed by Dumitrescu and Hurlin (2012). The application of this procedure is also supported by the recent literature (Ahmed et al., 2022; Farouq et al., 2021; Pujiati et al., 2023)

With these approaches, the following model is estimated to explore the impacts of the selected variables on REC in G7 countries:

$$REC_{i,t} = \beta_0 + \beta_1 RPCGDP_{i,t} + \beta_2 GD_{i,t} + \beta_3 UR_{i,t} + \beta_4 Open_{i,t} + \\ + \beta_5 Urban_{i,t} + \beta_6 HDI_{i,t} + \varepsilon_{i,t} \tag{1}$$

Table 2
Variables description.

Variable	Abbreviations	Measurement units	Data source
Renewable energy consumption	REC	% of total final energy consumption	World Development Indicators
Gross Domestic Product per capita at constant prices	RPCGDP	Purchasing power parity, 2017 international dollar	World Economic Outlook
General government debt	GD	% of GDP	Global Debt Database
Unemployment rate	UR	% of the total labor force	World Economic Outlook
Trade openness	Open	% of GDP	World Development Indicators
Urban population	Urban	% of the total population	World Development Indicators
HDI	HDI	Human Development Index	Our World in Data

1. https://data.worldbank.org/indicator/EG.FEC.RNEW.ZS 2. https://www.imf.org/en/Publications/WEO 3. https://www.imf.org/external/datamapper/datasets/GDD 4. https://www.imf.org/en/Publications/WEO 5. https://data.worldbank.org/indicator/NE.TRD.GNFS.ZS 6. https://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS 7. https://ourworldindata.org/human-development-index

Table 3
Descriptive statistics.

Variable	Mean	Median	Std.Dev.	Skewness	Kurtosis	Range	IQR	CV
REC	1.9214	1.9954	0.8639	−0.6849	3.1211	3.6191	1.0918	0.4496
RPCGDP	10.6664	10.6618	0.1459	0.3321	2.9673	0.7233	0.1809	0.0137
GD	4.4219	4.4336	0.4516	0.2237	3.0920	2.2559	0.5220	0.1021
UR	7.0421	7.2250	2.5284	−0.0140	2.0290	10.7000	3.9910	0.3590
Open	3.8091	3.9310	0.4321	−0.6753	2.4743	1.7251	0.6114	0.1134
Urban	4.3792	4.3841	0.0207	−0.7389	2.1850	0.0642	0.0334	0.0047
HDI	0.8849	0.8899	0.0364	−0.6812	3.0394	0.1700	0.0475	0.0412

Notes: Std. Dev.: Standard Deviation; IQR: Inter-Quartile Range; CV: Coefficient of Variation.

We utilized yearly data spanning from 1990 to 2022, chosen based on data availability. REC represents the share of REC in total final energy consumption. A country's openness to trade (Open) is defined as the share of trade in GDP. UR denotes the unemployment rate, and Urban signifies the share of the population living in urban areas.

The variables REC, GDP, and Urban were extracted from the World Development Indicators (WDI) of the World Bank. RPCGDP is the real GDP per capita (in Purchasing Power Parity and international dollars 2017). UR and RGDP were sourced from the World Economic Outlook (WEO) of the International Monetary Fund (IMF). Government debt (GD) data, measured as a percentage of GDP, are obtained from the IMF's Global Debt Database. The HDI data is sourced from Our World in Data. Logarithms for REC, total income, government debt, trade openness, and urbanization were calculated to limit the fluctuation range of the data. Table 2 summarizes the main information of our dataset.

The values of mean and median (the 50th percentile) are similar for each of the series, while the skewness (the third moment) is generally close to 0, and the kurtosis (the fourth moment) is near 3. These results suggest that the analyzed data follow a Gaussian distribution (Table 3).

More details are presented in the scatter plot matrices (Fig. 1) and in the pairwise correlation matrix in Table 4.

4. Empirical results

Table 5 presents the preliminary analysis of the series with the cross-section dependence tests. The results clearly suggest evidence of a cross-sectional dependence for all series, using a battery of different tests. In fact, the null hypothesis of cross-section independence is rejected at the conventional significance levels.

