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Analyzing the contribution of renewable energy and natural resources for sustainability in G-20 countries: How gross capital formation impacts ecological footprints

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ABSTRACT

Sustainability ensures well-being for people and communities worldwide and helps shape the world's present and future. A global transformation is required by adopting renewable energy sources to achieve sustainability. Sustainability trends have been examined using this study for the period 1992–2018 for G20 countries. The study uses indicators like ecological footprints, natural resources, renewable energy (RE), and non-renewable energy (NRE), along with gross domestic product (GDP) and capital formation. A cross-sectional-ARDL approach has been used to examine short- and long-term relationships. The presence of stationarity property, cross-sectional dependence, panel cointegration, and slope heterogeneity have been confirmed during initial testing. The empirical result confirms that using renewable energy impacts environmental sustainability in the long run and causes a decrease in ecological footprints.

On the contrary, non-renewable energy and natural resources contribute to the negative shift in sustainable development. The consistency of results has also been confirmed using robustness checks under the AMG and FMOLS approaches. The study concludes that G20 countries should promote renewable energy to empower the United Nations' agenda for sustainable development.

1. Introduction

Since the 17th century, we have seen several dramatic changes, including the expansion of industry, the spread of globalization to increase communication and trade, and the development of farming techniques that have made it possible to guarantee adequate supplies of food around the world. However, these developments have resulted in a significant disaster for the climate and separated humans from the natural world [1]. The growing ecological disaster has prompted numerous countries to pursue sustainable development goals, including the call for carbon neutrality. Specifically, the UN has established an agenda for Seventeen (SDGs) Sustainable Development Goals to advance various causes, including but not limited to resource conservation, human well-being, environmentally responsible production and consumption, technological advancement, poverty alleviation, and more.

This research is vital because of the pressing need to address the worsening ecological crisis caused by industrial pollution and our

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dependency on traditional energy sources. Therefore, many countries, including those in the G-20, support the need for sustainable development and carbon neutrality as outlined in the SDGs [2]. Sustainable Development Goal 7 (SDG7) calls for universal access to modern, dependable, and environmentally friendly power sources by 2030. This goal can only be achieved by transitioning away from fossil fuels. This research focuses on the Group of Twenty (G-20) countries since they have pledged to completely phase out fossil fuels and convert them to renewable energy sources by 2040. This study on ecological sustainability in the G-20 countries and the impact of energy shift and non-renewable energy is meant to contribute to the existing body of knowledge and provide insights for policymakers, environmentalists, and the scientific community [3]. This study aims to use state-of-the-art panel models to assess the efficacy of energy transitions and patents in reducing ecological repercussions in the G-20 countries [4]. This will include looking at the link between non-renewable energy, natural resources, and the Ecological Footprint (EF). The study aims to inform ideas and strategies that promote environmental sustainability throughout the G-20 nations by reducing their reliance on natural resources.

The research offers several novel concepts. Natural resources, non-renewable energy, and the energy transition are all examined as part of a more comprehensive approach to addressing environmental issues throughout the G-20 nations. This holistic perspective sheds light on the interconnected nature of these factors and their bearing on the EF and the study's use of cutting-edge panel models for analyzing the dynamics between the relevant variables—including slope homogeneity, cross-sectional dependence, stationarity properties, and panel cointegration—adds further depth to this understanding. This methodological strategy enhances the robustness and reliability of the results. Third, the research looks at how the G-20 nations have reduced natural costs like EF thanks to changes in energy policy and technological advancements. This study helps to address a gap in our understanding of the effectiveness of energy transitions and patents in mitigating environmental consequences. The research also analyzes the role of GDP and the Green Finance Framework (GFF) in environmental success to examine the connections between economic development, financial processes, and environmental sustainability. Finally, the research examines the Ecological Footprint, natural resources, and non-renewable energy in the G-20 countries over the long and medium term, providing insights into the dynamics and trajectories of ecological effects. These new pieces supplement existing knowledge by providing a more holistic perspective on the interplay between renewable and non-renewable energy sources, the energy transition, and the Global Twenty's (G-20) impact on the planet's ecological footprint.

G20 has outlined an energy transformation strategy similar to other regional countries, emphasizing energy conservation while transitioning to a flawless energy system. In light of the urgency of the climate crisis, the G-20 countries have set a goal of reaching zero net emissions by 2040, five years earlier than originally planned. It plans to switch to green energy for all its energy needs by that same year.

Moreover, the necessity of the low carbon shift is now a highly discussed issue, with substantial attention from various countries. Eliminating fossil fuels as an energy source is a promising strategy for lowering carbon emissions and protecting the planet. While renewable energy causes can support achieving 92% of the carbon reduction even as the term "global transition of energy" is still in its infancy [5]. Various variables influence the volume and environmental effects of energy production and consumption.

Moreover, a high deficiency of natural resources is a major contributor to ecological stress brought on by the demands of developing our energy, water, and infrastructure systems [6]. The literature has considered the wide-ranging economic implications of the term "natural resources" (NRs) and their depletion. To this end, the Ecological Footprint (EF) has proven to be one of the most accurate measures of the environmental stress caused by humans' continuous use of natural resource regions (NRs) [7]. defend the original idea of EF, which centers on estimating the size of the bio-productive area needed to support a given population. Regarding the demand side, EF calculates how many ecological assets are required to produce the environmental resources. There are several reasons why focusing on G-20 as an area of focus for EF research on ecological viability is crucial.

For example, it has been asserted that the combined EF of the G-20 is significantly higher than the regional biocapacity. It demonstrates the ecosystem's ability to act as a sink for carbon emissions while producing useful biological material. Moreover, it is reasonable to assume that countries in the G-20, chosen as a group to investigate EF developments, have implemented some of the most stringent environmental standards and shared environmental policies [3].

Although technological advancements have made great strides toward environmental stewardship, a few knowledge voids have emerged. Although renewable energy is often used as a stand-in for technological advancement, not all are necessarily tied to cutting energy use and thus may not have a major effect on greenhouse gas production. In addition, there is no formal information linked to renewable energy related to non-renewable energy (NRE). In contrast to unlimited natural resources (NR, gross fixed capital formation (GFF) and GDP are more strongly associated with environmental achievement [8,9].

