



Research Article

The Role of Public R&D Spending, Technological Innovation, and Renewable Energy in Advancing Sustainable Development: Evidence from G7 Countries

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Abstract

Achieving the Sustainable Development Goals has become a global priority, with COP28 emphasizing clean-energy financing and investment to advance sustainable development. However, many countries and regions still struggle to identify relevant policy-level indicators to encourage engagement with sustainability, even as rising reliance on fossil fuels accelerates global warming and environmental degradation. In this context, designing an effective policy mix is important for achieving sustainable development objectives. This study evaluates the primary determinants of sustainability in the G7 economies using panel data from 1990 to 2022. The study uses the CS-ARDL estimation. The findings reveal that public R&D spending on energy is positively associated with sustainable development in the short term (0.074) and long term (0.106). Additionally, Green technological innovation and renewable energy significantly improve sustainable development. In contrast, economic growth is negatively related to sustainable development. The study also suggests that public R&D spending, green technological innovation, and renewable energy help to reduce carbon emissions. Based on these outcomes, policymakers should prioritize greater investment in renewable energy infrastructure and implement policies that promote sustainable development and accelerate long-term sustainability across G7 economies.

Keywords: Sustainable development, Public R&D spending, Technological innovation, Renewable energy, Carbon emissions

1. Introduction

Sustainable Development has become a primary global concern, leading national policies towards a more robust and environmentally friendly future [1, 2]. Sustainable Development Index measures a country's development profile across several dimensions, including carbon emissions, education levels, average life expectancy, income, and material footprint [3]. In terms of sustainable development, economies struggle with numerous obstacles associated with rising CO₂ emissions, climate change, extensive urbanization, waste production, and pollution from non-renewable energy sources. If governments do not increase their efforts to combat environmental deterioration, global GHG emissions are projected to rise by almost 50% by 2050, creating substantial challenges to achieving the SDGs [4]. Within the framework of sustainable development, researchers globally are actively investigating the main factors of sustainability. Since the late 20th century, carbon emissions have remained the predominant variable of interest in the extant sustainability literature.

Despite their widespread use, carbon emissions as a proxy for environmental sustainability have notable limitations, leading contemporary studies to adopt a broader set of complementary proxies to capture the multidimensional nature of sustainability outcomes, such as waste generation, land biodiversity, and water [5]. Nevertheless, these indices do not comprehensively capture environmental sustainability, as each index focuses on a distinct environmental dimension. Furthermore, these measures may not accurately reflect sustainable development. Focusing only on the environmental aspect and neglecting multifaceted sustainability may lead to biased findings [6]. Additionally, previous literature on sustainable development has relied on inadequate indices, including adjusted net savings [7], renewable energy transition, and economic growth [1], which failed to capture the multidimensional nature of sustainability comprehensively.

This study examined key factors of sustainability for the G7 economies by assessing the impact of public R&D spending, green technology innovation, renewable energy, economic growth, and trade openness. The G7 economies play a significant role as



global economic leaders and technological innovators. The G7 economies account for approximately 46% of nominal global GDP and hold a significant influence in international institutions. Despite their advanced institutional structures, strong technological capacity, and international commitments to net-zero emissions by 2050, G7 economies have consistently failed to achieve comprehensive sustainable development. Figure 1 shows the average SDI values for G7 economies.

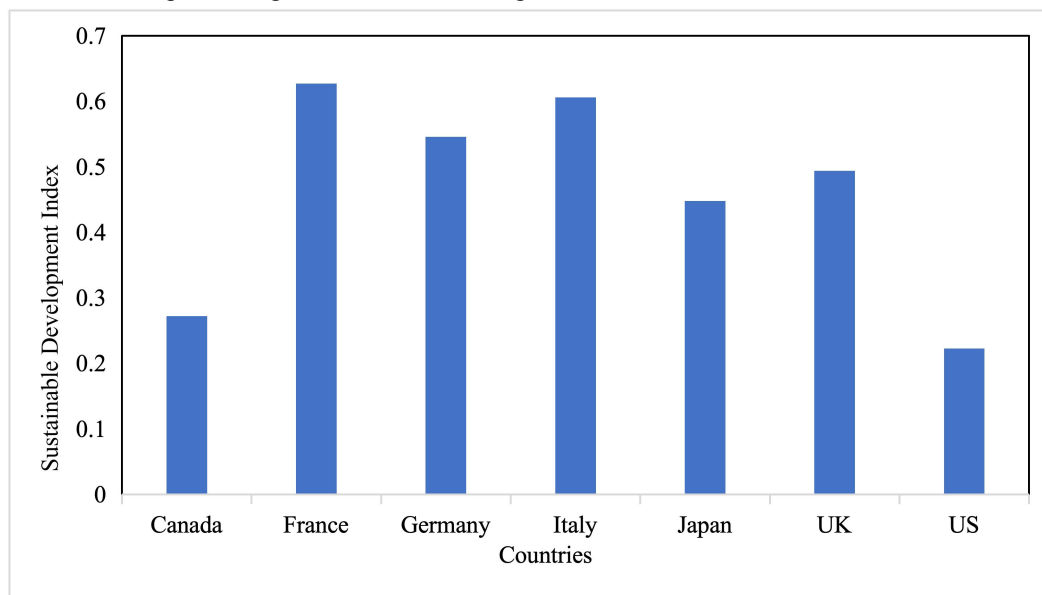


Figure 1. Overview of the sustainable development of the G7 economies. Source: Authors' constructions based on data from Hickel [3], average 1990-2022.