To test the null hypothesis of no correlation among units, three additional tests are conducted. The outcomes of the error tests for cross-section independence align with the earlier results, once again indicating that the series are not cross-sectionally independent (Table 6).

In fact, both LM and LM adj* reject the null hypothesis of no correlation among the countries for all t, while LM CD* fails to reject it. This result suggests the use of second-generation panel unit root tests instead of first-generation tests.

The results of the panel unit root tests in the presence of cross-section dependence are shown in Table 7. These results clearly show that the null hypothesis, which assumes non-stationarity for each of the series, is rejected for each series, regardless of the deterministic specification chosen (constant or constant plus trend).

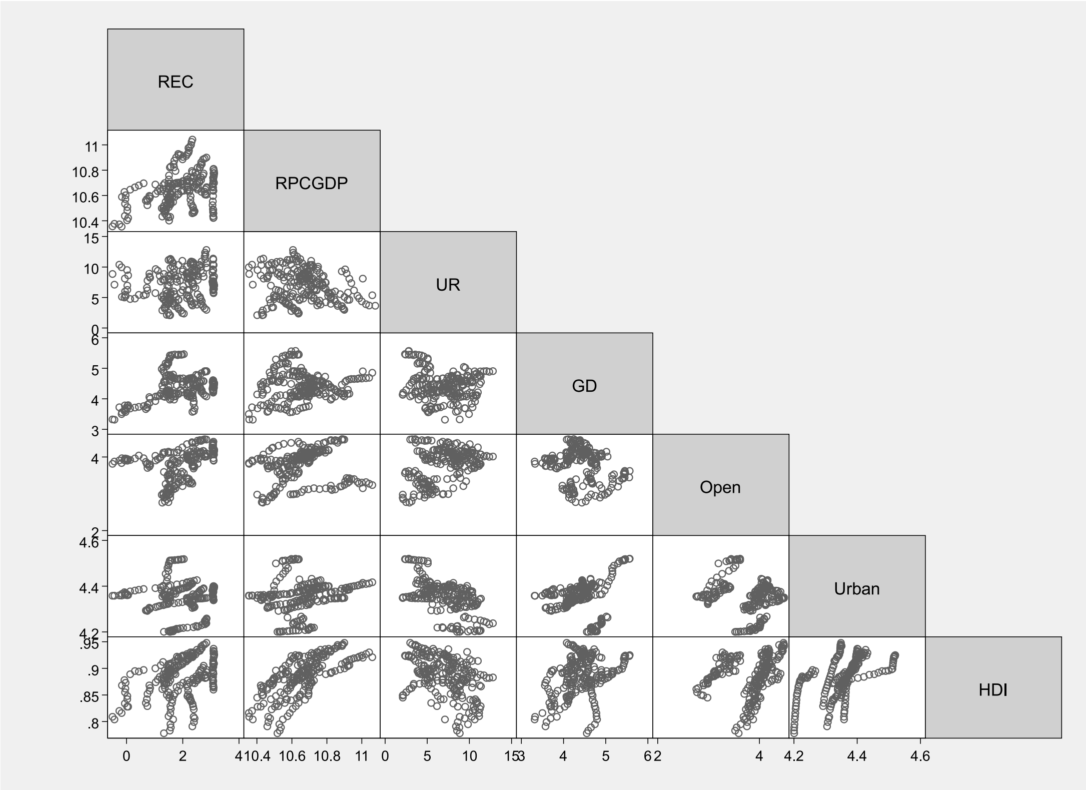

Fig. 1. Scatterplot matrices.

Table 4
Correlation matrix.

