Carbon Footprints

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Environmental footprint impacts of green energies, green energy finance and green governance in G7 countries

Gulzara Tariq[1], **Huaping Sun**[1,2], **Sajjad Ali**[3]

[1]School of Finance and Economics, Jiangsu University, Zhenjiang 212013, Jiangsu, China.
[2]School of Economics and Management, University of Science and Technology Beijing, Beijing 100083, China.
[3]School of Management, Jiangsu University, Zhenjiang 212013, Jiangsu, China.

Correspondence to: Dr. Gulzara Tariq, School of Finance and Economics, Jiangsu University, Zhenjiang 212013, Jiangsu, China. E-mail: gulcute327@gmail.com/1000005752@ujs.edu.cn

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Abstract

The demand for resources and energy increases as the global population grows, leading to increased ecological and carbon footprints. This study aims to contribute to the global sustainability agenda by assessing the impact of green energy projects, green energy finance, and green governance on reducing ecological and carbon footprints in G7 countries from 1990 to 2020. The findings reveal that there is a noteworthy negative association between ecological footprint, green governance, geothermal energy consumption, hydro-power consumption, and green energy finance. However, a significant positive correlation exists between ecological footprint and biofuels. Additionally, the outcomes lend support to the Environmental Kuznets Curve (EKC) theory in G7 nations. Carbon footprints are evaluated in this study as an alternate measure, and the results are similarly robust. These insights hold the potential to guide policy decisions and investment strategies, and promote the shift to a low-carbon economy by highlighting the connections between the adoption of green energies, green energy finance, green governance, and carbon and ecological footprint reduction, thus paving the way for a more equitable and sustainable future for all.

Keywords: Green energy finance, green governance, green energies, ecological footprint, carbon footprint

INTRODUCTION

The global community is faced with pressing ecological challenges linked to climate change and resource depletion. Climate change primarily results from carbon emissions, especially in the form of greenhouse gases such as carbon dioxide. The accumulation of these gases in the atmosphere, coupled with the ensuing rise in average global temperatures, has led to significant environmental concerns affecting both developing and industrialized nations[1]. The escalating human activities, both direct and indirect[2,3], have triggered considerable concerns about environmental responses, particularly regarding energy consumption, economic development, population dynamics, and various other influential factors[4–8]. Despite extensive research offering diverse policy suggestions to address these issues, there exists a range of inconsistent and contradictory conclusions. Therefore, to gain a broader perspective on ecological progress, assessment beyond carbon emissions, such as biocapacity, carbon footprint (CF), and ecological footprint (ECF), have been incorporated[9,10]. Recognizing the vital role of green governance and green financing systems becomes imperative in highlighting the urgency of reducing carbon emissions. This study presents a concise overview of crucial elements and challenges concerning the impact of green energy finance on carbon footprints.

The G7 nations, known for their diverse energy sources and expanding ecological carbon footprint, are not exempt from environmental issues due to the significant ecological problems brought about by their recent rapid economic and energy growth. Furthermore, the majority of the global population lives in countries facing environmental deficits, where approximately 80% of people depend on limited natural resources, exceeding the Earth's capacity for replenishment (Global Footprint Network). Figure 1 demonstrates that, with the exception of Canada, human demands in the remaining G7 countries have surpassed Earth's biocapacity, leading to ecological overreach and stresses on ecosystems through resource depletion, pollution emissions, and land degradation, as well as a decline in biodiversity. The current energy portfolio, heavily reliant on fossil fuel combustion (constituting almost 80%), stands as a significant contributor to global pollution[11]. Addressing global energy concerns becomes imperative for meeting escalating energy needs while protecting the environment throughout an energy transition. To tackle these problems, it is essential to modify the current energy model, transitioning towards low-carbon emission sources with minimal ecological footprint and maximal efficiency in resource utilization to conserve the limited resources essential for future energy generation[12,13]. These challenges may be effectively resolved through initiatives such as green energy finance, green governance, and the adoption of hydro-power, geothermal, and bio-fuel energy sources, which have witnessed significant growth due to enhancements in energy mix efficiency, institutional changes, and technological advancements. Given these contexts, this study concentrates on the carbon and ecological effects of bio-fuels, hydro-power, geothermal energy use, and the role of green governance and green energy finance in G7 countries.

Achieving a substantial and lasting reduction in ecological and carbon footprints requires a significant increase in both green governance and green energy finance. Green governance (GG) strategies, devised by economists and environmentalists, aim to mitigate ecological damage. Nevertheless, the governance practices can either expedite or impede the pace of environmental deterioration[14,15]. To help countries with large ecological footprints decrease their impact, greater emphasis should be placed on supporting green energy finance and implementing environment-related taxes. Consequently, financial transactions and the use of energy can directly influence carbon and ecological footprints. Notably, the previous research has yet to explore the impact of G7 countries' energy consumption from hydro-power, geothermal, and biofuels on their carbon and ecological footprints.

This research distinguishes itself from past studies by focusing on the effects of green energy financing, green governance, and the utilization of hydro-power, geothermal energy, and biofuels on the ecological and carbon footprint of the G7 economies between 1990 and 2020. It is the first study to explore how these factors influence carbon and ecological footprints and thus aid economists in formulating suitable energy finance policies. Additionally, it seeks to analyze how the adoption of green energy finances and green governance impact the carbon footprints of nations and to what extent financial institutions contribute to carbon footprint reduction through their investment strategies and sustainable finance practices. Robust estimators such as DOLS and FMOLS are employed to address various analytical challenges, including endogeneity, heteroscedasticity, cross-sectional

