Sustainable Futures 10 (2025) 101012

Contents lists available at ScienceDirect

Sustainable Futures

journal homepage: www.sciencedirect.com/journal/sustainable-futures

Energy sources and global sustainability connectedness: Evidence from green and dirty energy

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ARTICLE INFO

Keywords:
Sustainable development
Green energy
Dirty energy
Renewable energy

ABSTRACT

The type and efficiency of energy are crucial for achieving global sustainability goals. To empirically explore this relationship and provide valuable insights for various market stakeholders, this study analyzes the connectedness between global sustainability and green and dirty energy sources using Time and Frequency Domain Connectedness Analysis. Global sustainability (GSI), green energy (GEI), and dirty energy (DEI) are represented by the Nasdaq Future Global Sustainability Leaders Index, Nasdaq Clean Edge Green Energy Total Return Index, and Vanguard Energy Exchange-Traded Fund, respectively. The results show that, on average, 35.61 % of the forecast error variance spillovers of GSI can be attributed to green and dirty energy indices. Across all frequencies, GEI has a significantly greater influence than DEI in explaining forecast variance spillovers of GSI, as indicated by both static and pairwise dynamic directional connectedness analyses. These findings suggest that the relationship between global sustainability and green energy remains fragile, driven by short-term market dynamics often influenced by speculation and sentiment. Policymakers should implement stronger, more consistent policies to foster stable, long-term connections led by the green energy market, incentivizing entrepreneurs to invest in this sector and promoting sustainability.

1. Introduction

The United Nations Climate Change Conference (Conference of Parties – COP 27) held in Egypt in November 2022 has placed climate change and green finance at the center of the discussion on transition towards a sustainable economy. The concept refers to the need for economic activities to sustain a healthy, clean, just and equitable world. Sustainability encompasses three dimensions that form the pillars for all policies promoting it: the social, the economic and the environmental dimensions [1]. One of the major implications of pursuing sustainable economic activities is the need for a transition to low-carbon growth through appropriate energy sources, since they are deeply linked with global sustainability.

Frequently, sustainability is seen predominantly from an environmental perspective. However, the complexity of economic development process led to broadening this perspective to encompass several factors that shape global sustainability. These include state of the environment, the state of the economy, the level of social development of a country, the political and institutional setting, technological progress, cultural development, etc. These form the drivers of global sustainability. Interestingly, each of them is a composite dimension. For instance, the state of the economy refers to its ability to grow and fulfill the needs of people without depleting resources or damaging the environment. In turn, this calls for increased production but also more efficient processes, responsible production, higher human capital etc. Social development refers to the need to improve the well-being of individuals and communities with calls for a better access to health and to education along with a more ethical distribution of wealth. This would lead to the eradication of extreme poverty and other forms of deprivation. The concern for the environment calls for the need to internalize the external effects of production decisions. It calls also for the adoption of cleaner technologies, abating pollution and favoring energy efficiency and green investments taking into account, natural media including air and water quality, biodiversity and climate change. Political and institutional settings refer to the actions and policies of governments and other actors in promoting or hindering sustainable development. This is what is

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https://doi.org/10.1016/j.sftr.2025.101012
Received 26 April 2024; Received in revised form 1 April 2025; Accepted 13 July 2025
Available online 14 July 2025

referred to as the “enabling environment” for global sustainability in the development literature. Technological progress refers to the availability and use of technologies that can support sustainable development, such as renewable energy and sustainable transportation, etc. Finally, cultural development designates the values, beliefs and practices of individuals and communities that can promote or hinder sustainable development.

Sustainability has been the central themes debated by international organizations, leaders and practitioners. Reverting to an economy that promotes social justice, equity and the global environment has been always a concern for academics. However, these last years witnessed a gain of interest for this topic for politicians and the public. This shift in focus translates the concern of people for the increasingly perceptible effects of global warming on health, nature, climate and the economy. The call for a transition to a more sustainable economy has been widely echoed by the 2030 Agenda for Sustainable Development adopted by all countries members of the United Nations in 2015. At the heart of the agenda, there are the UN sustainable development Goals (SDGs). They stipulate that poverty eradication and reducing inequality must go in-hand with improving access to health and education for all as well as promote green growth that addresses climate change and other environmental concerns. In terms of countries' green recovery post-COVID-19, large disparities are reported. The relevant feature of the recovery paths is that those countries already engaged in the transition towards a greener economy pre-COVID-19 have been less vulnerable to the pandemic. Moreover, they have been more agile and ambitious in starting their green recovery [2]. This is the case for France, Sweden and Spain, for example. By contrast, Japan, Australia, South Korea and Germany are lagging behind in this race for green recovery.