Variable	REC	RPCGDP	GD	UR	Open	Urban	HDI
REC	1.0000						
RPCGDP	0.3901***	1.0000					
	(0.0000)						
GD	−0.3854***	0.0938	1.0000				
	(0.0000)	(0.9754)					
UR	−0.2022*	−0.2130**	−0.1229	1.0000			
	(0.0660)	(0.0233)	(0.7631)				
Open	−0.3844***	0.1489***	−0.1899*	0.3856***	1.0000		
	(0.0000)	(0.4233)	(0.0874)	(0.0000)			
Urban	0.0015	0.1500	0.2565***	−0.5877***	−0.1667	1.0000	
	(1.0000)	(0.4095)	(0.0022)	(0.0000)	(0.2319)		
HDI	0.4182***	0.6998***	0.3337***	−0.4321***	0.2229**	0.5634***	1.0000
	(0.0000)	(0.0000)	(0.0000)	(0.0000)	(0.0162)	(0.0000)	

Notes: Sidak's correction has been applied, P-Values in parentheses.*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

The results of Pedroni's panel residual cointegration test, as shown in Table 8, suggest the establishment of a long-term relationship among the analyzed variables. Notably, four out of seven statistics reject the null hypothesis of no cointegration, demonstrating significance at a 1% level.

We used the FMOLS and DOLS methods to analyze the relationship between REC and the set of independent variables (Table 9). Both models exhibit high explanatory power, with DOLS performing slightly better in terms of fit and long-term variance estimation.

Our findings reveal that a higher GDP per capita is associated with an increase in REC: as GDP per capita rises, REC also shows an upward trend. In both FMOLS and DOLS models, RPCGDP exhibits a highly statistically significant ($p < 0.01$) and positive coefficient. This observation is consistent with previous studies by Apergis and Payne (2010), Marinaş et al. (2018), and Sadorsky (2009a, 2009b).

Additionally, higher overall GD leads to lower REC; as GD increases, REC declines. GD displays a statistically significant ($p < 0.01$) negative coefficient in both models. This result aligns with the findings presented by Onuoha et al. (2023b) and those reported by Hashemizadeh et al. (2021a).

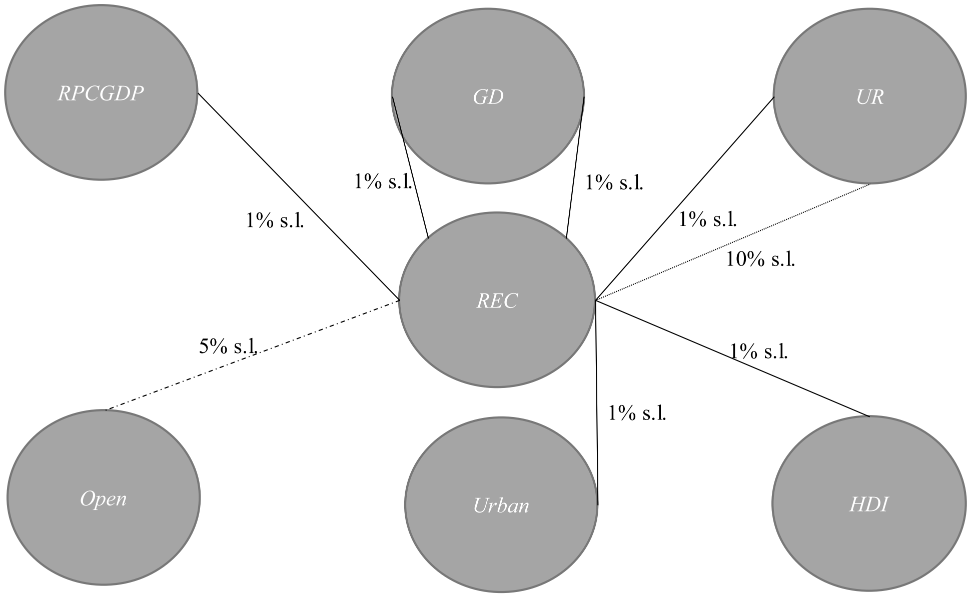

Fig. 2. Summary of causality results.

The relationship between the unemployment rate (UR) and REC appears to be weak. UR has a small negative coefficient, which is not statistically significant ($p > 0.10$).

An increase in the degree of openness is estimated to reduce REC. The two coefficients are highly statistically significant ($p < 0.01$).

High rates of urbanization are correlated with elevated levels of REC. Urbanization exhibits a positive coefficient in both models. However, it is marginally significant in FMOLS at $p < 0.10$, but highly significant ($p < 0.01$) in DOLS.