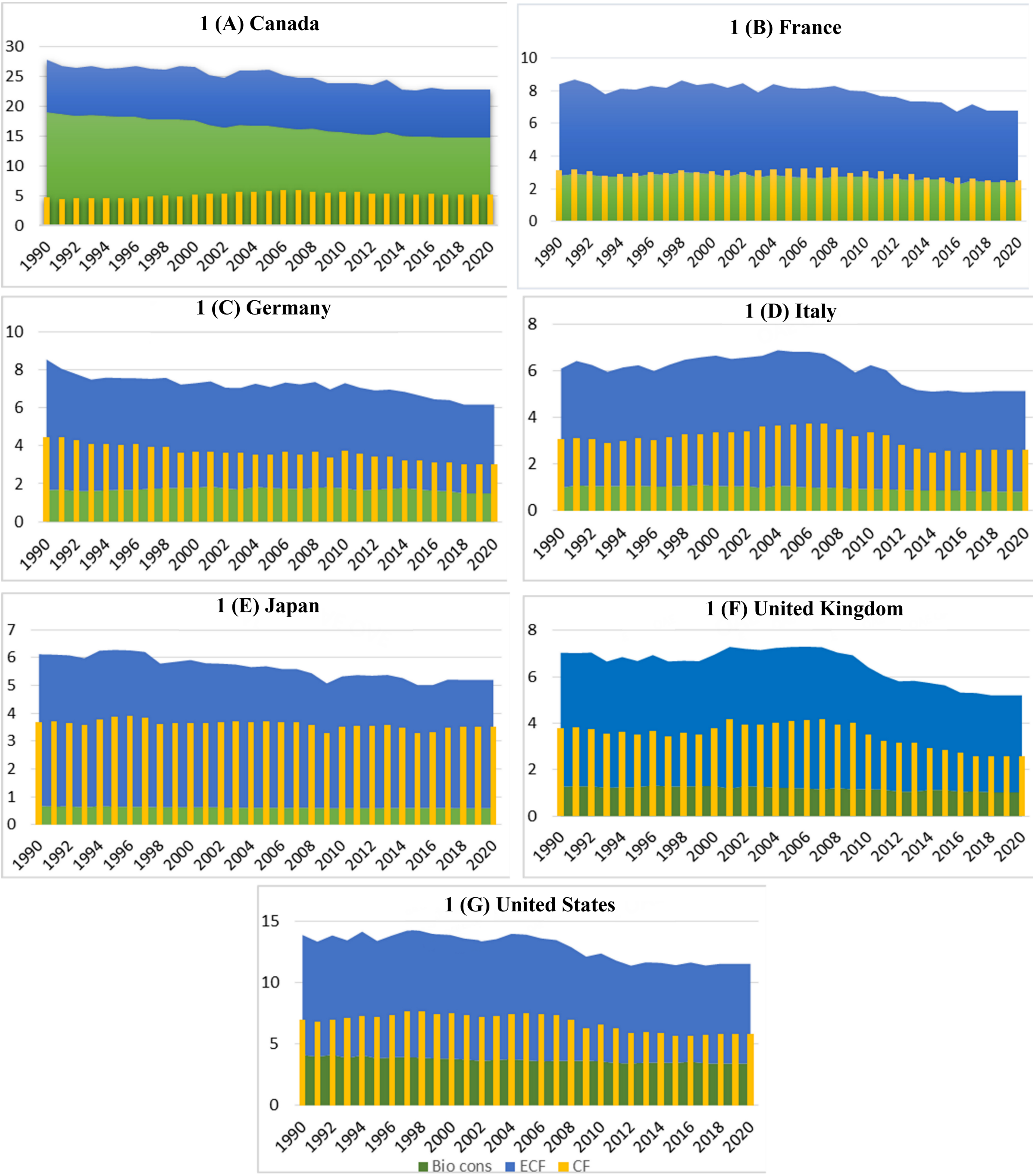

Figure 1. Ecological footprint (global hectare per capita).

dependence, autocorrelation, and the presence of regression coefficients with different integration levels.

The remaining four sections of this study are arranged as: section two provides a review of previous studies, section three outlines the empirical model used in this study, section four details the statistical results with accompanying explanations, and finally, section five encompasses the conclusion, future policy endorsements, and limitations of the study.

REVIEW OF PREVIOUS STUDIES

The impact of carbon and ecological footprint impacts, and their contribution to climate change, constitute a central and primary concern on a global scale. In this scenario, societal, economic, and environmental sustainability - the three pillars of sustainable development-have emerged as crucial factors for human survival[16]. Environmental sustainability holds particular significance due to its direct influence on climate change and the degradation of ecological conditions[17,18]. The ecological footprint serves as a comprehensive measure of environmental damage, reflecting the state of environmental sustainability[19–21]. Thus, previous studies have extensively examined the ecological footprint as an indicator of environmental deterioration from various perspectives. Moreover, several studies have investigated the correlation between energy consumption and its implications on the ecological footprint. For instance, Charfeddine[22] explored the impact of income and energy consumption on the ecological footprint in Qatar, revealing a positive correlation.

Bello *et al*. revealed that hydroelectricity consumption has reduced ecological footprint and economic development and ecological footprint have inverted U-shaped connection in developing economies[23]. Baloch *et al*. investigated the economic growth and ecological impact of the Belt and Road Initiative (BRI) countries[24]. The findings revealed that financial prosperity generates a larger ecological footprint. By taking into account the contribution of GDP from the tourist industry, Ozturk *et al*. and Katircioglu *et al*. verified the EKC theory for high-income and upper-middle-income countries[25,26]. Furthermore, Solarin and Al-Mulali investigated the impact of foreign direct investment (FDI) on the ecological footprints of 20 different nations[27]. Their findings suggest that while FDI does not reduce the ecological footprints of developing nations, it does so in developed nations.

Destek *et al*. employed second-generation panel econometric approaches to assess the EKC theory for the EU member states. Their results lead to the conclusion that ecological footprints and income have a U-shaped relationship[28]. More utilization of non-renewable energy increases ecological footprints, while trade activities and consumption of renewable energy stop environmental deterioration.

According to Wang and Dong, economic growth has a favorable effect on ecological footprints[29]. Additionally, several studies support the notion that utilizing biomass energy is environmentally beneficial, as it reduces CO_2 emissions, greenhouse gas emissions, and ecological footprints[16,30–32]. However, an opposing view from another group of researchers[33–35] argues that biomass energy leads to increased pollutant emissions and is detrimental to the environment. On the contrary, a study focusing on 24 European countries by Ahmed *et al*. found no conclusive evidence regarding the effects of biomass energy usage on ecological influences[36]. Furthermore, Wang *et al*. suggested a positive correlation between the ecological footprints of G7 nations and biomass energy output[37].

Additionally, Zeraibi *et al*. stated that although technical innovation and increased renewable electricity generating capacity elevate ecological footprints, higher levels of financial development and economic growth decrease them[38]. Pata and Caglar[39] supported the notion that financial development and renewable energy contribute to the reduction of environmental footprints. On the other hand, it has been claimed that the usage of power generated from fossil fuels is environmentally detrimental due to their composition of hydrocarbons[40–42]. Moreover, estimations using FMOLS and DOLS showed that the SAARC nations' ecological footprints increased due to the utilization of biomass energy and economic expansion[43].