Second, NRE can have varying effects on environmental stability. Therefore, the three primary origins of renewable energy (RE) are scholarly research in businesses and universities [8].

Extraction of NRs is encouraged as economic growth and urbanization strengthen one another. Deforestation, mining, urbanization, and cultivation use NRs, which is bad news for the ecosystem in the long run [4,10] presents a historical perspective on the connection between NR and EF, and NRE argues that GDP reduces biocapacity and leaves a greater environmental impact. While extracting and using NRs can cause environmental damage, this impact can be lessened through the use of sustainable management techniques. As a result, there is a connection between air, land, and water contamination. As an alternative to this study looks at the evolution of EF within the framework of G-20 countries over the previous few decades, with patterns being decided by both measures. As a result of the above debate and the crucial holes in the literature, this study adds to the extant literature from multiple viewpoints, which benefits the general audience, environmental advocates, and the research community. The primary input of this research is researching environmental sustainability practices across G-20 countries with EF as the main dependent variable.

The EF, for example, factors in the secondary effects of human creation and consumption on the environment. Meanwhile, it's a full-fledged measure of global demand and resource allocation [7]. However, EF catches various biological data as the best indicator, making it one of the most powerful observations. As a result, results for environmental contamination metrics that don't include the EF may be deceptive, which could have dire consequences for policy [3]. In addition to the role of natural resources and non-renewable energy, our research has included the role of energy shift and non-renewable energy and GDP as key explanatory factors. Previous writing has noticed patterns regarding environmental viability for G-20 countries, but this study fills the void on a firm footing by focusing on EF and the energy shift. Considering this gap, this study is a welcome addition to the extant body of work.

Thirdly, various advanced panel models, including slope homogeneity, cross-sectional dependence, stationarity characteristics, and panel cointegration, have been applied to examine the correlation between the variables of interest. The results show that the EF load in the G-20 can be decreased through energy shifts and patents, reducing natural harm. EF has been trending up in the long and near term, as NR and NRE show. The proposed study queries and goals are grounded in the above justifications. Is it possible to reduce or manage G-20 countries' ecological impacts using cutting-edge panel estimates, and if so, are the energy shift and patents helpful? To what extent, as measured by cutting-edge panel projections, do NRE and natural resources drive EF in G-20 economies? Following are some of the goals of this study: To reduce natural costs like EF across the G20, we will use state-of-the-art statistical techniques to analyze the role and process of the energy transition and inventions. Therefore, this work aims to answer the following questions: How do renewable and nonenergy impact EF? Are natural resources helpful in reducing ecological footprints?

Ecological catastrophes, climate change, and sustainable development are complicated issues that need the collaborative efforts of many parties. National governments must enact laws and regulations that promote sustainability, carbon neutrality, and the transition to renewable energy sources. Setting lofty targets, drafting and enforcing environmental rules, and providing incentives for eco-friendly conduct are all essential. The United Nations, the World Bank, and the International Monetary Fund are all responsible for advising and assisting member nations globally in achieving sustainable development. They may facilitate collaboration, provide financial support, and promote sharing best practices and worldwide expertise. Sustainable behaviors, reduced carbon footprints, and investment in green technology are all major contributions from the commercial sector. Adopting CSR and integrating environmental concerns into company operations may have a positive impact. Civil society organizations like NGOs and environmental groups are vital for public backing, lobbying for policy change, and raising public awareness. They might participate in studies, classes, and local initiatives that promote sustainable practices and hold governments and businesses accountable. We can only find effective and comprehensive answers to the ecological challenge through collaboration and communication between these groups, paving the road for a robust and sustainable future.

The upcoming text is organized as follows: The methodology for the research and a summary of this research are presented in Part 2 and Part 3, respectively. At the same time, Part 4 of the article debates the assumptions and discussion surrounding the study, while Part 5 focuses on the study's conclusion, policy ramifications, and plans.

2. Literature review

2.1. RE and sustainability

The term "renewable energy" referring the shift from relying on traditional sources like fossil fuels to a scheme that uses renewable energy sources. This change is important because it reduces dependence on traditional energy sources and is crucial for promoting climate pliability and continuing luxury [11,12] report about the importance of affordable RE as a catalyst for the worldwide shift towards sustainability. The author's statement suggests that the energy system's efficiency has improved due to the adoption of electrification and DE fossilization, which aligns with the goals of restricting global warming to 1.5° [13]. explores the role of regional trade integration in promoting the shift towards sustainable energy in South Asia. The study gathered information from 1992 to 2018, and initial tests were conducted to manage the variability in slope and cross-sectional dependence (CSD). The practical results support the notion that local inter-trade between South Asian nations can increase the production of enviro-friendly energy, thereby promoting a sustainable environmental resolution [14]. studied OECD countries to understand the effects of renewable energy, ecological inventions, and environmental policies on the ecological footprint (EF). Their results indicate that eco-innovation and renewable energy can promote ecological sustainability and decrease EF [15]. [16] Examined the relationship between energy equilibrium, hygienic energy transition, economic expansion, and eco-friendly sustainability, known as the trilemma association. GLS and mixed-effect models based on generalized least squares indicate that a shift towards clean energy can aid in mitigating the degradation of the natural environment. A rise of 1% in using clean energy could decrease the environmental impact by 0.027%. According to Ref. [17], governments and policymakers have become increasingly interested in renewable energy, technology, and low carbon emissions due to the SDGs agenda and COP26 summit. The study uses the GMM-PVAR model to examine the connections between renewable energy, GDP, carbon emissions, and information technologies (ICTs), emphasizing the BRICS sample [18].

The European Union's (EU) renewable energy sources are praised as a policy intervention and green resilience is researched as a strategy for overcoming the multifaceted crisis. The results confirm various difficulties associated with the clean energy transition, such as competition, security, safety, susceptibility, and climate change. In conclusion, promoting climate resilience and sustainable development requires switching to renewable energy sources. Numerous studies have shown that renewable energy sources contribute to environmental sustainability, reduce ecological footprints, and boost economies in various regions and countries. Global agendas like the SDGs and the COP26 conference demonstrate how governments and legislators increasingly acknowledge the significance of renewable energy in addressing global challenges like climate change. However, obstacles to switching to renewable energy must be overcome, such as competitiveness, security, safety, vulnerability, and climate change. Using renewable energy is an encouraging movement toward a more secure and long-lasting future.