Achieving global sustainability requires addressing them in a holistic and integrated approach. Nevertheless, ensuring low-carbon growth is the guiding line of all these drivers. At the heart of the low-carbon growth approach is the use of green energy sources that do not harm the environment and do not diminish natural resources. Examples of sustainable energy sources include solar, wind, hydro and geothermal power. They do not generate harmful emissions or pollutants or at least generate drastically less of them compared to fossil fuel sources such as coal, oil and natural gas. A report by the National Renewable Energy Laboratory (US Department of Energy) estimates that CO2 emission for non-renewable energy sources is multiple times more important than for renewable energy. Emission of CO2/kWh is typically <50 g for renewable energy sources over their lifetime, compared to about 1000 g CO2/kWh for coal and 475 g CO2/kWh for natural gas. More specifically, green energy is a concept designating energy types that emanate from natural sources (example, sunlight, wind or water). Although it is often mixed up with renewable energy, the concept of green energy can be slightly different. Actually, it is a broader concept englobing renewable energy sources. This implies that not all energy sources are green. For example, power generation that entails burning organic material even from sustainable sources may be renewable, but it is not necessarily green, due to the CO2 produced during the process. The contribution of green energy to global sustainability is found to be so important that promotion of green energy stands as a goal in its own right among the SDGs of the United Nations (Goal 7).

In terms of investments, the transition to green energy has vehiculated enormous amounts. For instance, the International Environmental Agency (IEA, 2022) estimates the global investment in clean energy technologies and efficiency worldwide in 2021 to reach USD 750 billion. The tendency is set to continue over the next years with the increasing need for more sustainable energy and the falling cost of clean energy technologies. IEA's report (2022) conjecture that through 2030, more than USD 50 billion of public funds could be levied for pilot-projects of large-scale low-carbon energy technologies to sustain the green transition. The IEA's report also indicates that although it is still not very clear how the public energy R&D spending would evolve following the pressure on government budgets post-pandemic, it has been steadily increasing until 2020 and the impact of the stimuli whether financial or economics as part of governments anti-pandemic policies would boost spending R&D spending. The private sector has a leading role in supporting public policies regarding clean energy and energy efficiency.

The primary motivation of this study is to uncover both short- and long-term connectedness between global sustainability and clean/dirty energy sources. To achieve this, we employ frequency-domain connectedness measures, which allow for the identification of connections across specific frequencies of interest, unlike traditional time-domain methodologies. As noted in Baruník and Křehlík [3], short-term cycles in variables correspond to higher frequency bands, while long-term patterns emerge in lower frequencies. This distinction is crucial, as economic agents, investors, and policymakers often adopt strategies tailored to varying time horizons and maturities in their activities and decisions. Consequently, evidence derived from frequency-specific analyses is necessary to address these differing perspectives. Time-domain connectedness measures (e.g., VAR, Q-VAR, TVP-VAR) are limited in that they provide an aggregate measure of connectedness, failing to distinguish between short- and long-term dynamics. In contrast, our study captures both transmitted and received spillovers from clean and dirty energy sources to global sustainability by decomposing the variability of time series into distinct frequency bands. This approach provides nuanced insights into the interconnectedness of these factors across varying time scales.