The country's ecological footprint growth potential is consolidated by the BRICS-T ecological footprint level increased by every 1% rise in agriculture value-added. Additionally, there is a decrease in ecological footprints with a 1% increase in non-renewable energy usage and financial growth. This suggests a considerable improvement in environmental quality over time; specifically, a 1% increase in forestry and a 1% rise in renewable energy usage result in a 0.7483% and 0.2248 reduction in ecological footprint, respectively[44]. Nathaniel *et al*. explored the relationship between environmental protection laws and ecological footprints in the N11 nations from 1990 to 2016[45]. The results demonstrated that the existing environmental legislation in these countries is ineffective in curbing their ecological footprints. It is anticipated that environmental regulations in South Asian nations will positively impact the environment by promoting the use of green energy while mitigating the negative environmental effects associated with foreign direct investments, economic growth, and non-renewable energy combustion[46]. In their study, Murshed *et al*. found that the use of nuclear energy, population density, and environmental technology had significant adverse effects on the environment[46]. However, economic expansion and globalization were observed to yield favorable outcomes.

It is clear from the discussion above that there are conflicting findings in the scientific literature about how economic development affects environmental footprints. To the best of the authors' understanding, no study has specifically examined the influence of green energy finance, green governance, hydro-power, geothermal, and bio-fuels energy consumption on the ecological and carbon footprints of the G7 countries. Therefore, it is justified to further investigate this association.

METHODOLOGY

Theoretical analysis

The G7 countries' consumption of geothermal energy, hydro-power, biofuels, economic growth, green energy finance, and green governance are all examined in this study to determine their environmental footprints. The ecological footprint is enlarged by the increased consumption and production of commodities, which boosts the use of energy and resources. Over recent years, the ecological footprint has gained prominence as a comprehensive indicator and a significant environmental proxy that more accurately captures the potential environmental impacts of energy and production operations[47]. In this work, the functional form proposed by Brandao *et al*. is used to evaluate the desired long-run model, which takes into account the influence of economic growth, biofuels, hydro-power, and geothermal energy consumption on the environmental footprint[48], the equation is as folllowing:

$$ECF = f(HPC, GTC, BFC) \tag{1}$$

In comparison to coal, natural gas, and other energy sources, hydro-power and geothermal energy are recognized as green energy sources and among the least expensive energy sources to produce more electricity. It can reduce the nation's budget deficit by reducing the dependency on foreign energy imports and promoting sustainable economic growth by solving the problems with energy supply and baseload. As a result, it can significantly contribute to energy efficiency, economic sustainability, and a decrease in the environmental footprint of the energy sector. Despite the fact that biofuels are renewable and are regarded as green energy, their use nevertheless contributes to environmental deprivation as it upsurges CO_2 emissions.

In order to achieve long-term prosperity, governments should manage natural resources responsibly and preserve the planet's ecosystems. This is the goal of green governance, which seeks to strike a balance between economic growth and environmental conservation. It includes a wide range of regional, governmental, and worldwide initiatives that all strive to build a more ecologically friendly and sustainable world. Green energy finance involves providing funding and investment for renewable energy projects, such as solar, wind, hydro, and geothermal power. By implementing laws and policies that encourage the development and use of renewable energy technology, green governance plays a critical role in fostering a climate that is favorable for these investments. Green governance creates the legal framework required to promote the expansion of green energy. This covers regulations like tax incentives, feed-in tariffs, carbon pricing methods, and mandates for renewable energy sources. These regulations provide financial incentives for companies and individuals to invest in and utilize green energy technology. Green governance ensures that the funds are distributed fairly and in accordance with environmental goals, eliminating improper allocation of resources. In summary, green energy finance and green governance are closely intertwined. Although green energy financing provides the required funding for renewable energy projects, green governance establishes the legislative and administrative framework that promotes investment, controls risk, and assures less environmental pollution. Collectively, they assist in the shift to an energy system that is more environmentally friendly and sustainable.

Environmental tax and revenues are used as a proxy for green governance. By levying higher taxes on polluting enterprises to prevent the loss of natural resources, these tariffs encourage green growth. Additionally, green energy finance can help the green energy industry during the energy transition, lowering pollutants and advancing the goals of sustainable development. Extreme biodiversity loss can result from over-harvesting natural resources owing to increased economic activity. However, implementing green energy finance and establishing environmental taxes and revenues, as well as encouraging the use of hydro-power and geothermal energy, can mitigate this adverse effect. Therefore, the following equation is established, denoted as Equation (1):

$$ECF = f(HPC, GTC, BFC, GEF, GG) \tag{2}$$

Prior to estimating the model, all variables are converted to natural logarithms to standardize the data and generate precise estimates that assist the analysis of the elasticity of the regression coefficient. Additional variables like economic growth and square of economic growth are added to the model to reduce the bias caused by the missing variable and to ensure its accuracy. The panel log-linear econometric functions of Equation (2) may thus be expressed as follows:

$$lECF_{i,t} = a_0 + a_1 lHPC_{i,t} + a_2 lGTC_{i,t} + a_3 lBFC_{i,t} + a_4 lGDP_{i,t} + a_5 lGDP^2_{i,t} + \varepsilon_{i,t} \tag{3}$$

$$lECF_{i,t} = a_0 + a_1 lHPC_{i,t} + a_2 lGTC_{i,t} + a_3 lBFC_{i,t} + a_4 lGDP_{i,t} + a_5 lGDP^2_{i,t} + a_6 lGEF_{i,t} + a_7 lGG_{i,t} + \varepsilon_{i,t} \tag{4}$$