H1. Among the G20 nations, renewable energy is closely related to sustainability metrics like ecological footprints.

2.2. NRE and sustainability

Studies examining data from various economies have drawn substantial attention [19]. The study shows that increasing the proportion of NRE sources increases damages like EF using cutting-edge panel analysis methodologies. From 1990 to 2018, Usman and [20] studied the effects of energy use, economic development, farming, and forestry on the BRICT region's EF. They discovered cross-sectional dependence and looked into it using long-run elasticity, cointegration, causality tests, and second-generation panel unit roots. According to the study, using renewable energy decreased the EF by 0.2248%, whereas using NRE sources increased it by 0.5507%. They also saw a good relationship between the EF, forest area, and the utilization of traditional and renewable energy sources [21]. Usman et al.'s study from 2021 aims to investigate the variables affecting economic development and ecological footprint (EF) in the world's top 15 emitting nations. They conclude that the Turkish economy displays an environmental Kuznets curve (EKC) pattern, where economic expansion and non-renewable energy favor EF, using the QARDL technique [22]. study the drivers required to attain sustainable development goals (SDGs) by lowering environmental pollution in EU member countries using the Panel Pool Mean Group Autoregressive Distributive Lag (PMG-ARDL) model. The study demonstrates that although renewable energy sources (RE) increase ecological quality, non-renewable energy sources (NRE) erode it. According to the authors, varying the energy portfolio by including RE technologies would be a sustainable option. They also urge EU nations to commit to doing more to decarbonize their growth trajectory and meet emission targets. Additionally [23], fills a gap in the literature by examining how renewable and non-renewable energy sources affect ASEAN economies' ecological footprint (EF) and carbon dioxide emissions. The findings show that renewable energy resolves environmental filth, while NRE has a large and negative impact on ecological deputations.

The need for studies on how energy use affects environmental contamination in oil-exporting and -importing countries is addressed by Ref. [24]. They used the AMG method, which successfully considers several variables, including slope heterogeneity, cross-sectional dependence, structural discontinuities, and stationarity features. The study found that non-renewable energy (NRE) significantly contributes to ecological degradation in both sample economies. However, because of their heaviest reliance on natural resources, net oil exporting economies are more significantly impacted by NRE. EF, NRE, renewable energy, and unemployment in South Asian economies were the subjects of a different study [25]. The findings revealed a unidirectional causal link between NRE, renewable energy, income, and EF, with increasing NRE leading to worsening ecological sustainability.

Finally, several studies have examined the correlation between economies' use of non-renewable energy sources (NRE) and their environmental footprints (EF). This study used cutting-edge panel analysis methods, repeatedly finding evidence that increasing the percentage of NRE sources is associated with ecological impact and environmental degradation. The results also show how RE improves environmental quality, suggesting that integrating RE technology into the portfolio's energy mix might be a long-term, viable option. A stronger negative effect of NRE on EF is seen in net oil exporting nations due to their heavy dependence on natural resources. These results call for increased efforts to decarbonize growth trajectories, fulfill emission targets to accomplish sustainable development goals, and for more research into the connection between energy usage and environmental pollution across economic systems.

H2. The G20 countries' use of non-renewable energy is closely related to sustainability indicators like ecological footprints.

2.3. NR and sustainability

Natural resource rent (NR) may be effectively extracted and used to promote ecological well-being, and researchers are increasingly looking at how it affects the calculation of ecological footprint (EF). For instance Ref. [26], examined the effects of clean energy, natural resources, and urbanization on the EF factors in the BRICS. They looked into the long-term relationships between these variables from 1992 to 2016 using recent panel data estimation techniques like FMOLS and DOLS. Their data suggest that EF, a factor in ecological quality, is negatively impacted by clean energy and NR. They also verified that the BRICS economies exhibit the Environmental Kuznets Curve (EKC) [27]. examined the effects of the NR on ecological health by researching the US economy over the previous 50 years. They discovered that investing in NR and human capital can lessen environmental damage and EF. According to Ahmed et al., the literature on the connection between NR and EF produced mixed results. The connection between environmental pollution and EF in Latin America, an area with less development and more biodiversity, was examined by Ref. [28].

They looked at the impact of natural resource rent and utilized Per Capita EF as an environmental proxy. The impact of NR and economic complexity on the distribution of EF is diverse and varies across different countries, according to their findings. Furthermore, from 1992 to 2018 [29], focused on the G7 region and examined how NR, human capital, and financial inclusion contribute to tackling sustainability issues like EF. They found that NR and human capital harmed EF in G7 economies using state-of-the-art panel techniques like Cup-FM and Cup-BC. There is a link between lack of access to financial services and environmental deterioration. Thus, today's financial goods and services should prioritize these sustainable goals. Mixed results have been found in studies examining the correlation between a country's EF and its NR from its natural resources. Some scholars argue that NR may be utilized to successfully enhance ecological well-being, while others highlight its negative impacts on EF. Furthermore, the relationship between NR and EF is complicated and context-dependent, as the findings vary among regions and countries. This connection and the need for further study in this area have also been highlighted through cutting-edge panel data estimation techniques. Understanding the connection between NR and EF is crucial for developing effective strategies and policies to slow the rate of environmental deterioration and speed up the pace of ecological sustainability.

H3. Among the G20 nations, natural resources are closely related to sustainability metrics like ecological footprints.

3. Methodology

3.1. Cross-sectional dependence (CSD) test

In conventional panel estimation-based models, it is presumed that cross-sectional units are not interdependent. However, failing to consider the potential existence of cross-sectional dependence (CSD) in panel data estimations may result in inaccurate policy conclusions and misleading findings ([30,31]. Additionally, it's important to note that the calculated coefficients may vary among the different sets of observations. As a result, it makes sense to study the cross-sectional dependence (CSD) when using panel data estimation. The present study investigates CSD, particularly by analyzing it before evaluating the unit root, which can be highly advantageous [14]. Various factors in any cross-sectional data investigation can impact the specified area or group of studied parsimonies [14]. Some factors that can influence cross-sectional data include financial crises, fluctuations in oil prices, regional political climates, inter-regional policies, and so on. While some variations from these factors can be adequately explained, others may remain unexplained. Consequently, paying attention to cross-sectional dependence (CSD) is crucial, as disregarding this issue may result in incorrect pragmatic estimations [32]. As per the presented urgings [31], test was utilized to investigate the data's cross-sectional dependence (CSD). For appropriate policy conclusions and findings, it is essential to consider the potential for cross-sectional dependence (CSD) in panel data calculations. Traditional panel estimation-based methods frequently assume that cross-sectional units are not correlated; however, failing to consider CSD can produce false findings. Cross-sectional statistics can be impacted by various variables, some of which may remain unexplained, including financial crises, oil price changes, regional political environments, and interregional policies. As a result, it is crucial to look into CSD before assessing other metrics, and methods like Pesaran's test can be utilized to do so. Researchers can improve the reliability and validity of their findings and develop more well-informed policy recommendations by accounting for the potential existence of CSD.