Furthermore, renewable energy accounted for only 20% of total electricity generation in G7 economies in 2020, reflecting the significant and persistent structural dependence on fossil fuels that continues to jeopardize SDGs commitments and collective net-zero goals despite decades of climate policy engagement [8]. Figure 2 illustrates the average share of renewable energy consumption in total energy demand across the G7 economies from 1990 to 2022. Canada recorded the highest share (21.8%), followed by France at 11.1%, whereas the United States (6.5%), the United Kingdom (3.1%), and Japan (4.6%) recorded the lowest proportions of renewable energy in their overall energy mix.

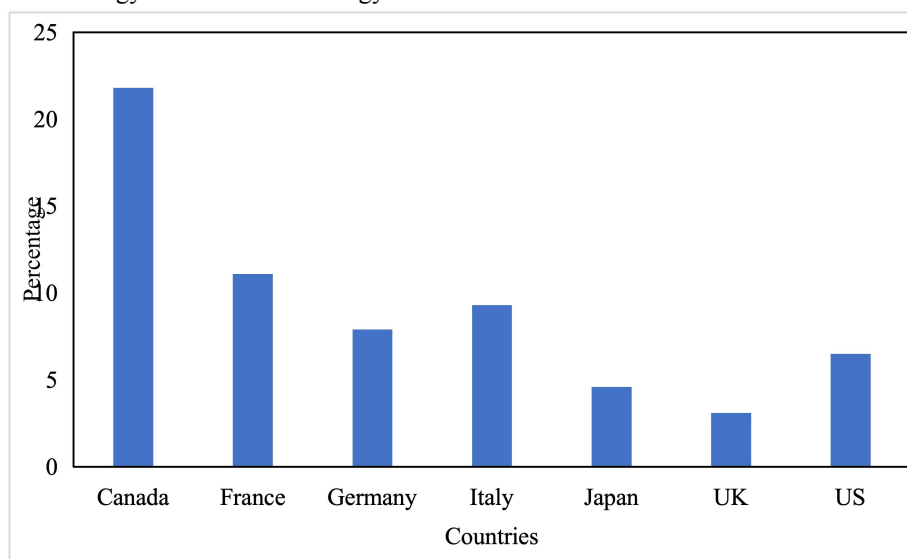


Figure 2. Share of renewable energy consumption of the G7 economies. Source: Authors' constructions based on WDI data [9].

Public R&D spending on energy has emerged as a particularly effective, evidence-based strategy for enhancing the environmental and socioeconomic dimensions of sustainability [10]. For example, Germany's significant R&D investment through the "Energiewende" initiative has expedited advancements in solar and offshore wind technologies, while France's 2030 national investment strategy, featuring EUR 34 billion, designates EUR 8 billion for the energy sector, EUR 1.9 billion for green hydrogen initiatives, and EUR 4.5 billion for industrial decarbonization [11]. France's allocation for public R&D spending nearly doubled from USD 2.6 billion to USD 4.9 billion between 2021 and 2022. The United States' public R&D investment amounted to USD 9.8 billion in 2022, while Japan maintained an annual budget of about USD 4 billion [12].

Despite these substantial investments, existing funding remains insufficient to meet anticipated energy requirements. At COP28, [13] underscored the need to triple worldwide renewable energy production capacity and double the pace of energy efficiency enhancements by 2030. Nevertheless, G7 countries allocated an unprecedented USD 282 billion in fossil fuel subsidies in 2023, nearly tripling the amount from 2020 and underscoring their persistent dependence on fossil fuels [14]. In this context, evaluating public R&D spending in G7 economies is essential to assess its effects on sustainable development and reallocate fiscal resources from fossil fuels to green energy innovations.

Technological innovation has become a critical instrument for mitigating climate change by accelerating the adoption of green technologies, fostering energy efficiency, and lowering the energy intensity of economic activities [15, 16]. This approach leads to eco-friendly product development and processes [17]. Additionally, technological innovation is crucial for addressing the challenges of operating a profitable business in ways that significantly affect the environment. It promotes a shift from production-driven to innovation-driven economic development, thereby mitigating carbon emissions related to industrialization [18]. Although the ecological benefits of technological progress are not inherently guaranteed, because this progress may have a rebound effect, in which efficiency gains may lead to increased demand, production, and consumption of resources, potentially reducing part of their expected environmental benefits [19, 20]. Therefore, it is important to examine the long-term effect of technological innovation on sustainable development in G7 economies.