Furthermore, a potentially positive relationship between REC and HDI is observed. Although HDI has a positive coefficient in both the FMOLS and the DOLS models, it is not statistically significant in the latter.

To evaluate the robustness of these findings, we conducted bootstrapped QR to analyze the relationship between REC and the regressors across the distribution of the dependent variable (Table 10).

Our findings reveal that at various quantiles, an increase in RPCGDP is linked to higher levels of REC. The positive coefficient for the squared term suggests that as RPCGDP increases, REC initially decreases, but beyond a certain threshold, it starts to increase. This implies the existence of a nonlinear (concave) relationship between RPCGDP and REC. Conversely, GDP is associated with lower levels of REC across all quantiles. Similarly, as the unemployment rate increases, REC declines across all quantiles.

The relationship between openness to trade and REC varies across quantiles, exhibiting a significantly stronger negative association at lower quantiles but a relatively weaker negative relationship at the 75th percentile. Furthermore, both the urbanization rate and HDI indicate that higher levels of these variables are associated with higher REC at all quantiles.

The Dumitrescu–Hurlin test yields valuable insights into the pairwise causal relationships between REC and the set of regressors. The results indicate the presence of a unidirectional causal flow from real per capita GDP, openness to trade, urbanization degree, and HDI to REC (see Table 11). The "conservation hypothesis", predicting a unidirectional causal link from GDP to REC, aligns with the findings of Baye et al. (2021), Poumanyvong et al. (2012), and Sadorsky (2009a), among others. Further, a unidirectional flow from urban population to REC was identified by Baye et al. (2021).

Additionally, a bidirectional causality is identified between REC and GD, as well as the unemployment rate (see Fig. 2). This feedback mechanism aligns with the conclusions of Hashemizadeh et al. (2021a) and Sharma et al. (2021), but differs from the findings in Akram et al. (2021).

5. Conclusions

This paper addresses a gap in the literature by employing a novel approach to further investigate the relationship between a country's government debt and renewable energy deployment, as measured by REC. Our analysis integrates various socioeconomic and financial variables crucial for achieving SDG-7 goals, and aims to assess their susceptibility to influencing REC in G7 countries.

Our findings underscore the significant policy implications of the bidirectional causality between government debt and REC for sustainable economic development. This dual-directional causality between government debt and REC has notable policy implications for fostering sustainable economic development, as supported by our empirical findings. On one hand, escalating government debt may constrain the financial capacity to invest in renewable energy infrastructure. Hashemizadeh et al. (2021a) highlight that high debt levels can divert resources from essential environmental initiatives, hindering the transition to cleaner

Table 5
Panel cross-section dependence tests.