The dependent variable ECF indicates ecological footprint, and the explanatory variables HPC, GTC, BFC, GDP, GEF, and GG signify hydro-power consumption, geothermal energy consumption, bio-fuel consumption, economic growth, green energy finance, and green governance. The factors a_1 to a_7 are the long-run coefficients of HPC, GTC, BFC, GDP, GEF, and GG, while a_0 represents the intercept term. i denotes the number of countries (1-7), t specifies research time (1990-2020), and ε represents the normally distributed error term. Additionally, for robustness checks in Equations (5) and (6) below, this research explores the impacts of given variables on carbon footprint (CF) as additional proxies of environmental degradation:

$$lCF_{i,t} = a_0 + a_1 lHPC_{i,t} + a_2 lGTC_{i,t} + a_3 lBFC_{i,t} + a_4 lGDP_{i,t} + a_5 lGDP^2_{i,t} + \varepsilon_{i,t} \tag{5}$$

$$lCF_{i,t} = a_0 + a_1 lHPC_{i,t} + a_2 lGTC_{i,t} + a_3 lBFC_{i,t} + a_4 lGDP_{i,t} + a_5 lGDP^2_{i,t} + a_6 lGEF_{i,t} + a_7 lGG_{i,t} + \varepsilon_{i,t} \tag{6}$$

The proposed study uses yearly balance panel data for the G7 countries from 1990 to 2020. Canada, Italy, the United Kingdom, France, Japan, the United States, and Germany constitute the G7 nations. Table 1 presents the dataset and the variables under investigation, Figure 1 elaborates on the ecological and carbon footprints, and Table 2 displays the descriptive statistics for the data series.

Table 1. Description of Variables

Variable names	Symbol	Measurement unit
Ecological footprint	ECF	Global hector per person
Carbon footprint	CF	Global hector per person
Hydro-power consumption	HPC	Exajoules
Geothermal energy consumption	GTC	Exajoules
Bio-fuels energy consumption	BFC	Petajoules
Green Governance	GG	Environmentally related tax revenue (% of GDP)
Green Energy Finance	GEF	Investment in grants, debts,equity, and bonds (2019 US$ million)
Economic growth	GDP	GDP (constant 2015 US$)

Table 2. Descriptive Statistics

	IECF	IGDP	IGTC	IHPC	IBFC	ICF	IGG	IGEF
Mean	1.8358	28.8080	-1.7678	-0.4609	3.7480	1.4031	0.5576	3.0040
Median	1.7290	28.5774	-2.0869	-0.5459	4.0548	1.3072	0.7841	3.6621
Maximum	2.3363	30.6230	-0.0720	1.3465	7.3113	2.0285	1.2800	8.1280
Minimum	1.4301	27.5900	-4.0201	-3.3902	-2.7315	0.9166	-0.3227	-4.6051
Std. Dev.	0.2830	0.8311	1.1358	1.4357	1.8985	0.3452	0.4598	3.1582
Skewness	0.3665	1.0516	-0.0668	-0.2270	-0.6386	0.3686	-0.5463	-0.6847
Kurtosis	1.7193	2.8374	1.9220	1.9601	4.0350	1.7989	1.9292	2.4971

ECF indicates ecological footprint, CF is carbon footprint, GDP is economic growth, BFC indicates bio-fuel consumption, GTC is geothermal energy, HPC is hydro-power consumption, GEF is green energy finance, and GG is environment-related tax revenues proxy for green governance.

Econometric strategy

The hydro-power consumption, geothermal energy and bio-fuel consumption in our sample countries are consistent. The common economic and industrial traits of these countries may lead to cross-sectional dependency. Therefore, it is more important to look at the possibility of cross-sectional dependence when using panel data sets. Four tests have been regularly used to verify cross-sectional dependency: the Pesaran CD test [49], Breusch and Pagan LM test [50], Pesaran LM test [49], and Baltagi *et al.* test [51].

To evaluate the cross-sectional dependence, the model below was introduced by [50]:

$$\mathrm{CD_{BP}} = \sum_{i=1}^{N=1} \sum_{j=i+1}^{N} \hat{P}_{ij}^{2} \tag{7}$$

Where cross-sectional dependency is signified by $\mathrm{CD_{BP}}$, $\hat{P}_{ij}^{2}$ denotes pairwise cross-sectional residuals , N represnets panel's cross-sectional dimensions, and t is the time.

$$\mathrm{CD_{LM}} = \sqrt{\frac{1}{N(N-1)}} \sum_{i=1}^{N=1} \sum_{j=i+1}^{N} \left(\hat{P}_{ij}^{2} - 1\right) \tag{8}$$

Baltagi *et al.* recommend the following LM test statistics [51]:

$$\mathrm{CD_{BC}} = \sqrt{\frac{1}{N(N-1)}} \sum_{i=1}^{N=1} \sum_{j=i+1}^{N} \left(\hat{P}_{ij}^{2} - 1\right) - \frac{N}{2(T-1)} \tag{9}$$

Where pairwise cross-sectional correlation coefficient of the residual is $\hat{P}_{ij}^2$, Baltagi *et al.* cross-sectional dependency is denoted by CD_{BC}, N denotes the panel's cross-sectional measurements, and T time is the period[51].

This study used first- and second-generation panel unit root tests, as Breitung[52], Levin[53], Im[54], to assess if the variables were stationary.

Breitung[52] contemplates the given equation:

$$Z_{it} = \sum_{k=1}^{p+1} \tilde{A}_{ik} X_{it-k} + \omega_{it} \tag{10}$$

Breitung[52] used altered vectors. $Yi^* = Ayi = [Yit^* \ldots\ldots YiT^*$ and $X1^* = Axi = xiT^*]$ to test the alternative hypothesis as follows:

$$Y_B = \frac{\sum_{i=1}^{N} \delta_1^{-2} Y_i^{*/} X_i^{*/}}{\sqrt{\sum_{i=1}^{N} \delta_1^{-2} A_i^{*/} A^{/} X_i^{*/}}} \tag{11}$$

Im presented null and alternative hypotheses that are comparable to those of the Breitung test[54].

LLC recommend the associated equation:

$$t_p^* = \frac{t_p}{\sigma_T^*} - NT\hat{S}_N \left(\frac{\widehat{\sigma}_{\hat{p}}}{\hat{\sigma}_{\tilde{\varepsilon}}^2}\right)\left(\frac{\mu_T^*}{\sigma_T^*}\right) \tag{12}$$

where $\mu\dot{T}$ and $\sigma\dot{T}$ are mean and standard deviation. $\hat{S}_N$ equal to (1/N).