3.2. Unit root test

The stationarity or unit root tests of the data were next examined [33,34]. evaluated the stationarity of the data and considered the benefits and drawbacks of stationarity. These tests have different stages. The third-generation test is more sophisticated because it considers structural fractures, slope uniformity, and CSD [14]. With the previous discussion in mind, contemporary research uses [35,36] evaluations to address the issue of non-stationarity and CSD. In panel data analysis, stationarity or unit root tests are crucial because they reveal the stability and long-term behavior of the data. Prominent researchers [33,35] have made significant contributions to this field of research and offered insightful analyses of the advantages and disadvantages of stationarity testing. Unit root tests are divided into first-, second-, and third-generation tests to reflect the development of approaches in this area. The third-generation tests are considered more sophisticated since they consider various characteristics, such as structural fractures, slope uniformity, and cross-sectional dependence (CSD) [14]. Examples of these tests include [35,36] evaluations. Modern panel data analysis research recognizes the significance of addressing non-stationarity and CSD. The evaluations of [31,37] are frequently applied in recent studies to reduce the effects of non-stationarity and consider the likely existence of CSD, which can improve the robustness of the findings and produce more accurate results.

3.3. Slope heterogeneity

The following stage involves employing a test created by Ref. [31], an updated version of the [38] study, to assess the heterogeneity of the slope coefficients. The alternative hypothesis disputes the notion put out for this inquiry that the slope coefficients are homogeneous. To comprehend the variety and variability of the interactions between variables, evaluating the heterogeneity of slope coefficients is crucial [33]. created a test that expands on the [38] study to measure slope heterogeneity. This test is now commonly utilized in research. Slope heterogeneity is assessed after considering the elements of the data's cross-sectional dependence (CSD) and stationarity. This sequential approach offers a solid foundation for generating reliable findings from panel data analysis and permits a thorough study of potential sources of variation in the predicted coefficients. To account for the unpredictable outcomes of standard testing due to CSD [39], suggests using the cointegration test. There are two tildes. The slope heterogeneity in this inquiry's particular interest equations is measured using adjusted statistics, a component of the enhanced [33]. The investigation's alternate hypothesis, supported by this study, asserts that the slope coefficients are homogeneous. This study attempts to provide a thorough knowledge of the relationships between variables in the panel data, considering potential variations and differences across the cross-sectional units by studying the heterogeneity of slope coefficients by considering equations (1) and (2).

$$\widetilde{\Delta} = \sqrt{N}\left(\frac{N^{-1}\overline{S} - k}{\sqrt{2k}}\right) \sim X_k^2 \tag{1}$$

$$\widetilde{\Delta}adj = \sqrt{N}\left(\frac{N^{-1}\overline{S} - k}{v(T,K)}\right) \sim N(0,1) \tag{2}$$

in the equations above, N represents the count units, which are G20 economies, S denotes Swamy's testing, and K signifies the primary descriptive variables of the model. If the P-value is insignificant at a 5% level, then the H0 hypothesis can be accepted, which states homogeneity in the slope coefficients.

3.4. Cross Sectional Auto Regressive Distributed Lag (CS-ARDL) Test

Due to the prevalence of CSD in the data, this research uses the CS-ARDL, which is significantly better than alternative methods because it considers both the interdependence of the under-researched regional units and the heterogeneity of the slope coefficients [14]. The dynamic common correlated effects are used in the CS-ARDL calculations. The ecological footprint, abbreviated as EF in this study, is the major endogenous variable, while the primary independent variables are RE, NRE, and NR. Additionally, as control variables, GFF and GDP were tracked. The letters i and t in equation (3) represent the research's cross-sectional units and period, respectively. The letter f represents the functional relationships between the variables. This study employs the CS-ARDL because of the high incidence of CSD in the data; this method is much superior to alternative ones since it considers both the interdependence of the understudied local units and the heterogeneousness of the slope coefficients [14]. The CS-ARDL calculations employ the dynamic common correlated effects. The main endogenic variable in this study is the ecological footprint, or EF, while the main independent variables are RE, NRE, and NR.

Additionally, GFF and GDP were monitored as control variables. In equation (3), the cross-sectional units and period are denoted by the letters i and t, respectively. The letter f symbolizes the functional relationships between the variables.

$$EF_{,i,t} = f\left(RE_{i,t}, \mathrm{NRE}_{i,t}, NR_{i,t+} GFF_{i,t} + GDP_{i,t}\right) \tag{3}$$

$$EF_{it} = \beta_{1it} + \beta_{2it} RE_{it} + \beta_{3it}\,\mathrm{NRE}_{it} + \beta_{4it} NR_{it} + \beta_{5it} GFF \alpha_i + \beta_{6it} GDP_{it} + \delta_{it} \tag{4}$$

$$W_{i,t} = \sum_{i=0}^{pw} \varphi_{i,t} W_{i,t-1} + \sum_{i=0}^{pz} \gamma_{i,t} Z_{i,t-1} + \varepsilon_{i,t} \tag{5}$$

$$W_{it} = \sum_{i=0}^{pw} \varphi_{i,t} W_{i,t-1} + \sum_{i=0}^{pz} \gamma_{i,t} Z_{i,t-1} + \sum_{i=0}^{px} \alpha_i \overline{X}_{t-1} + \varepsilon_{i,t} \tag{6}$$