REC		Open	
Test	Results	Test	Results
1. Pesaran (2004)	3.77*** (0.0015)	1. Pesaran (2004)	1.81* (0.0989)
2. Pesaran (2004) CD	1.533 (0.1252)	2. Pesaran (2004) CD	14.060*** (0.0000)
3. Friedman (1937)	37.159*** (0.0000)	3. Friedman (1937)	114.329*** (0.0000)
4. Breusch and Pagan (1979)	389.4331*** (0.0000)	4. Breusch and Pagan (1979)	377.4218*** (0.0000)
5. Chudik and Pesaran (2015)	0.3695 (0.7117)	5. Chudik and Pesaran (2015)	10.9074*** (0.0000)
6. Pesaran (2015)	19.3751*** (0.0000)	6. Pesaran (2015)	17.1347*** (0.0000)
7. Baltagi et al. (2012)	56.7298*** (0.0000)	7. Baltagi et al. (2012)	54.8842*** (0.0000)
8. Pesaran (2004) scaled	56.8505*** (0.0000)	8. Pesaran (2004) scaled	54.9971*** (0.0000)
RPCGDP		Urban	
Test	Results	Test	Results
1. Pesaran (2004)	2.84** (0.0111)	1. Pesaran (2004)	2.55** (0.0211)
2. Pesaran (2004) CD	19.428*** (0.0000)	2. Pesaran (2004) CD	1.020 (0.3079)
3. Friedman (1937)	132.667*** (0.0000)	3. Friedman (1937)	105.935*** (0.0000)
4. Breusch and Pagan (1979)	548.4896*** (0.0000)	4. Breusch and Pagan (1979)	590.4631*** (0.0000)
5. Chudik and Pesaran (2015)	16.1990*** (0.0000)	5. Chudik and Pesaran (2015)	−0.8425*** (0.3995)
6. Pesaran (2015)	23.0637*** (0.0000)	6. Pesaran (2015)	24.2699*** (0.0000)
7. Baltagi et al. (2012)	81.2840*** (0.0000)	7. Baltagi et al. (2012)	87.7572*** (0.0000)
8. Pesaran (2004) scaled	81.3934*** (0.0000)	8. Pesaran (2004) scaled	87.8701*** (0.0000)
GD		HDI	
Test	Results	Test	Results
1. Pesaran (2004)	2.53** (0.0223)	1. Pesaran (2004)	3.32*** (0.0039)
2. Pesaran (2004) CD	16.367*** (0.0000)	2. Pesaran (2004) CD	9.032*** (0.0000)
3. Friedman (1937)	107.763*** (0.0000)	3. Friedman (1937)	78.429*** (0.0000)
4. Breusch and Pagan (1979)	343.1618*** (0.0000)	4. Breusch and Pagan (1979)	646.0889*** (0.0000)
5. Chudik and Pesaran (2015)	13.3670*** (0.0000)	5. Chudik and Pesaran (2015)	7.6166*** (0.0000)
6. Pesaran (2015)	16.9185*** (0.0000)	6. Pesaran (2015)	25.4160*** (0.0000)
7. Baltagi et al. (2012)	49.5977*** (0.0000)	7. Baltagi et al. (2012)	96.3404*** (0.0000)
8. Pesaran (2004) scaled	49.7106*** (0.0000)	8. Pesaran (2004) scaled	96.4533*** (0.0000)
UR			
Test	Results		
1. Pesaran (2004)	2.37** (0.0309)		
2. Pesaran (2004) CD	10.277*** (0.0000)		
3. Friedman (1937)	105.660*** (0.0000)		
4. Breusch and Pagan (1979)	100.7717*** (0.0000)		
5. Chudik and Pesaran (2015)	6.8975*** (0.0000)		
6. Pesaran (2015)	5.2639*** (0.0000)		
7. Baltagi et al. (2012)	12.1997*** (0.0000)		
8. Pesaran (2004) scaled	12.3091*** (0.0000)		

Notes: 1: Pesaran (2004) cross-sectional dependence in panel data models test; 2: Pesaran (2004) CD test for cross-section dependence in panel time-series data; 3: Friedman (1937) test for cross-sectional dependence by using Friedman's $\chi 2$ distributed statistic; 4: Breusch and Pagan (1979) LM test of independence; 5: Chudik and Pesaran (2015) test for weak cross-sectional dependence; 6: Pesaran (2015) CD test for cross-sectional dependence; 7: Baltagi et al. (2012) bias-corrected scaled LM test; 8: Pesaran (2004) scaled LM and CD test. Tests include the intercept. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 6
Error tests for cross-section independence.

Test	Specification	
	Constant	Constant and trend
Breusch and Pagan (1980): LM	66.80*** (0.0000)	58.94*** (0.0000)
Pesaran et al. (2008) bias-adjusted LM: LM adj*	15.55*** (0.0000)	11.99*** (0.0000)
Pesaran (2004) LM CD dependence: LM CD*	1.52 (0.1275)	0.78 (0.4371)

Notes:*** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

energy sources. Conversely, an increased adoption of renewable energy can positively impact government debt dynamics. As countries shift towards sustainable practices, they reduce dependence on costly non-renewable resources, potentially mitigating fiscal pressures associated with energy imports (Magazzino et al., 2023). This bidirectional relationship between government debt and REC underscores the importance of a comprehensive policy approach. Policymakers need to prioritize fiscal responsibility to ensure the availability of resources for renewable energy investments while simultaneously incentivizing renewable energy adoption, creating a positive feedback loop with long-term fiscal benefits.

Achieving an optimal balance necessitates a nuanced comprehension of the intricate relationship between government finances and environmental sustainability. This underscores the importance of integrated policies capable of addressing both economic

Table 7
Panel unit root tests in the presence of cross-section dependence.