This study advances the existing literature by offering several contributions. First, it moves beyond prior literature that largely relied on single-dimensional sustainability proxies, including economic growth, waste generation, carbon emissions, renewable energy, and adjusted net savings [1, 5, 7]. This study uses the Multidimensional Sustainable Development Index, which captures the development index (income, education, and life expectancy) and the environmental index (material footprint and carbon emissions) [3]. Second, to the best of our knowledge, no prior study has examined the nexus among public R&D spending, green technological innovation, renewable energy, economic growth, and sustainable development within the G7 context. Third, the study extends the analysis by examining the environmental implications of the explanatory variables by using CO₂ emissions as a separate dependent variable. Fourth, this study applies advanced econometric techniques, including the Cross-Sectional Augmented IPS (CIPS) unit root test and CS-ARDL approach. The study also uses the CCEMG and FMOLS estimators as robustness checks to validate the findings. The following research questions are posed: (i) Does public energy R&D spending improve sustainable development? (ii) Does technological innovation improve sustainable development? (iii) Does renewable energy improve sustainable development? (iv) Do public R&D spending, technological innovation, and renewable energy reduce carbon emissions?

2. Literature review

2.1. Literature on Public R&D Spending

The empirical literature has paid substantial attention to the relationship between public R&D spending and sustainable development, with studies employing diverse methodological frameworks and country-specific contexts. For example, [21] examined the impact of renewable energy R&D investment on environmental quality in emerging and advanced countries and found that renewable energy R&D significantly improves environmental quality. Khan et al. [22] used the total energy R&D budget to assess its influence on sustainable development and found that the public R&D budget is positively associated with sustainable development.

The study by [5] employed the CS-ARDL method across the G7 to demonstrate that R&D spending positively impacts environmental quality. Likewise, [23] used the Pooled Mean Group Autoregressive Distributed Lag method on panel data for 38 EU countries and acknowledged that R&D expenditure significantly decreases CO₂ emissions. In the Chinese context, [24] employed the CS ARDL framework across a sample of Chinese cities and found that energy R&D investment improves environmental performance. [25] confirmed that energy innovation significantly determines carbon emissions mitigation, while [26] corroborated these results across a broad sample of 40 countries, concluding that R&D spending has a favourable impact on pollution reduction.

Conversely, [27] examined public R&D investment in OECD economies and found a positive association with CO₂ emissions, potentially reflecting a rebound effect whereby efficiency stimulates increased overall energy consumption. Similarly, [28] used wavelet estimation for Nordic countries; their findings suggest that institutional and structural conditions, as well as R&D spending, may unintentionally increase carbon emissions. A study by [29] investigated the influence of R&D spending on renewable and biofuel sources across OECD countries. The findings show that R&D spending may be insufficient to drive the transition to renewable energy sources.

2.2. Literature on green technological innovation

Green technological innovation is a pivotal catalyst for sustainable development, significantly contributing to environmental sustainability and economic growth. By focusing on environmentally sustainable technologies and methods, GTI helps reduce GHG emissions and address climate change, which are crucial to achieving SDG targets pertaining to climate action and sustainable industrialization [30, 31].

The study by [32] examined carbon emission dynamics across N-11 economies from 1990 to 2017. The results demonstrated that technological innovation and green energy diminish carbon emissions. Similarly, [33] examined dynamic relationships among innovation, economic growth, environmental quality, and CO₂ emissions in OECD countries, finding that environmental innovation mitigates carbon emissions and highlighting the crucial role of innovation-driven frameworks in advancing sustainability goals. The study by [34] used FMOLS and DOLS to provide empirical evidence that technological innovation contributes to environmentally friendly innovations and reduces carbon emissions. The findings further showed that technological innovation facilitates the adoption of cleaner energy and improves environmental performance.

However, certain studies suggest that the relationship between GTI and sustainable development may not be straightforward. Realizing GTI's full potential often requires additional elements, including improvements in green performance indicators and supportive regulatory structures [35]. Cheng et al. [36] found that technological innovation had an insignificant effect on environmental sustainability in OECD countries. Despite these challenges, GTI remains an essential catalyst for progressing the green economy and achieving sustainable development.

2.3. Literature on renewable energy

Numerous empirical studies have examined the relationship between renewable energy and sustainable development. Using data for G7 economies spanning from 1990 to 2017, [37] found that renewable energy consumption helps to from G7 economies spanning 1990 to 2017, [37] found that renewable energy consumption helps mitigate carbon emissions. Xiong and Dai [38] used carbon emissions as a proxy to study sustainable development in China and found that sustainable energy adaptation reduces carbon emissions. Furthermore, [39] and [40] reported that renewable energy consumption reduces CO₂ emissions, suggesting that progressively substituting fossil fuels with clean energy sources provides consistent and statistically significant environmental benefits. Bilgili et al. [41] showed that renewable energy significantly decreases carbon emissions in OECD economies. Abbas et al. [42] found that increased renewable energy substantially mitigates carbon emissions in Pakistan. Similarly, [43] examined the effect of various forms of renewable energy consumption on carbon emissions in G7 nations. The results indicated that biomass, wind energy, and hydroelectricity significantly affect CO₂ emissions. Nathaniel et al. [44] reported that renewable energy is negatively associated with carbon emissions in G7 economies, while green energy consumption reduced emissions in Canada and France. Pata et al. [45] examined the effects of sustainable resources on ecological footprint in France and reported that these resources are insignificantly associated with ecological footprint.