The cross-sectional augmented Dickey-Fuller (CADF) regression used by Pesaran is as follows[55]:

$$Z_{it} = \beta_i + p_i\overline{y}_{t-1} + \sum_{j=0}^{k} aij\Delta\overline{y}_{it-1} + \sum_{j=0}^{k} \delta ij\Delta\overline{y}_{it-1} + \varepsilon_{it} \tag{13}$$

Where $\overline{y}_{t-1}$ and $\Delta\overline{y}_{it-1}$ are cross-sectional averages and first differences, respectively. Following the CADF statistics, the cross-sectionally augmented (CIPS) statistic is generated.

$$CIPS = \left(\frac{1}{N}\right)\sum_{i=1}^{N} ti(N,T) \tag{14}$$

The following step is to determine whether co-integration between the chosen variables by Pedroni and Kao[56,57]. Pedroni and Kao are two recommended co-integration checks based on residuals. Every single one of these statistics has an asymptotically normal distribution using the residuals obtained from the long-run models:

$$Z_{it} = \beta_i + \partial_i + \sum_{j=1}^{m} y_{ij} X_{ij} + \varepsilon_{it} \tag{15}$$

where it is anticipated that Z and X would integrate on a level of one.

The equation below illustrates the structure of the calculated residuals:

$$\varepsilon_{it} = p_i \varepsilon_{it-1} + \mu_{it} \tag{16}$$

Where panel statistic test is denoted by p_i, adjustment term is denoted by μ_{it}, and ε_{it} is residual.

The panel data cointegration system used by Pedroni is detailed below:

$$Z_{it} = \beta_i + \beta X_{it} + \varepsilon_{it} \tag{17}$$

where it is predicted that Z and X would merge on a level of order one and residual is denoted by ε_{it}.

Following the validation of the co-integration of the variables, this research now uses the FMOLS estimate to analyze the long-term relationship between the selected variables. The FMOLS panel provides a number of benefits. It supports cross-sectional heterogeneity, endogeneity, and serial correlation. It also provides advice for both inside and between dimensions. The following equation is made to get between the dimensions:

$$\hat{Z}_{NT} = \left[N^{-1} \sum_{i=1}^{N} \left\{ \sum_{i=1}^{t} \left(y_{it} - y^{/} \right)^2 \right\}^{-1} \right] \left[\sum_{i=1}^{t} \left(y_{it} - y^{/} \right) \gamma_{it}^{/} - T \gamma_i^{/} \right] \tag{18}$$

where $\hat{Z}_{NT} = N^{-1} \sum_{i=1}^{N} Z_{FMi} \times Z_{FMi}$ is the FMOLS estimator for individual variables. The last step is to check heterogeneous panel causality test[58]. The model below identifies causality in panel data:

$$Z_{it} = \alpha_i + \sum_{j=1}^{J} \tau_{ii}^{J} Z_{i,t-J} + \sum_{j=1}^{J} \beta_{ii}^{J} X_{i,t-J} + \varepsilon_{i,t} \tag{19}$$

Where an auto-regressive parameter is denoted by τ_i^J, $X_{(i,t)}$ and $Z_{(i,t)}$ are the observations of two stationary variables for individual, t and j are the lag length, regression coefficients are denoted by I, and β_i^J that changes across groups. The lag order J is taken to be constant for a balanced panel.

Table 3. Cross-sectional dependence

Tests	Model 1		Model 2		Model 3		Model 4	
	Stats	Prob.	Stats	Prob.	Stats	Prob.	Stats	Prob.
Breusch-pagan LM	127.432	0.0000	106.21	0.0000	135.618	0.0000	126.210	0.0000
Pesaran scaled LM	20.5272	0.0000	16.652	0.0000	22.0218	0.0000	20.3041	0.0000
Pesaran CD	8.6112	0.0018	9.6031	0.0000	9.1742	0.0000	10.5229	0.0000

Table 4. First and second generation unit root test

Vr.	Breitung		LLC	
	Level	1st diff	Level	1st diff
IECF	-0.690	-6.525***	0.414	-3.267***
ICF	0.028	-6.999***	0.314	-4.331***
IGTC	2.704	-2.411***	1.017	-1.583**
IHPC	-2.434***	-9.171***	-3.818***	-1.863***
IBFC	2.325	-2.089***	-0.173	-1.839***
IGG	2.188	-1.648***	1.691	-3.508***
IGDP	6.729	-2.834***	3.762	-5.150***
IGEF	2.135	-1.205*	0.478	-9.72861***
	CIPS		CADF	
IECF	0.394	-6.602***	0.425	-5.986***
ICF	1.257	-5.880***	1.378	-5.545***
IGTC	0.297	-3.115***	0.231	-3.118***
IHPC	-3.744***	-9.0780***	-3.825***	-7.807***
IBFC	1.021	-2.087***	1.082	-2.140***
IGG	2.064	-2.748***	2.189	-2.769***
IGDP	2.158	-3.050***	2.288	-3.014***
IGEF	-0.541	-4.382***	-0.564	-3.875***

The significance level represents ***, **, and * for 1%, 5%, and 10%, respectively.

EMPIRICAL RESULTS AND DISCUSSION

The descriptive statistical analysis is given in Table 2. The mean (median) values of the ecological footprint (ECF), hydro-power consumption (HPC), geothermal energy consumption (GTC), bio-fuel consumption (BFC), economic growth (GDP), green energy finance (GEF), and green governance (GG) are 1.8358 (1.7290), -0.4609 (-0.5459), -1.7678 (-2.0869), 3.7480 (4.0548), 28.8080 (28.5774), 3.0040 (3.6621), and 0.5576 (0.7841), respectively.

Figure 1 represents data on the ecological footprint, carbon footprint, and bio-capacity of the United States, Canada, Italy, United Kingdom, France, Germany, and Japan from 1990 to 2020. Ecological and carbon footprints retrieved from the global footprint network[59]. Data for Hydro-power consumption, geothermal energy consumption, and bio-fuel consumption are retrieved from BP statistical review[60], data for green energy finance are taken from IRENA[61], data for green governance and economic growth are extracted from OECD[62] and WDI[63], respectively.

The model for the variables used in the cross-sectional dependence inquiry, and the Pesaran CD techniques used to model the residual cross-sectional investigation are shown in Table 3. The significance of the results from all tests provides strong evidence against the null hypothesis (H_0) of cross-sectional independence for all model residuals.