Variable	Specification	
	Constant	Constant and trend
Pesaran CADF test		
REC	−1.058 (0.972)	−2.310 (0.500)
RPCGDP	−1.178 (0.955)	−1.971 (0.866)
GD	−1.870 (0.400)	−1.642 (0.982)
UR	−2.115 (0.173)	−2.384 (0.447)
Open	−2.205 (0.116)	−2.386 (0.445)
Urban	−0.881 (0.994)	−1.874 (0.919)
HDI	−1.421 (0.844)	−2.602 (0.216)

Notes: $t - bar$ statistics are reported; P-Values in parentheses. Deterministic chosen: constant: Critical Values: −2.210 (10%), −2.330 (5%), −2.570 (1%); deterministic chosen: constant and trend: Critical Values: −2.730 (10%), −2.860 (5%), −3.100 (1%). *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 8
Panel cointegration tests.

Pedroni's residual cointegration test		
	Relation	Individual intercept and trend
Within-dimension	Panel v	1.1991 (0.1152)
	Panel ρ	2.5636 (0.9948)
	Panel PP	−5.7421*** (0.0000)
	Panel ADF	−3.7519*** (0.0001)
Between-dimension	Group ρ	3.6871 (0.9999)
	Group PP	−9.7398*** (0.0000)
	Group ADF	−3.3872*** (0.0004)

Notes: 1: Trend assumption: Deterministic intercept and trend. Variance calculation: d.f. corrected Dickey–Fuller variances. Automatic lag length selection based on Modified Hannan-Quinn. Bandwidth selection: Newey–West automatic. Spectral estimation: Bartlett kernel. P-Values in parentheses. $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 9
Results of cointegrating regressions.

Variable	Cointegrating regressions	
	FMOLS	DOLS
RPCGDP	4.4048*** (0.3065)	4.0813*** (1.0160)
GD	−0.1898*** (0.0680)	−1.0620*** (0.2364)
UR	−0.0052 (0.0040)	−0.0313 (0.0187)
Open	−1.0106*** (0.0872)	−1.3647*** (0.3254)
Urban	3.7658* (0.6685)	5.1838*** (1.2705)
HDI	3.0286*** (1.0997)	7.5438 (4.6879)
R2	0.9779	0.9976
Adjusted R2	0.9756	0.9907
SER	0.1332	0.0809
Long-Run Variance	0.0498	0.0012

Notes: Coefficient covariance computed using sandwich method. Long-Run covariance estimates (Prewhitening with lags = 1, Bartlett kernel, Newey–West automatic bandwidth, NW automatic lag length). SER: Standard Error of the Regression. *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

Table 10
Results of bootstrapped quantile regressions (with 100 bootstraps).

Variable	Quantile Regressions		
	0.25	0.50	0.75
RPCGDP	2.0933*** (0.3071)	2.2483*** (0.3271)	2.4515*** (0.4687)
RPCGDP2	4.8656*** (0.7889)	5.5882*** (0.8322)	6.5355*** (1.0354)
GD	−0.7357*** (0.1233)	−0.7147*** (0.1656)	−0.6871*** (0.2423)
UR	−0.0516*** (0.0122)	−0.0673*** (0.0168)	−0.0878*** (0.0262)
Open	−0.7823*** (0.1597)	−0.4999*** (0.1735)	−0.1298 (0.2322)
Urban	5.5457*** (0.9308)	4.9981*** (0.9629)	4.2803*** (1.2816)
HDI	16.0470*** (1.1549)	17.3022*** (1.3087)	18.9476*** (1.8333)

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$. Robust Standard Errors in parentheses.

Table 11
Dumitrescu–Hurlin panel pairwise causality tests.