From the above discussion, determining the appropriate combination of policy measures to achieve sustainable development remains a significant global challenge. Researchers have thoroughly studied the impacts of public R&D spending, green technological innovation, renewable resources, and economic growth on environmental sustainability; yet, empirical evidence has largely yielded contradictory and ambiguous results. Furthermore, achieving sustainable development is crucial for every country worldwide. Empirical research has not examined the main processes underlying multidimensional sustainability in G7 economies. Prior research has focused on specific facets of sustainability, such as economic growth, energy efficiency, ecological footprint, and CO₂ emissions, so evidence on multidimensional sustainability remains scarce. This study used a multidimensional sustainable development indicator that combines the environmental impact index (material footprint and carbon emissions) with the development index (education, income, and life expectancy). Therefore, utilizing data from 1990 to 2022, this study identifies the key fiscal and technological drivers of sustainable development for G7 countries.

3. Data and Methodology

3.1. Model specification and conceptual framework

The model specification is unclear and needs improvement. Please clearly define all variables, explain the rationale for including them, and present Equations (1) and (2) properly. Also, ensure that the conceptual framework illustrates the hypothesized relationships among the variables and sustainable development (SD).

$$\ln SD_{it} = \alpha_0 + \alpha_1 \ln PRND_{it} + \alpha_2 \ln GTI_{it} + \alpha_3 \ln RE_{it} + \alpha_4 \ln GDP_{it} + \varepsilon_{it} \quad (1)$$

$$\ln CO2_{it} = \beta_0 + \beta_1 \ln PRND_{it} + \beta_2 \ln GTI_{it} + \beta_3 \ln RE_{it} + \beta_4 \ln GDP_{it} + \mu_{it} \quad (2)$$

This study has two dependent variables: Model 1 uses sustainable development, derived from [3]. The study uses a multidimensional sustainable development index (the development index) based on life expectancy, education, and income. The environmental impact index quantifies the degree of material footprint and carbon emissions. Model 2 uses CO₂ emissions as the dependent variable to directly reflect the explanatory variables' environmental impact for G7 economies, providing an accurate, comparable assessment of environmental performance separate from broader development outcomes. Where SD_{it} denotes the sustainable development index, $CO2_{it}$ denotes carbon emissions, $PRND_{it}$ denotes public energy R&D spending, GTI_{it} represents green technological innovations, RE_{it} denotes renewable energy, GDP_{it} denotes economic growth, and ε_{it} denotes the error term.

Public R&D on energy is widely acknowledged as a crucial tool for attaining sustainable development. Public R&D provides essential financial and technological support to promote the development and deployment of renewable energy technologies. Endogenous Growth Theory emphasizes that R&D investments develop new knowledge and technological capabilities that improve long-term economic growth. Public R&D therefore represents the input side of the innovation process by providing the finance and institutional resources to advance energy efficiency, environmental technology development, and sustainable manufacturing systems. Therefore, public R&D spending is expected to enhance sustainable development $\left(\beta_1 = \frac{\partial \ln SD}{\partial \ln PRND} > 0\right)$.

According to the innovation theory of sustainability. Technological innovation can boost economic competitiveness and environmental outcomes by encouraging firms to adopt more efficient production practices. Technological innovation is the output side of the innovation process, reflecting the development and implementation of new technologies that enable firms to produce more efficiently. Implementing eco-friendly technologies enables firms to reduce raw material use and energy consumption, cut waste, and mitigate environmental harms linked to manufacturing. Therefore, technological innovation is expected to be positively associated with sustainable development $\left(\beta_2 = \frac{\partial \ln SD}{\partial \ln GTI} > 0\right)$.

Energy transition theory posits that shifting from conventional energy sources to renewable energy for both consumption and production supports economic growth and environmental sustainability, and generally contributes to sustainable development. This

suggests that, under energy transition theory, renewable energy is expected to contribute positively to sustainable development ($\beta_3 = \frac{\partial \ln SD}{\partial \ln RE} > 0$).

3.2. Data

The study focuses on G7 economies from 1990 to 2022. The Sustainable Development Index developed by Hickel [3] is used to assess the extent to which different nations achieve human development, considering ecological sustainability. The indicator builds on three Human Development Index (HDI) indicators (education, life expectancy, and income), which also comprise the Human Development Index (HDI). However, unlike the HDI, the SDI adjusts these three indicators by a country's ecological impact. In particular, the indicator compares income, education, and life expectancy per capita with the planetary boundaries of carbon emissions and material footprint. Therefore, the SDI enables the comparison of whether a country achieves high levels of human development with ecological sustainability. Carbon emissions data are measured as consumption-based per capita in tonnes, and data were collected from the Global Carbon Budget [46] database. Public R&D spending on energy is measured as a percent of the total R&D budget; the data are collected from the [47] database. Technological innovation is measured by patents related to environmental technologies and collected from the [47] database. The percentage of renewable energy consumption is collected from the WDI. The data on GDP per capita (GDP (Constant USD, 2015)) are collected from the WDI database.