The independent and control variables' beta coefficients (1–6) are included in equation (4). The cross-sectional units (chosen G20 economies) and period are denoted by the letters i and t, respectively. Previous studies suggest that EF and RE have a negative correlation, but non-renewable and natural resources have a positive correlation. Additionally, W in equation (5) denotes EF, the main dependent variable. The ARDL model is described in equation (5). Equation (6), which also incorporates the cross-sectional average for each repressor, has been added to equation (5). The cross-sectional averages also reduce the impacts of cross-sectional dependence.

equation (7) below displays the mean values of all variables, whether they are dependent, independent, or control variables.

$$\overline{X}_{t-1} = \left(\overline{W}_{i,t-1}, \overline{Z}_{i,t-1}\right) \tag{7}$$

The major endogenous variable is Wit EF per capita, which is the variable of interest. Additionally, Zi, t1 represents the explanatory and controlling variables such as natural NR, NRE, GFF, and GDP. To solve the problem of CSD brought on by the spillover effect, Xt1 represents the average of research variables. Pw, Pz, and Px stand in for the lag variables. In the CS-ARDL, the long-run coefficient values are estimated using the short-run data. Below is a representation of the long-run coefficients and mean group estimator in equation (8):

$$\widehat{\pi}_{CS-ARDL,i} = \frac{\sum_{I=0}^{pz} \widehat{\gamma}_{Ii}}{1 = \sum_{I=0} \widehat{\varphi}_{I,t}} \tag{8}$$

The coefficients that were estimated for the short run are presented below in equations (9)–(13):

$$\Delta W_{it} = \vartheta_i\left[W_{i,t-1} - \pi_i Z_{i,t-1}\right] - \sum_{i=0}^{pw-1} \varphi_{i,t} \Delta_i W_{i,t-1} + \sum_{i=0}^{pz} \gamma_{i,t} \Delta_i Z_{i,t-1} + \sum_{i=0}^{px} \alpha_i \overline{X}_t + \varepsilon_{i,t} \tag{9}$$

whereas

$$\Delta_{\mathrm{i}} = \mathrm{t} - (\mathrm{t} - 1) \tag{10}$$

$$\widehat{\tau}_i = -\left(1 - \sum_{i=0}^{pw} \widehat{\varphi}_{i,t}\right) \tag{11}$$

$$\widehat{\pi}_i = \frac{\sum_{i=0}^{pz} \widehat{\gamma}_{i,t}}{\widehat{\tau}_i} \tag{12}$$

$$\hat{\overline{\pi}}_{MG} = \frac{1}{N}\sum_{i=1}^{N}\hat{\pi}_i \tag{13}$$

The work conducts a robustness check that considers the problems of CSD, slope heterogeneousness, panel cointegration, and stationarity chattels to assure the dependability of the results. The study employs two techniques to carry out this check: the augmented mean group (AMG) and the common correlated effects mean group (CCEMG), both of which were proposed by Refs. [14,35], respectively. Even when dealing with nonstationary common and undetected common variables, the AMG and CCEMG estimators help produce reliable results. The additional benefit of the CCEMG estimator is that it addresses the identification issue and considers non-homogeneous slope parameters that change over time. The factors utilized in the investigation are described and quantified in Table 2. The energy transition was measured using measures such as clean energy investment, CEM, energy intensity, and carbon intensity using an index based on principal component analysis suggested by Ref. [40]. Here is Table 1, in which all variables are described and their source.

4. Results and discussion section

CSD analysis was used to confirm CSD. This test assures that future tests in this article will be more accurate. CSD analysis is crucial. H0 represented no CSD, but H1 rejected it. Table 2 shows a 1% significance for ecological footprint, renewable energy, non-renewable energy, natural resources, gross fixed capital formation, and GDP. CSD is in the dataset, confirming our H1. The (Swamy 1970) slope coefficient heterogeneity test was performed next. (He et al., 2021; Chien et al., 2022; Suki et al., 2021). H1 rejects the slope coefficient homogeneity null hypothesis. Table 3 demonstrates slope coefficient heterogeneity. Table 3 shows that the p values for delt a and adjusted delta are 0.009 and 0.002, indicating variation in slope coefficient. Development ratio, technology, and ecology changes may explain slope variability in G20 nations' data.

The finding highlights the interconnectedness of the study's variables, suggesting that they cannot be investigated separately. To ensure the validity and trustworthiness of the results, the existence of CSD is considered in the subsequent tests and analyses. This study ensures that the variables' interdependence is considered in the statistical models used and the conclusions produced, providing a more thorough and accurate comprehension of the interconnections and dynamics within the dataset by recognizing and addressing CSD.

The stationarity of data is essential in studying databases. If the mean, variance, and covariance of a time series do not change during the series, then we say that the series is stationary. This quality ensures the reliability and validity of statistical analysis, making it essential. With static data, conventional statistical methods and models may be safely used, allowing for precise relationship interpretation and reliable statistical inference. By creating stationarity in datasets, researchers may effectively study data, draw valuable insights, and make judgments based on appropriate statistical analysis and modeling approaches.

We check data stationarity when CSD is present. A unit root test was used for this. Table 4 shows unit root findings. Two tests—CADF and CIPS—supported the findings. These techniques may detect data stationarity. Results show that the null hypothesis was not rejected. Hence alternative was accepted. We used 1st difference to check data stationarity since the test accepted the null hypothesis before 1st difference. Values show CADF and CIPS findings are significant at 1st difference. Data is stationer at 1st difference. This study's variables confirm stationarity or unit. If CSD is verified, utilize the Westerlund test (Westerlund 2008) to check CSD cointegration under panel cointegration. H0 asserts no CSD cointegration, but H1 says it does. Table 5 shows that Gt's stat value is significant at 1%, proving cointegration in CSD and rejecting H0.

Table 5 shows the short-term and long-term relationships between variables using CS-ARDL. The short-term CS-ARDL findings show that renewable energy has a negative association with ecological footprint with a coefficient value of −0.156 at a p-value of 0.003—significant at a 1% level.

Given the inverse correlation between the ecological footprint and renewable energy, increasing the usage or acceptance of renewable energy sources is associated with decreasing the ecological footprint. In other words, the percentage of renewable energy in the energy mix is inversely related to the environmental effect or footprint. The coefficient value of −0.156 demonstrates the statistical significance of the connection between renewable energy and the ecological footprint. For every 1 unit increase in the usage of renewable energy, the ecological footprint is decreased by 0.156 units, as shown by the negative coefficient in this case. The p-value of 0.003 indicates that the association is statistically significant. The p-value for the correlation between renewable energy and ecological footprint in this study is 0.003, meaning that the link is significant at the 1% level. This provides empirical evidence that the purported inverse relationship between renewable energy and environmental impact is not coincidental. These findings point to the need to

Table 1
Authors compile variables and their sources.