Null Hypothesis	W Statistics	Z-bar Statistics	P-Value
REC ⇏ RPCGDP	2.1227	−0.0744	0.9407
RPCGDP ⇏ REC	5.7012	3.8541	0.0001***
REC ⇏ GD	6.3454	4.5613	0.0000***
GD ⇏ REC	4.7335	2.7917	0.0052***
REC ⇏ UR	3.9253	1.9045	0.0568*
UR ⇏ REC	5.1887	3.2914	0.0010***
REC ⇏ Open	4.5005	2.5360	0.0112**
Open ⇏ REC	3.3089	1.2278	0.2195
REC ⇏ Urban	2.5401	0.3838	0.7012
Urban ⇏ REC	7.4900	5.8178	0.0000***
REC ⇏ HDI	1.9915	−0.2185	0.8271
HDI ⇏ REC	9.4617	7.9824	0.0000***

Notes: *** $p < 0.01$, ** $p < 0.05$, * $p < 0.10$.

and ecological objectives (Onuoha et al., 2023a) as well as environmental considerations into decision-making processes. This necessitates implementing regulations and incentives that promote sustainable practices, such as carbon pricing mechanisms, subsidies for renewable energy, and stringent emissions standards. Furthermore, fostering collaboration among G7 nations is crucial to address transboundary environmental challenges and to incentivize the adoption of best practices. By prioritizing sustainable development policies, G7 countries can mitigate risks, drive innovation, and pave the way for a resilient and prosperous future that balances economic growth with environmental stewardship. The mutual effect between financial sustainability and environmental sustainability holds profound policy implications for G7 countries. Policymakers are compelled to adopt a holistic approach. The implications that emerge from our findings underscore the crucial role of policy in promoting sustainable economic development.

1. Fiscal responsibility and investment in renewable energy: This research highlights the need for policymakers to take fiscal responsibility and recognize the potential constraints that escalating government debt places on investment in renewable energy infrastructure. As highlighted by Hashemizadeh et al. (2021a), high debt levels can divert resources away from important environmental initiatives. Therefore, the policy framework should maintain a balanced fiscal environment to ensure the availability of funding for sustainable energy projects.
2. Incentives for the development of the renewable energy sector: Our findings show that the increased adoption of renewable energy can have a positive impact on government debt dynamics. Countries that adopt sustainable practices can potentially reduce the fiscal pressure associated with energy imports. This finding argues in favor of policies that incentivize the widespread use of renewable energy sources, thereby reconciling economic and environmental goals.
3. Comprehensive policy approach: The bi-directional relationship between government debt and REC underscores the need for a holistic policy approach. Policymakers are called upon to develop integrated policies that pursue both economic and environmental objectives simultaneously. Striking a balance between fiscal responsibility and the promotion of renewable energy is of paramount importance to promote a positive feedback loop with lasting fiscal benefits.
4. Nuanced understanding of the relationship: Our study emphasizes the importance of a nuanced understanding of the complicated relationship between public finance and environmental sustainability. Policymakers should develop a nuanced understanding of how fiscal decisions influence the deployment of renewable energy and vice versa. This nuanced understanding is critical to formulating effective policies that contribute to both economic and environmental goals.
5. Future research and methodological exploration: Given the novelty of the topic, our conclusions also extend to future research directions. Thus, subsequent studies could address the concept of double sustainability in different groups of countries using alternative empirical strategies. This methodological extension can further enrich our understanding of the complicated dynamics between government debt and renewable energy consumption.

In essence, our policy conclusions argue for a balanced and integrated approach that recognizes the bidirectional relationship between government debt and renewable energy consumption. Policymakers are encouraged to pursue strategies that simultaneously target fiscal responsibility and promote the adoption of sustainable energy practices to support a harmonious coexistence of economic and environmental objectives.

Given the novelty of this topic, future research could explore the concept of "double sustainability" across different groups of countries, employing alternative empirical strategies such as Artificial Intelligence algorithms, Markov Switching Regressions, Panel Threshold Regressions, and System-Generalized Method of Moments.

The limits of this research primarily stem from the limitations in data accessibility and the possibility of generalizing the results obtained to other geographical areas or groups of countries.

CRediT authorship contribution statement

Monica Auteri: Writing – original draft, Formal analysis, Conceptualization. **Marco Mele:** Data curation. **Isabella Ruble:** Writing – review & editing, Formal analysis. **Cosimo Magazzino:** Writing – original draft, Methodology, Investigation, Formal analysis, Data curation.

Declaration of competing interest

Declarations of interest: none

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