The outcomes of the Breitung, LLC, CIPS, and CADF panel unit root testing are compiled in Table 4. These findings suggest that level series cannot rule out the unit root null hypothesis (H_0). However, after the first difference is taken into account, all variables exhibit stationarity at the 1. The anticipated results allow us to proceed with co-integration analysis because it is believed that all of the study variables adhere to the I(1) process integrated with order one.

Table 5. Co-integration test

Pedroni cointegration test				
	Stat.	**Prob.**		
Panel v-statistics	-1.7393	0.9590		
Panel rho-statistics	0.1909	0.5757		
Panel pp-statistics	-8.9183	0.0000		
Panel ADF-statistics	-3.5552	0.0002		
Group rho-statistics	1.6258	0.9480		
Group PP-statistics	-8.7529	0.0000		
Group ADF-statistics	-2.7376	0.0031		
Kao cointegration test				
ADF	-5.7158	0.0000		
Johansen fisher panel cointegration test				
Hypothesized no. of CE(s)	Fisher stat (from trace test)	Prob.	Fisher stat (from max-eigen test)	Prob.
None	187.5	0.0000	167.7	0.0000
At most 1	204.9	0.0000	108.8	0.0000
At most 2	126.0	0.0000	75.29	0.0000
At most 3	94.19	0.0000	62.87	0.0000
At most 4	67.75	0.0000	44.82	0.0000
At most 5	35.55	0.0001	24.40	0.0066
At most 6	32.95	0.0000	32.95	0.0003

Table 6. Estimates using FMOLS

ECF dependent variable					**CF dependent variable**			
	Model 1		**Model 2**		**Model 3**		**Model 4**	
Vr.	**Coef.**	**Std. Er**	**Coeff.**	**Std. Er**	**Coeff.**	**Std. Er**	**Coeff.**	**Std. Er**
IGDP	0.09664***	0.0255	0.0865***	0.0024	0.1779***	0.0510	0.0796***	0.0033
IGDP2	-0.0960***	0.0229	-0.1478***	0.02531	-0.0898***	0.0293	-0.1502***	0.0302
IBFC	0.01458***	0.00514	0.0406***	0.0179	0.01861	0.0288	0.0837***	0.0246
IGTC	-0.0646***	0.00787	-0.0696***	0.0115	-0.1130***	0.0082	-0.091872	0.0158
IHPC	-0.1154***	0.02635	-0.06208***	0.0006	-0.1770***	0.0274	-0.47153***	0.0351
IGG	-	-	-0.4764***	0.0548	-	-	-0.6435***	0.07539
IGEF	-	-	-0.3586**	0.1912	-	-	-0.3669**	0.1439
Estimates using DOLS								
IGDP	0.0440***	0.0041	0.0796***	0.0037	0.2231*	0.3530	0.0708***	0.0033
IGDP2	-0.2000***	0.0602	-0.2220**	0.0846	-0.2739***	0.0730	-0.2530***	0.1091
IBFC	0.04151***	0.0092	-0.0324**	0.0161	0.01861	0.0288	.0155*	0.0438
IGTC	-0.4314***	0.1118	-0.0324**	0.0161	-0.10589***	0.0434	-0.4333**	0.0218
IHPC	-0.3947***	0.0599	-0.0778***	0.0088	-0.15620*	0.2016	-0.0012*	0.0629
IGG	-	-	-0.3402**	0.1653	-	-	-0.7695***	0.2212
IGEF	-	-	-0.1765**	0.0981	-	-	-0.0635	0.0700

The significance level represents ***, **, and * for 1%, 5%, and 10%, respectively. GDP is economic growth, BFC indicates bio-fuel consumption, GTC is geothermal energy, HPC is hydro-power consumption, and GG is environment-related tax revenues proxy for green governance.

This study investigates all potential long-term connections among dependent and independent variables using Pedroni, Kao, and Johansen Fisher panel co-integration tests. The panel co-integration results are displayed in Table 5. In Pedroni test, four out of the seven estimates are significant at 1%, and both the Johansen Fisher Panel Co-integration test and the Kao Co-integration test had significant levels of 1 percent. It is given that the null hypothesis H_0 of no co-integration be rejected in favor of the alternative hypothesis H_1 of co-integration among the variables.

The model's underlying variables are then long-run estimated using the fully modified ordinary least square (FMOLS) and panel dynamic ordinary least square (DOLS) techniques. The FMOLS and DOLS estimates for ECP and CF show that all of the long-run coefficients of the examined variables are statistically significant at a 1% level of significance Table 6.

The outcomes of models 1 and 2 show that the long-run geothermal energy consumption coefficient (GTC) is notably negative, and they forecast that a 1% increase in geothermal energy consumption lowers the ecological footprint by around 0.064% and 0.069%, individually. Additionally, it is anticipated that a 1% increase in the utilization of geothermal energy lowers the carbon footprints of Models 3 and 4 by 0.1% and 0.9%, respectively. Moreover, a 1% upsurge in hydroelectric energy use results in a 0.1% and 0.06% decrease in the ecological footprints of the G7 nations. Likewise, it is anticipated that a 1% increase in hydroelectric energy use results in carbon footprint reductions of 0.1% and 0.4% in Models 3 and 4, respectively. The utilization of hydro-power and geothermal energy is indeed acknowledged as clean energy sources with low carbon footprints that can deliver base-load electricity at a reasonable price. Geothermal energy and hydro-power energy consumption have positive effects on ecological footprint reduction despite providing a large amount of carbon-free energy, supporting their claim that they protect the ecosystem with a limited environmental footprint. Hydro-power and geothermal energy are far more concentrated, have higher power and energy density, and can generate electricity more quickly than other renewable energy sources. Additionally, geothermal and hydroelectric generation of electricity generates little waste that may be collected and processed, decreasing the ecological consequences by safeguarding the finite natural resources needed to generate energy. Therefore, it is essential for the chosen countries to diversify their energy sources to include geothermal and hydro-power in order to reduce emissions and reliance on fossil fuels, simultaneously fostering energy security and achieving sustainability.

Our research shows that, at a level of 1%, the use of biofuels significantly affects ecological footprints, which means that it leads to an increase in ecological footprints. Models 1 and 2's ecological footprints increase by 0.01 percent and 0.04 percent for every 1% increase in biofuel consumption, respectively. Furthermore, a 1% increase in biofuels raises the carbon footprint in models 3 and 4 by 0.01 and 0.08 percent, respectively. These outcomes are the same as [33,43]. Additionally, most of the energy in biofuel comes from food plants; therefore, it produces more CO_2 emissions. This advantage, however, is insufficient to lower air pollution in the G7 nations. Energy plant care can lead to concerns such as soil issues, nutrient loss, poor water quality, and deforestation. Furthermore, using biofuels may exacerbate existing climatic issues.