Variables	Short form	Measurement and Definition	Source
Ecological footprints	EF	GHA per capita	GFN
Renewable energy consumption	RE	% of total final energy consumption	WDI
Non-renewable Energy	NRE	Fossil fuel energy consumption (% of total)	WDI
Natural Resource	NR	natural resource rents (% of GDP)	WDI
Gross Fixed Capital Formation	GFF	% of GDP	WDI
Gross domestic product	GDP	Per capita, USD	WDI

Table-2
Results of Cross-sectional dependence analysis.

Variable	Test Statistics (p-values)
EF	67.943*** (0.000)
RE	45.664*** (0.000)
NRE	67.942*** (0.000)
NR	3.202*** (0.002)
GFF	67.880*** (0.000)
GDP	67.856***(0.000)

Note: ***explains the level of significance at 1%.

Table 3
Unit root test results.

		CADF test	CIPS	
Variable	At Level	1st difference	At level	1st difference
$lnEF_t$	−1.97	−3.51***	−2.35	−5.11***
$lnRE_t$	−2.38	−3.77***	−2.62	−4.71***
$lnNRE_t$	−2.29	−3.55***	−2.59	−4.94***
$lnNR_t$	−2.74	−4.17***	−2.78	−5.22***
$lnGFF_t$	−2.42	−3.41***	−2.34	−4.64***
$lnGDP_t$	−2.88	−3.58***	−2.55	−4.43***

Note: ***, ** & * explain the level of significance at 1%, 5% and 10% respectively.

Table 4
Results of the Westerlund test.

Stat	value	Z value	P value
G_t	−4.586***	−8.871	0.000
G_a	−0.206	7.810	1.000
P_t	−1.277	8.831	1.000
P_a	−0.086	5.872	1.000

Note: ***, ** & * explain the level of significance at 1%, 5% and 10% respectively.

Table 5
CS-ARDL outcomes.

Short Run	Coefficient	ST ERROR	PROB
$\Delta lnRE_t$	−0.156***	0.002	0.003
$\Delta lnNRE_t$	0.585***	0.009	0.000
$\Delta lnNR_t$	0.017***	0.012	0.000
$\Delta lnGFF_t$	0.299***	0.001	0.000
$\Delta lnGDP_t$	0.147***	0.003	0.000
Long Run			
$lnRE_t$	−0.063***	0.001	0.000
$lnNRE_t$	0.245***	0.003	0.000
$lnNR_t$	0.021***	0.000	0.000
$lnGFF_t$	0.119***	0.006	0.000
$lnGDP_t$	0.051***	0.002	0.000
ECM	−0.842	0.001	0.000

***, ** & * explain the level of significance at 1%, 5% and 10% respectively.

expand the usage of renewable energy sources in creating a more environmentally friendly and sustainable energy system.

Renewable energy use would reduce G20 nations' ecological load. The study's beginning addressed the move from fossil fuels to renewable energy. Reducing ecological pressures improves environmental sustainability. Thus, renewable energy and environmental footprints are strongly coupled and complimentary. A similar analysis for OECD nations (A. A. Khan et al., 2022) found a negative relationship between renewable energy and ecological footprints. This paper's findings match Ahmed et al., 's 2022 investigation. Both studies recommend switching to renewable energy to safeguard the environment and energy security. Su and Tan 2023) recommend switching from non-renewable to renewable energy for green environmental sustainability. Sustainability requires renewable energy policies for a net zero carbon benchmark (Bashir et al., 2023). However, non-renewable energy, natural resources, gross fixed capital creation, and GDP have a positive short-term relationship with the ecological load. More usage of such resources will raise G20 nations' ecological burden. Thus, NRE, NR, and EF negatively impact environmental sustainability. If all other parameters are unchanged, a 1%

change in NRE and NR brings 0.585% and 0.017% change in EF across G20 countries in the short term. Keeping all other parameters fixed, the 1% change in NRE and NR states a long-term shift of 0.245% and 0.021% in EF across G20 economies.

More frequent usage or reliance on these resources means the G20 nations will incur a higher ecological cost or environmental effect. A positive relationship between these two metrics suggests that growing economic activity, use of non-renewable resources, and investment in physical capital all add to environmental stress. This indicates that the rising usage of these resources threatens the G20 countries' environmental sustainability. The quantitative measures reported in the findings provide insight into the importance of the correlation. Variations of 0.585% and 0.017% in the ecological footprint (EF), for example, are caused by 1% variations in non-renewable energy and natural resources across the G20 nations. This demonstrates that with some tweaks to how these resources are utilized, a big impact may be made on the environment.

The findings also highlight the long-term implications. Without changing anything else, the G20 economies' long-term ecological footprint shifts by 0.245% and 0.021% for every 1% change in their use of non-renewable energy and natural resources, respectively. This exemplifies the persistent link between resource depletion and environmental degradation. These results show that increasing non-renewable energy, natural resources, gross fixed capital production, and GDP harm environmental sustainability in the G20 countries. It stresses the need for sustainable resource management techniques and greener alternatives to reduce environmental stress and ensure a sustainable future.

Table 5 shows long-term ecological footprint relationships with renewable energy and other factors. Table 5 shows that in the long run, ecological footprint and renewable energy have a significant negative relationship, indicating that more renewable energy use in G20 countries would improve sustainability at −0.063 with a p-value of 0.00. Non-renewable energy, natural resources, gross fixed capital creation, and GDP exhibit significant positive relationships, indicating that increasing usage of such resources would increase ecological footprint value. For sustainable development, G20 nations should switch to renewable energy. According to the research, dependency on fossil fuels and natural resources significantly strains the ecological environment and damages sustainability.

There is a long-term, considerably inverse relationship between the use of renewable energy and the ecological footprint in G20 countries. This indicates that an increase in the use of green energy is associated with improved environmental impact. A coefficient value of −0.063 indicates the strength of this connection, which demonstrates that increasing the share of renewable energy reduces environmental impact. The statistical significance of this negative association is shown by the p-value of 0.00, which strongly supports the assertion.