Table 1. Variable definitions

Variable	Unit	Source
Carbon dioxide emissions	Consumption-based Per Capita in tonnes	Global Carbon Budget
Sustainable Development Index	Index	Hickel [3]
Public R&D spending	% of total R&D budget	OECD
Green technological innovations	Patent applications (environment-related technologies)	OECD
Renewable Energy Consumption	% of Total Energy Consumption	World Bank
Economic Growth	GDP per capita (Constant USD, 2015)	World Bank

3.3. Empirical Strategy

3.3.1. Cross-sectional Dependence Test

We apply a CSD test to the panel data because the G7 economies rely on one another due to their shared structural and institutional characteristics. However, ignoring CSD by assuming cross-sectional independence may lead to biased and inconsistent regression results. CSD test is important because it allows precise cointegration testing [48]. For these reasons, the current study chooses the [49] CSD test. Accordingly, we look for any cross-sectional slope heterogeneity. In practice, differences in economic, social, and demographic trends, among other factors, can explain variability across G7 economies. The [50] test was employed to evaluate CSD in order to consider potential heterogeneity.

3.3.2. Unit root test

After addressing the CSD and heterogeneity tests, a unit root test is important to determine stationarity and avoid spurious regression results. The CIPS [51] addresses both heterogeneity and CSD. The cross-sectional augmented Dickey-Fuller (CADF) unit root test is employed to empirically determine the CIPS test. It can be reported as follows:

$$\Delta x_{it} = \alpha_{it} + \beta_i x_{it-1} + \delta_i \bar{x}_{it-1} + \sum_{j=0}^p \gamma_{ij} \bar{\Delta x}_{it-1} + \sum_{j=0}^p \gamma_{ij} \Delta x_{it-1} + \varepsilon_{it} \quad (3)$$

In the above equation, $\bar{x}_{it-1}$ and $\bar{\Delta x}_{it-1}$ denote the cross-sectional averages; Δ indicates the differences between them, and ε_{it} represents the stochastic error term. The formula is stated as follows [52]

$$CIPS = \frac{1}{N} \sum_{i=1}^N CADF_i \quad (4)$$

Where $CADF_i$ denotes the CADF unit root test.

3.3.3. Cointegration Test

The panel cointegration test used [53] to evaluate the existence of a long-run equilibrium relationship. The test is based on the error-correction framework and provides four statistics: G_a , G_t , P_a , and P_t . Panel datasets are particularly well suited to the Westerlund approach, as it verifies cointegration directly by testing the error-correction mechanism, rather than relying on residual-based procedures. The following cointegration test includes equations 5-8.

$$G_a = \frac{1}{N} \sum_{i=1}^N \frac{a'_i}{SE(a'_i)} \quad (5)$$

$$G_t = \frac{1}{N} \sum_{i=1}^N \frac{Ta'_i}{a'_i(1)} \quad (6)$$

$$P_t = \frac{a'}{SE(a')} \quad (7)$$

$$P_a = Ta' \quad (8)$$

Where G_a and G_t represent group statistics, P_t and P_a indicate panel statistics, and a' denotes the speed of adjustment from short-term to long-term equilibrium.

3.3.4. CS-ARDL

This study examines the short- and long-run relationships among the variables using the Cross-Sectional ARDL model developed by [54]. This model enables a thorough analysis of the relationship between the variables and is a modified version of the panel ARDL-PMG by [55]. The CS-ARDL framework incorporates cross-sectional averages in both short- and long-run relationships, as well as error correction terms, thereby enhancing several methodological advantages over other panel data approaches. It can produce accurate estimates even when variables are included in various orders, such as $I(0)$ or $I(1)$. Chudik et al. [54] showed that this technique accurately predicts short- and long-term CSD events. An improved ARDL model that includes average cross-sectional estimates for every cross-section is called the CS-ARDL model. Lastly, the CS-ARDL approach produces reliable results despite CSD and heteroscedasticity [56], and is the best fit for both small panels (seven nations) and long time periods (1990–2022). The CS-ARDL specifications for models 1 and 2 are given:

$$\Delta \ln SD_{it} = a_{it} + \sum_{j=1}^p \beta_{it} \ln SD_{i,t-j} + \sum_{j=1}^p \theta x_{i,t-j} + \sum_{j=0}^1 \delta \bar{z}_{i,t-j} + \varepsilon_{it} \quad (9)$$

While for carbon emissions, the equation is given below,

$$\Delta \ln CO2_{it} = a_{it} + \sum_{j=1}^p \beta_{it} \ln CO2_{i,t-j} + \sum_{j=1}^p \theta x_{i,t-j} + \sum_{j=0}^1 \delta \bar{z}_{i,t-j} + \varepsilon_{it} \quad (10)$$

To improve the robustness of our research, we applied a CCEMG estimation approach alongside CS-ARDL. Pesaran [57] developed the CCEMG model to asymptotically eliminate CSD. The model allows slope coefficients to vary across group members, with overall estimates derived as the mean of individual country coefficients. Furthermore, the study employs fully modified ordinary least squares (FMOLS) after confirming a long-run co-integrating association through the Westerlund cointegration test. FMOLS improves the traditional OLS estimator by accounting for endogeneity from cointegrated regressors and serial correlation in the error term using non-parametric adjustments.

4. Results and Discussion

4.1. Results analysis

This section offers the empirical outcomes, along with their interpretation and economic justification. This discussion covers variable descriptions, CSD test, unit root testing, cointegration analysis, CS-ARDL estimation, and robustness checks.