Additionally, it is noted that green energy finance provides a strong and encouraging indicator for sustainable growth in the G7 nations. All four-panel regression coefficients are -0.35, -0.36, -0.17, and -0.06, significant at 1%. According to this, green energy finance is a solid way to reduce the impact on the environmental footprints and discover a long-term solution. The relationship between green finance and sustainable development strategies has also been the subject of several studies. As an indication, Khan *et al.* have concentrated on the financing of sustainable development and energy, and claim that this has a considerable potential to evolve into a new strategy[64].

Because the long-term effects of green governance (GG) on ecological footprints are negative and statistically significant, green governance enhances environmental quality in the G7 countries. If all other factors remain constant, a 1 increase in green governance results in a 0.47 percent decrease in ecological footprint and a 0.07 percent decrease in carbon footprint. Green governance encourages cleaner manufacturing, successfully addressing environmental challenges and fostering green growth, as demonstrated by the supportive function of green governance in G7 countries. Environmental pressure from high socioeconomic growth, fast industrialization, and increased goods production is also expected to force these economies to investigate alternative energy sources through tax increases and adopt environmental tax revenue. Green governance helps minimize ecological footprints. These findings are supported by Murshed *et al.*[46].

Economic growth's long-run FMOLS coefficient appeared to be positively significant, suggesting that accelerating it has an adverse effect on the environment. For the G7 economies, a 1 rise in economic growth causes 0.9 and 0.8 increases in ecological footprint and carbon footprint, respectively, while all other factors remain constant. This affirmative result suggests that the panel's chosen countries are primarily concerned with boosting their productivity at the expense of environmental quality through massive production and polluting activities.

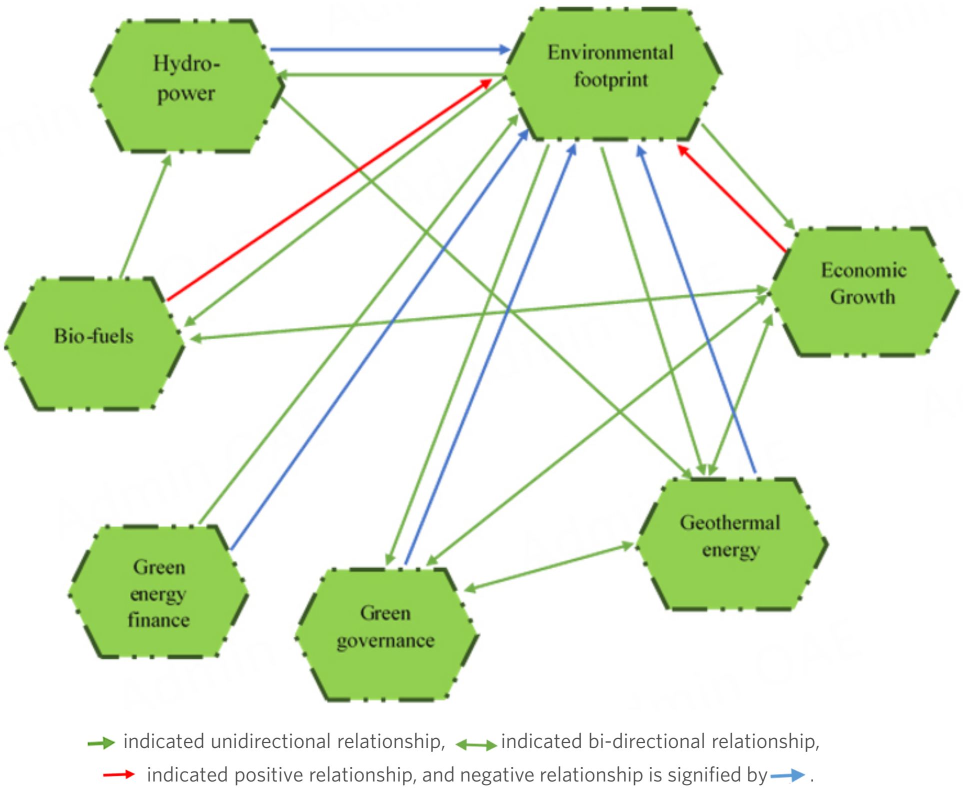

Figure 2. Causal relationship.

It is necessary to explain this pattern by noting that as economic activity increases, so does the demand for limited natural resources to drive manufacturing operations. As a result, rapid economic growth deteriorates ecological resources due to increased production activities and industrialization that have a disastrous environmental impact by converting agricultural land to manufacturing plants, ruining and reducing habitat for wildlife, overusing natural resources, and causing forest destruction. These outcomes are in line with[13,65,66].

The early stage of economic development indicates that in the G7 countries, as income levels increase, there is an amplification of environmental degradation, according to the negative and substantial square of the economic growth coefficient; but, once income levels pass a certain threshold, environmental destruction reduces. As economic levels rise, so does the population's awareness of the environment, which motivates people to advocate for environmental protection and follow laws, policies, and regulations. This legalizes the EKC theory[67,68]. To test the reliability of FMOLS findings, this study also uses DOLS estimation. The results of the FMOLS estimations in Models 1, 2, 3, and 4 are supported by the coefficients of DOLS for all variables, as shown in Table 6. The findings supported the consistency and robustness of FMOLS estimates by showing that all regressors consistently have the same directional relationships with carbon and ecological footprint at different levels of significance.