Literature shows varied outcomes. Sharif et al. (2020) panel estimate tested BRICS economies. BRICS validated the environmental Kuznets Curve (EKC), and NR reduces EF. (Zafar et al., 2019). Our research and (Ahmad et al., 2020) agree that NR and economic expansion increase EF. Countries should prioritize environmental sustainability (Jahangir et al., 2022). They recommend efficient natural resource usage. Deforestation, industrialization, mining, and agriculture use NR, which increases EF (Danish et al., 2019). These findings suggest NRE and NR increase EF. Thus, governments worldwide must create sustainable and eco-friendly legislation.

Table 5 shows that GFF increases EF with time. G20 economies' EF changes 0.119% for every 1% change in GFF. Literature suggests that higher GFF values increase economic growth, which increases energy demand and harms the environment. Rahman and Ahmad 2019. A. A. Khan et al. (2022) found that GFF shares vary with the economy. Thus, technical progress and development affect GFF-EF relationships in various economies. GDP and capital creation harm environmental quality in OECD nations (Mujtaba et al., 2022). (Nathaniel et al., 2021). Literature suggests that increasing GFF would increase productivity and growth. Thus, it would pollute and degrade the environment (Acar, Altıntaş, and Haziyev, 2023). Nathaniel et al. (2021) examine G7 GDP-EF relationships from 1980 to 2016. GDP harms the environment like EF. These results show that NRE, NR, GFF, and GDP must be carefully considered and managed for long-term environmental sustainability. Table 5 shows that GDP positively impacts EF at a 1% level across G20 countries. In G20 countries, 1% GDP growth increases EF by 0.051% over time (Mujtaba et al., 2022). Examine GDP-EF relationships in OECD economies. Their analysis found that a 1% GDP growth increases the EF by 0.53%.

These findings highlight the need to properly manage and consider NRE, NR, GFF, and GDP factors to ensure environmental sustainability over the long run. They stress the need for ecologically sound sustainable development practices that mitigate the negative results of economic expansion. If policymakers and stakeholders have a firm grasp of the links between economic development and environmental protection, they will be better equipped to strike a balance between the two.

Table 6 shows FMOLS and AMG robustness checks in the final stage of the study. Tables 6 and 7 show that both estimates agree and support each other. Hence robustness check results match CS-ARDL conclusions. Table 7 indicates that renewable energy reduces ecological load and helps G20 nations achieve environmental sustainability. It indicates G20 nations can manage environmental imbalance through renewable energy and efficient technology.

These findings further demonstrate the importance of renewable energy sources in achieving environmental and sustainable

Table 6
Robustness check.

Variables	AMG	FMOLS
$lnRE_t$	−.066**	0.051**
$lnNRE_t$	.295**	−0.301***
$lnNR_t$	.014**	0.901***
$lnGFF_t$	.144**	0.921**
$lnGDP_t$	.079***	0.410***

***& ** explain the level of significance at 1% & 5% respectively.

Table 7
Granger Causality test.

Null Hypothesis:	Obs	F-Statistic	Prob.
GDP → EF	475	7.397***	0.000
EF →GDP		0.496*	0.609
GFF →EF	475	0.497*	0.608
EF →GFF		1.559*	0.211
NR →EF	475	3.818***	0.022
EF →NR		1.715*	0.181
NRE →EF	475	0.087**	0.916
EF →NRE		4.829***	0.008
RE →EF	475	3.005**	0.0505
EF →RE		0.066*	0.936
GFF →GDP	475	0.623*	0.536
GDP →GFF		2.094*	0.124
NR →GDP	475	0.143*	0.866
GDP →NR		0.998*	0.369
NRE →GDP	47	0.658*	0.517
GDP →NRE		11.788***	0.000
RE →GDP	475	0.583*	0.558
GDP →RE		14.401***	0.000
NR →GFF	475	2.990**	0.050
GFF →NR		1.236	0.291
NRE →GFF	475	0.142*	0.867
GFF →NRE		2.649*	0.071
RE →GFF	475	0.857*	0.424
GFF →RE		0.677*	0.508
NRE →NR	475	1.574*	0.208
NR →NRE		3.250**	0.039
RE →NR	475	0.454*	0.635
NR →RE		8.139***	0.000
RE →NRE	475	3.078**	0.047
NRE →RE		0.077*	0.925

***, ** & * explain the level of significance at 1%, 5% and 10% respectively.

development goals. They highlight the promise of renewable energy to promote environmental harmony and provide a path ahead for the G20 nations to embrace greener, more sustainable development methods. In a time series context, the Granger causality test measures the strength of an assumed relationship between two variables. An important question is to what extent one variable may be used to predict or "cause" another. Table 7 displays the results of a Granger causality analysis.

Table 7 shows that the p-value of 0.007 indicates a statistically significant relationship between GDP and EF. If the p-value is less than the commonly used 0.05 threshold, there is strong evidence against accepting the null hypothesis. Changes in GDP are seen to predict or influence EF shifts, suggesting a Granger causal relationship between the two variables. The f-statistic corresponding p-value is 0.6090. There is inadequate evidence to reject the null hypothesis since the p-value is greater than the typically accepted significance threshold of.05. Changes in ecological footprints were not observed to predict or impact changes in GDP, implying that the conclusion implies that EF does not Granger cause GDP.

Considering the null hypothesis that GFF does not Granger Cause EF, we find that the corresponding p-value for the F-Statistic is 0.6083. There is inadequate evidence to reject the null hypothesis since the p-value is greater than the typically accepted significance threshold of0.05. This finding is consistent with the conclusion that GFF is not a Granger cause of EF. In this case, the F-statistic has a p-value of 0.2114. There is inadequate evidence to reject the null hypothesis since the p-value is greater than the typically accepted significance threshold of0.05. This finding is consistent with the hypothesis that GFF is not a Granger cause of EF.

F-Statistic (3.81876) has a p-value of 0.0226%. There is significant evidence to reject the null hypothesis since the p-value is lower than the typically accepted significance threshold of0.05. Changes in Natural Resources are observed to predict or impact shifts in ecological footprints, indicating that the two are causally related. No statistically significant correlation exists between ecological footprint changes and Natural Resources variations. In other words, EF does not Granger cause NR. Changes in non-renewable energy sources do not predict or affect ecological footprints, according to an examination of the relationship between NRE and EF. Changes in ecological footprints may have a predictive or causative impact on non-renewable energy, but the opposite is true. EF Granger causes NRE.