Table 2 presents the statistical description of the chosen variables (SD, CO₂, PRND, GTI, RE, and GDP). The G7 economies' average SD score is 0.49, indicating that even for developed countries like the G7, the score is relatively low and that a comprehensive focus is needed to improve overall SD performance. Regarding volatility, GTI is highly volatile among the G7 countries, followed by RE. The table below shows the distribution characteristics of each variable. Table 3 shows no multicollinearity, thus supporting the validity of the following econometric analysis.

Table 2. Variable descriptions.

Variables	Observations	Mean	Std. Dev.	Minimum	Maximum
lnSD	231	-0.704	0.458	-1.820	-0.281
lnCO ₂	231	2.473	0.325	1.801	3.113
lnPRND	231	0.616	0.704	-1.108	1.585
lnGTI	231	7.267	1.199	4.939	9.235
lnRE	231	1.958	0.864	0.510	3.173
lnGDP	231	10.531	0.191	10.22	11.085

Table 3. Multicollinearity test.

Variable	VIF	1/VIF
lnPRND	3.82	0.261
lnGTI	2.70	0.587
lnRE	1.25	0.797
lnGDP	1.68	0.595
Mean VIF	2.54	---

Table 4 presents the CSD test findings. These results demonstrate how the selected economies are interconnected and vulnerable to worldwide economic shocks. Thus, based on these diagnostic findings, this study employed estimation methods consistent with the problems of diverse slope coefficients and CSD.

Table 4. CSD Test.

Variables	Coefficient
lnSD	16.09***
lnCO ₂	14.34***
lnPRND	12.02***
lnGTI	25.83***
lnRE	20.40***
lnGDP	23.57***

Note: ***, **, * represent significance levels of 1%, 5%, and 10%.

Further, the study applied the [50] test for slope heterogeneity. Both statistics reject the null of slope homogeneity at 1%, as listed in Table 5; this shows that slopes are heterogeneous, supporting the CSARDL estimator

Table 5: Slope heterogeneity test.

	Model 1	Model 2
Delta	6.401***	7.546***
Delta Adjusted	7.722***	8.746***

Note: ***, **, * represent significance levels of 1%, 5%, and 10%

The CIPS test evaluates the unit root characteristics of each variable [51], as shown in Table 6. The results show that SD, PRND, CO₂, RE, and GDP are non-stationary at level but become stationary after first differencing. In contrast, GTI is stationary at level. The mixed stationarity structure across the variables is significant at the 1% level, confirming the appropriateness of the CS-ARDL estimation.

Table 6: Unit root test.

Variable	CIPS		CADF	
	Level	1st Difference	Level	1st Difference
lnSD	-1.296	-4.731***	-1.780	-3.451***
lnCO ₂	-1.715	-5.509***	-2.061	-4.476***
lnPRND	-2.023	-5.930***	-2.071	-7.590***
lnGTI	-2.786**	-5.464***	-2.551**	-4.521***
lnRE	-1.365	-4.903***	-1.140	-3.174***
lnGDP	-1.524	-4.684***	-1.518	-3.728***

Note: ***, **, * denote significance levels at 1%, 5%, and 10%.

Table 7 displays the panel cointegration test. The results confirm cointegration and support the empirical model's long-term cointegrating relationship. After verifying cointegration, we used the CS-ARDL to estimate the main findings shown in the table.

Table 7. Cointegration test.

Statistics	Model 1				Model 2			
	Gt	Ga	Pt	Pa	Gt	Ga	Pt	Pa
Value	-2.792***	-4.837	-7.435***	-3.573***	-4.384***	-5.876	-9.435***	-4.163**
Z-value	-3.934	2.003	-2.354	-2.612	-5.243	2.343	-3.438	-2.891

Note: ***, **, * denote significance levels at 1%, 5%, and 10%.

This study selected the lag order using the Akaike Information Criterion. AIC and BIC jointly identified CS-ARDL(2,1) as the optimal specification for Model 1, while CS-ARDL(1,1) was selected for Model 2. The study then used these specifications to estimate the long-run and short-run coefficients. Table 8 reports the CS-ARDL estimation results, illustrating the impact of public R&D spending, technological innovation, renewable energy, and economic growth on sustainable development. Model 1 shows that PRND is positively associated with SD in both the short run (0.074) and long run (0.106), confirming that investing in energy R&D improves sustainability. Similarly, green technological innovations (GTI) are positively related to SD in both the short run (0.144) and the long run (0.231), suggesting that progress in environmentally oriented technologies plays an essential role in improving sustainability by enhancing energy efficiency, reducing environmental pressure, and supporting economic and social development. The findings indicate that RE is positively related to sustainable development. In contrast, GDP is negatively associated with sustainable development.

Model 2 included CO₂ emissions as the dependent variable to examine the environmental outcomes associated with the explanatory variables. The coefficient of PRND in Model 2 is negative in both the short run (-0.032) and long run (-0.087), indicating that public R&D investment significantly helps reduce carbon emissions. Similarly, green technological innovations (GTI) significantly reduce carbon emissions in both the short run and long run, with coefficients of -0.134 and -0.364, respectively.