The outcomes of a pairwise Dumitrescucite[58] causality analysis to determine the causal links among data are shown in Table 7. The findings illustrate two-way Dumitrescu-Hurlin causality between several factors: geothermal energy use and economic development (GTC ⇔ GDP), biofuel energy combustion and economic development (BFC ⇔ GDP), environment-related tax revenue and economic growth (ERT ⇔ GDP), and environment-related tax revenue and geothermal energy consumption (ETR ⇔ GTC). This research also revealed unidirectional causality: ecological footprint and economic development (GDP ⇐ ECF), ecological footprint and geothermal energy consumption (GTC ⇐ ECF), ecological footprint and hydro-power con-

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Table 7. Panel causality test

Null hypothesis	F-stats.	Null hypothesis	F-stats.
GDP ⇐ ECF	0.8361, 5.8128***	GTC ⇔ GDP	2.1634*, 5.52410***
GEF ⇒ ECF	7.2178***, 1.34786	BFC ⇔ GDP	4.0410***, 9.5223***
GTC ⇐ ECF	0.3403, 2.9821**	ERT ⇔ GDP	3.8275***, 2.3559***
HPC ⇐ ECF	0.8555, 2.4632**	HPC ⇒ GTC	7.7935***, 0.2720
ETR ⇐ ECF	0.1590, 2.1106*	ETR ⇔ GTC	3.2958**, 1.8994*
BFC ⇒ HPC	2.2758*, 0.3760	BFC ⇐ ECF	1.1739, 1.8599*

The significance level represents ***, **, and * for 1%, 5%, and 10%, respectively. GDP is economic growth, BFC indicates bio-fuel consumption, GTC is geothermal energy, HPC is hydro-power consumption, and ETR is environment-related tax revenues proxy for governance.

sumption (HPC ⇐ ECF), ecological footprint and biofuels ingesting (BFC ⇐ ECF), ecological footprint and environment-related tax revenue (ETR ⇐ ECF), biofuels consumption and hydro-power consumption (BFC ⇒ HPC), green energy finance and ecological footprints (GEF ⇒ ECF), and hydro-power consumption and geothermal energy consumption (HPC ⇒ GTC) (shown in Figure 2).

CONCLUSION, POLICY IMPLICATIONS, AND FUTURE DIRECTIONS

In our research, the ecological footprint effects of hydro-power and geothermal energy as green energy sources are evaluated. This study utilized yearly panel data for the G7 countries from 1990 to 2020, focusing on ecological footprint and carbon footprint as two distinct measures of environmental degradation; to check EKC theory, we added GDP square to the basic model. To evaluate the series' stationarity, the unit root tests developed by Breitung, LLC, CIPS, and CADF were employed. Additionally, we utilized Pedroni, Kao, and Johansen Fisher testing methodology to test cointegration. To investigate the long-term relationship, we applied FMOLS and DOLS. Furthermore, we used the Dumitrescu and Hurlin causality test to explore the direction of the long-term causal link between the variables. Investment in the form of debts, bonds, stocks, and equity in renewable energies is considered green energy finance. Environment-related tax revenue is also added to the models to investigate the governance impacts on the carbon and ecological footprint. The findings show a long-term link between the controlled variables and environmental footprint measures. The results are in line with an inverted U-shaped relationship between environmental footprint and economic development, which validates the EKC hypothesis. Environmental footprints are reported to be greatly reduced by geothermal and hydroelectric energy, but consumption of biofuels results in an increase in environmental footprint. Furthermore, green energy finance and green governance significantly reduce our environmental footprint. The results of the Dumitrescu and Hurlin causality test indicate that there is a unidirectional causal relationship between ecological footprint and economic growth, geothermal energy consumption, hydro-power consumption, bio-fuels consumption, and environmental-related tax revenue. In conclusion, combating climate change and securing a sustainable future depends critically on how green energy and green energy financing affect carbon and ecological footprint implications. This study aims to investigate the complex interactions between these variables and offer insightful information on methods for lowering carbon emissions and lessening the effects of climate change.

The results of this study hold significant implications for addressing climate change and promoting sustainability worldwide. First, the relevance of the square of GDP coefficient in relation to ecological footprint and carbon footprint in G7 nations validates the EKC hypothesis. Even while economic expansion inevitably exacerbates environmental footprints, the governments of the G7 countries must implement effective ways to reduce their environmental impacts. To uphold the EKC hypothesis, G7 governments must promote economic diversification by investing in green sectors such as sustainable agriculture and renewable energy.

Second, this study can assist in informing policy choices, directing investment strategies, and promoting the shift to a low-carbon economy by highlighting the connections between the adoption of green energy, green energy finance, green governance, and carbon and ecological footprint reduction. In the end, the results may assist society in dealing with the urgent problem of climate change and contribute to the attainment of international climate objectives, such as those outlined in the Paris Agreement.

Third, it seems likely that the G7 countries would benefit from policies that promoted the use of more hydro-power and geothermal energy while also promoting economic growth, given the negative effects of the use of biofuels and the positive correlation between the use of hydro-power and geothermal energy and carbon and ecological footprints. These regulations might include tax incentives for the production of hydro-power and geothermal energy, as well as grants, subsidies, and refunds for the expansion of geothermal and hydro-power infrastructure. Additionally, the use of geothermal and hydroelectric energy is negatively correlated with both environmental footprint measures, supporting their status as environmentally friendly energy sources that can promote ecological growth and reduce the rate of environmental deprivation.

Fourth, the development of hydroelectric dams that can act as reservoirs, retaining and distributing water through droughts and floods, and enhancing an equitable water distribution, can be a better way to manage hydrogeological extremes with severe environmental and carbon footprints, such as floods and droughts. Given the potential for some engineering difficulties, it is necessary to fund studies that concentrate on cutting-edge engineering and global safety norms, particularly for contemporary dam developments.

This study presents unique findings and also provides some future directions. The ecological and carbon footprint consequences of hydro-power, geothermal energy, and biofuels are contentious issues influenced by various institutional, social, and cultural factors. This research evaluated energy finance and how the consumption of hydro-power, geothermal energy, and bio-fuels affected the ecological systems and carbon footprints of a panel of G7 nations. Consequently, there is a call to explore more green energy sources to curtail both carbon and ecological footprints. To furnish more precise insights, this research also offers recommendations for future studies on other growing and developing countries that use hydro-power, geothermal energy, and biofuels. Last but not least, expanding this research to incorporate diverse factors shaping specific case studies, such as urbanization and natural resources, might yield intriguing literature and broaden the understanding in this field.

DECLARATIONS

Authors' contributions

Conceptualization, Methodology, and analysis: Tariq G
Conceptualization, Methodology: Sun H
Validation and investigation: Ali S

Availability of data and materials

Data is available at the following websites: https://data.footprintnetwork.org/#/; https://data.oecd.org/; https://www.bp.com/; https://data.worldbank.org/indicator.

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Conflicts of interest

All authors declared that there are no conflicts of interest.

Ethical approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

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