In terms of the Granger causality between Renewable Energy (RE) and EF, the findings are inconclusive. This suggests no correlation exists between the growth of renewable energy and reductions in ecological footprints. According to the tests, gross domestic product (GDP) and gross fixed capital formation (GFF) are not Granger-caused by one another. As a result, we find little evidence that fluctuations in Gross fixed capital creation and GDP predict or impact one another. Natural Resources (NR) and Gross Domestic Product (GDP) are analyzed similarly, revealing that neither NR nor GDP Granger causes the other. This indicates no predictive or causal link between changes in natural resource availability and GDP. Looking at the correlations between NRE and GDP, we find little evidence that one drives the other. However, GDP Granger does generate NRE. Thus, the link works both ways. This suggests that fluctuations in GDP have a causative or at least predictive effect on using non-renewable energy.

The study between RE and GDP concludes that RE does not cause GDP, but GDP does. Changes in GDP are a predictor of, or at least an impact on, changes in renewable energy. When looking at the correlation between NR and GFF, we find no evidence that either variable is a Granger cause of the other. As a result, shifts in the Global Freedom Index and natural resource availability are independent variables. The Granger causality study between NRE and GFF demonstrates that neither variable is a cause of the other. As a result, no correlation or causation between non-renewable energy shifts and GFC growth was discovered. The study between RE and GFF demonstrates the same thing: neither RE nor GFF Granger causes the other. Therefore, there is no correlation between renewable energy growth and GFC growth.

The findings of this investigation on the link between NRE and NR indicate that NRE does not result in NR. However, NR Granger causes NRE, which suggests that changes in natural resource conditions act as a predictor or causative factor in the emergence of new forms of non-renewable energy. Finally, analyzing the relationship between RE and NR reveals that the latter Granger causes the former. This data demonstrates that shifts in renewable energy are predicted by, or at least influenced by, shifts in natural resources.

5. Conclusions and policy implications

The current study mainly examines the relationship between Ecological footprints (EF) and renewable energy (RE) under the sustainability agenda for G20 countries by considering the data from 1992 to 2018. Under the study, we also explore the relationship of EF with other parameters like NRE, NR, GFF, and GDP. To study such a relation, a series of tests have been conducted to support the evidence. The existence of cross-sectional dependence, heterogeneity of slope coefficient, and stationarity have been tested. It is confirmed from the results that G20 economies are interdependent, and there exist heterogeneity and stationarity of variables. After the confirmation for panel cointegration, the CS-ARDL test was performed to study the relations in the short and long run.

It is evident from the results that renewable energy helps reduce the ecological footprints among G20 economies. On the other hand, the variables like NRE, NR, GDP, and GFF negatively impact the environment and hence are causing a threat to environmental sustainability. Therefore, it is the need of the hour to reshape the utilization of GFF, GDP, NRE, and NR to protect environmental sustainability. The results have also been verified using AMG and FMOLS under robustness check. The empirical findings of this study can be extrapolated to have practical policy consequences, particularly in the setting of the G20 economies. The details are described below:

1. It is advised that the G20 economies, governments, and relevant ministries proactively address the considerable obstacles preventing progress in this field to ease the transition to clean energy. To achieve a low-carbon economy, G20 member nations are also urged to work together to transfer energy-efficient technologies. Another possible strategy is to encourage community knowledge and societal demand for green energy solutions while simultaneously reducing fossil fuel dependency to advance the energy transition.
2. Given that natural resources greatly impact environmental deterioration, it is crucial to look into solutions emphasizing efficient management of these resources through enhanced human capital and technology. This strategy could produce a sustainable outcome. Promoting alternative industries that are in line with sustainable growth and a reduction in dependency on revenue from natural resources could also be a successful tactic.
3. The G20 economies must shift their present growth models towards green and sustainable characteristics as economic growth continues to leave an ecological impact. A further way to safeguard diverse businesses from environmental pollution is to transition them to green energy sources progressively. These industries play a vital role in the production and consumption of a variety of goods and services.

The study's results and conclusions might lead to several actionable proposals to promote environmental sustainability among the G20 nations. First, we need to increase funding for renewable energy like hydroelectric, solar, and wind. Providing financial assistance and legislative incentives to encourage the development of renewable energy infrastructure is one way to achieve this goal. The G20 nations should develop comprehensive energy transition initiatives to help the world wean itself off fossil fuels and onto more sustainable forms of energy production. Goals for renewable energy uptake and the progressive elimination of fossil fuel subsidies are two examples of these strategies. Third, it's crucial to encourage research and development in environmentally friendly technologies and new ideas. To speed up the development and widespread use of environmentally friendly and energy-efficient technology across various sectors, the G20 countries should invest in research and development (R&D) programs. Fourth, promoting environmentally responsible methods of production and consumption is critical. The circular economy, waste minimization, and resource efficiency should all be prioritized in policymaking. Promoting environmentally responsible company practices and raising consumer awareness are two ways to get there. Fifth, we must strengthen global collaboration and coordination to address environmental issues. The G20 nations should work together to solve global environmental problems by sharing information and solutions.

Last but not least, it is essential to establish reliable monitoring and evaluation methods to track progress toward emerging environmental sustainability goals. Reviewing policies regularly and making data on environmental indicators publicly available may help with evidence-based decision-making and highlight areas for growth. BY IMPLEMENTING THESE POLICIES, the G20 nations may help reduce their ecological footprints and contribute to global efforts to combat climate change.

The study's concluding stage discovers several restrictions and potential future directions. For example, because the study only focuses on the G20 economies, regional implications for strategic initiatives relating to the Sustainable Development Goals (SDGs) may need to be properly considered. In addition, the study does not consider how elements like financial inclusion, financial development, green investment, unique renewable energy indicators, and human capital influence the sustainability agenda among G20 economies.

Future studies should address these restrictions to produce new empirical findings and directives for policy. Furthermore, dividing G20 nations into highly and less polluted groups based on ecological footprint (EF) or carbon emissions may allow for cross-sectional comparisons and solid policy suggestions.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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