These results show that developing and diffusing environmental technology increases energy efficiency, reduces carbon emissions, and supports greener industrial practices across G7 economies; these findings align with [58]. Further, the results indicate that RE is negatively associated with carbon emissions in the short and long run. However, economic growth is positively associated with emissions in both the short and long run.

Table 8. Cross-Sectional ARDL.

Variables	SDI Model 1		CO ₂ Model 2	
	Short-run	Long-run	Short-run	Long-run
lnPRND	0.074* (0.039)	0.106** (0.062)	-0.032* (0.017)	-0.087* (0.052)
lnGTI	0.144* (0.081)	0.231* (0.124)	-0.134*** (0.056)	-0.364*** (0.117)
lnRE	0.067** (0.022)	0.153** (0.076)	-0.053*** (0.135)	-0.156* (0.091)
lnGDP	-1.303*** (0.429)	-1.733*** (0.545)	0.940*** (0.258)	0.943*** (0.226)
ECM		-0.546***		-0.639***
R ² (MG)		0.656		0.684
Wooldridge test		0.299		0.576

Note: The symbols***, **, * denote a significance level at 1%, 5%, and 10%.

Table 9. Robustness estimations.

Variables	CCEMG		FMOLS	
	SDI model 1	CO ₂ model 2	SDI Model 1	CO ₂ Model 2
	Coef.	Coef.	Coef.	Coef.
lnPRND	0.094** (0.034)	-0.117* (0.061)	0.251** (0.125)	-0.060*** (0.017)
lnGTI	0.159*** (0.036)	-0.009** (0.004)	0.050*** (0.006)	-0.201* (0.102)
lnRE	0.029* (0.016)	-0.165*** (0.032)	0.090*** (0.008)	-0.360*** (0.056)
lnGDP	-1.369** (0.598)	0.757** (0.280)	-1.530*** (0.327)	0.170*** (0.029)
R ²			0.564	0.613

Note: ***, **, * denote a significance level at 1%, 5%, and 10%.

In addition, the study conducted a robustness check to ensure the reliability of the empirical findings, using the CCEMG and FMOLS estimators to validate the CS-ARDL results. FMOLS provides an alternative long-run estimator that accounts for potential endogeneity and serial correlation. As reported in Table 9, the robustness check results align closely with the baseline CS-ARDL estimates. In both approaches, the variables in model 1, PRND, GTI, and RE, show a positive relationship with Sustainable Development, while in model 2 the association is negative, indicating that PRND, GTI, and RE help improve environmental sustainability. The robustness check confirms the reliability of the main outcomes, underscoring that public R&D spending, green technological innovation, and renewable energy adoption are important factors of sustainable development in G7 economies. These findings demonstrate the crucial importance of advancing clean energy and strengthening innovation policies to achieve long-term sustainable development objectives.

Table 10 presents the findings of the Dumitrescu and Hurlin causality test [59]. The findings indicate a causal relationship among sustainable development, public energy R&D spending, green technological innovation, renewable energy, and economic growth. The findings confirm bidirectional causality between PRND and SD, GTI and SD, and RE and SD in Model 1. In contrast, the study found a unidirectional causal association between economic growth and sustainable development, indicating that economic activities substantially affect sustainable outcomes in the G7 countries. In Model 2, PRND and CO₂ emissions show a unidirectional causal link, indicating that government investments in public energy R&D are significantly associated with environmental outcomes, while GTI and RE have a bidirectional causal relationship with CO₂ emissions. Economic growth and CO₂ emissions show a unidirectional causal relationship. This research supports the notion that economic activity primarily affects environmental outcomes. It indicates a partial separation between economic expansion and ecological damage, implying that advanced economies may address environmental consequences through growth strategies without immediately harming growth through environmental degradation.

Table 10. Causality estimation.

Causality	W-stat	Z-stat	P-value
Model 1			
lnPRND→lnSD	2.845	2.915	0.003
lnSD→lnPRND	2.772	2.795	0.005
lnGTI→lnSD	3.629	4.915	0.000
lnSD→lnGTI	6.223	8.474	0.000
lnRE→lnSD	7.056	6.048	0.000
lnSD→lnRE	3.357	3.758	0.000
lnGDP→lnSD	2.936	3.065	0.002
lnSD→lnGDP	0.521	-0.909	0.363
Model 2			
lnPRND→lnCO ₂	6.731	6.254	0.000
lnCO ₂ →lnPRND	2.872	1.133	0.258
lnGTI→lnCO ₂	2.783	2.813	0.004
lnCO ₂ →lnGTI	8.444	12.130	0.000
lnRE→lnCO ₂	8.068	11.512	0.000
lnCO ₂ →lnRE	2.494	2.337	0.019
lnGDP→lnCO ₂	5.442	4.554	0.000
lnCO ₂ →lnGDP	1.330	-0.885	0.391

4.2. Discussion

The findings suggest that higher public R&D spending is associated with higher sustainable development and the expansion of green energy infrastructure. Because sustainable energy transitions require significant financial and technological capacity, these countries are better positioned to benefit from green energy adoption. In this regard, renewable energy is crucial for the economy and the environment because it reduces dependence on fossil fuels and offers an affordable way to achieve sustainable development [60].

According to [61], investments in energy infrastructure can improve electricity access in regions with unreliable supply, supporting economic growth and higher living standards. It may create jobs in the energy industry and related sectors, support economic expansion, improve living standards, and help achieve the 2030 SDGs goal. In addition, public R&D expenditure can encourage the development of innovative energy-related technologies and processes that will facilitate the transition of economies toward sustainable development and a low-carbon economy. Consequently, energy R&D plays a significant role in driving sustainable development within the G7 economies.

Moreover, the endogenous growth theory underscores that investment in knowledge creation and technological progress are fundamental factors of long-term economic development. Within this framework, public R&D spending plays a key role in shaping

sustainability by improving energy efficiency and supporting cleaner energy production. These mechanisms are especially important for G7 countries, where government investment in energy research is crucial to shifting toward more sustainable development trajectories [61]. These results align with recent research showing that public R&D funding is crucial for mitigating carbon emissions [21, 26]. One possible explanation is that public R&D expenditures help allocate the resources needed to develop, promote, and adopt clean energy.

Green technological innovation plays an important role in achieving sustainable development and effectively mitigates the environmental challenges in G7 countries. The estimated long-run results indicate that the benefits of GTI accumulate over time as environmentally friendly technologies are gradually adopted and diffused through the economy. Therefore, green technological innovations are likely to improve energy efficiency, which may help reduce carbon emissions from fossil fuel combustion [62]. Furthermore, by improving environmental quality and increasing global competitiveness, technological advancements support long-term sustainable development. These findings complement several studies on the positive role of GTI in improving environmental sustainability [63-65].

Likewise, renewable energy supports sustainable development and substantially reduces carbon emissions. This shows that by switching from non-renewable or conventional energy sources to cleaner sources for both production and consumption, the selected economies can not only ensure economic sustainability and development but also improve overall sustainable development [66, 67]. These results align with the literature, highlighting the positive relationship between renewable energy and environmental quality [5, 68-71].

5. Conclusion and Policy Recommendation

5.1. Conclusion

The Sustainable Development Goals, alongside the recent COP28 conference, have reaffirmed the importance of sustainable development in advancing energy transitions and sustainable climate financing. Given the significance and urgency of this subject, the current study empirically analysed the key fiscal and technological drivers of multidimensional sustainable development for the G7 countries using data spanning from 1990 to 2022. The study uses a multidimensional sustainable development index that integrates the development index (education, income, life expectancy) and the environmental dimension (carbon emissions and material footprint). Additionally, the study examines the environmental outcome separately by using CO₂ emissions as an additional dependent variable, providing a more focused assessment of the environmental dimension. Following rigorous CSD and heterogeneity diagnostic tests, the study used the second-generation CIPS and CADF unit root tests, the Westerlund cointegration test, and the CS-ARDL model to estimate the outcomes.

The study found that public energy R&D spending, green technological innovations, and renewable energy are positively associated with sustainable development. In contrast, economic growth is negatively associated with sustainable development. Furthermore, the findings indicate that PRND reduces carbon emissions in both the short and long run, underscoring the pivotal role of innovation-driven policies in advancing sustainable development. Similarly, environmentally related technologies serve as a key driver of carbon emissions reduction, indicating that environmentally focused technological advancements boost energy efficiency, promote cleaner production, and reduce environmental pollution.

5.2. Policy Recommendation

The study's findings provide valuable insight for policy recommendations. Public R&D contributes positively to sustainable development and reduces emissions in both the short and long run. The findings suggest that G7 governments need to allocate more funds to public energy R&D to achieve sustainable development goals. In the short run, governments can achieve this through fiscal mechanisms such as targeted R&D subsidies and green tax credits for firms that engage in renewable energy R&D initiatives, and they should allocate more funds to environmental technology, which encourages sustainable development; whereas in the long run, it should be consolidated through structural transformations such as energy grid modernization and large-scale energy storage deployment.

Despite growing budget deficits, G7 economies collectively allocated around USD 282 billion to fossil fuel subsidies in 2023. Such subsidies disrupt energy markets and expose budgets to unpredictable fossil fuel prices. Redirecting a small portion of these expenditures toward public R&D for renewable energy would not only help close the clean energy investment gap, but also strengthen long-term energy security and speed the transition to a sustainable, low-carbon economy. Moreover, policymakers should promote integrating green energy sources into the energy mix to reduce dependence on fossil fuels and mitigate environmental deterioration. Additionally, governments need to encourage firms to adopt and improve green technologies through financial incentives, innovation grants, and technical support. Wider adoption of sustainable technology can improve energy efficiency, reduce carbon footprints, and foster long-term sustainable development outcomes.

This study is limited to G7 economies, which differ, and covers 1990 to 2022 because of recent data availability constraints; future studies could include OECD countries and more recent years to capture evolving trends in public R&D spending, green technological innovation, and renewable energy. G7 countries differ from emerging and developing economies in their energy systems, innovation capacities, and institutional settings, which limits the applicability of the findings. The study used CS-ARDL as the main framework, with CCEMG and FMOLS for robustness; however, residual endogeneity cannot be fully eliminated. Future research could use country-specific estimates, mechanism-level data, alternative index construction, and instrumental-variable approaches to address this limitation.

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