Within this context, the insights generated can provide valuable guidance for various market stakeholders, particularly policymakers. Achieving SDGs requires a collective effort to adjust carbon emission ratios and adopt renewable and green energy sources, necessitating both short- and long-term planning. According to the latest UN statistics (2024), only 17 % of these goals are on track to be achieved. While the net-zero carbon emissions target by 2050 allows for a 25-year timeline, the objective of achieving a 45 % reduction in carbon emissions grants only a five-year window. These time constraints compel policymakers to revise their strategies and implement more efficient and timely actions. In this regard, empirical evidence on the varying lengths of cycles in the interaction between sustainability and alternative energy sources becomes increasingly relevant in guiding policymakers. By analyzing the connectedness between clean and dirty energy sources and global sustainability developments, this study aims to contribute empirical evidence that distinguishes short- and long-term dynamics. This approach departs from prior studies examining similar questions focusing on time-domain methods without accounting for the temporal characteristics of the relationship. These studies include Du and Xu [4], Ha et al. [5], Rezitis and Ahammad [6], among others. Indeed, these studies use time-domain connectedness methods, including VAR, Q-VAR, and TVP-VAR, to explore the relationship between energy sources (clean/-dirty) and sustainability (often through economic growth or market integration). Nevertheless, they tend to provide aggregate measures of connectedness without distinguishing between short-term dynamics and long-term trends. This distinction is critical for helping policymakers design context-specific and adaptive regulations, particularly during recurring market events like economic turbulence or geopolitical crises, including local and regional conflicts. By distinguishing the characteristics of connectedness across different time horizons, this study enables policymakers to develop tailored, event-oriented measures that are more effective in addressing energy-related hazards and advancing global sustainability efforts.

In the remainder of the study, we provide a comprehensive literature review that highlights prior research on similar questions and identifies the existing research gaps. Section three details the methodology, presenting the mathematical foundation of time-frequency connectedness analysis. Section four introduces the data and presents descriptive statistics to enhance understanding of the variables' characteristics. Section five presents the results of the empirical analysis. In section six, we discuss the relationship between energy sources and the sustainability framework, emphasizing key theoretical elements and our approach to addressing them. Finally, section seven concludes the study, organized into three subsections: empirical findings, policy implications, and limitations of the research.

2. Literature review

Sustainability is a multidimensional concept, particularly in the context of economics, which is grounded in four key pillars [7–10]. The first pillar addresses the relationship between humans and nature, while the second emphasizes the orientation towards long-term goals, acknowledging a certain degree of uncertainty. The third pillar is anchored in the concept of inter-generational justice, encompassing fairness between both humans and nature. Finally, the fourth pillar focuses on economic efficiency, striving to maximize well-being while minimizing harm and reducing the consumption of natural resources. This broad perspective is essential to capture the complexity of sustainability in a comprehensive way, though it also introduces ambiguity in its operationalization [9]. Despite this conceptual complexity, extensive literature has examined sustainability across various domains. In finance, the increasing attention to the relationship between sustainability and financial instruments has gained prominence, especially with the rise of green bonds, which are seen as pivotal in advancing sustainability [11–16]. Moreover, early studies such as those by Inderst et al. [17] and Eyraud et al. [18] have explored green investments, with the former developing methods to measure them and the latter analyzing trends and drivers linked to sustainability practices. Research has further investigated the role of green commodities [19,20] and green equities [21] in promoting sustainable development.

This paper specifically focuses on energy sources. According to the International Energy Agency [22], renewable energy usage globally increased by 3 % in 2020, driven by a nearly 7 % rise in electricity generation from renewable sources, with a 2 % increase in the share of renewables in global electricity generation between 2019 and 2020. In Europe, the share of renewables in gross final energy consumption reached 21.8 % in 2021, a 127 % increase compared to 2004 levels. The interdependencies between renewable energy, particularly green energy, and global sustainability are multifaceted. A higher reliance on green energy reduces dependency on fossil-based energy sources. Studies by Midilli et al. [23] and Bhowmik et al. [24] suggest that green energy, with its clean and inexhaustible nature, eases the pressure on natural resources and fosters sustainability. However, these studies largely rely on theoretical assertions and lack empirical evidence across different contexts. Therefore, while green energy contributes to sustainable economic development and is sustainable in itself due to its environmental neutrality and inexhaustibility, the literature lacks sufficient empirical grounding to substantiate these claims.

Khan et al. [25] explore the relationship between renewable energy consumption, economic growth, and environmental outcomes, finding significant differences in the contributions of green energy and fossil fuels. Their results show that unlike dirty energy sources, green energy plays a vital role in fostering the connection between economic growth and environmental protection. Similarly, Sarkodie et al. [26] demonstrate that green energy-based developments significantly enhance environmental sustainability in OECD countries. Chen et al. [27] confirm that renewable energy consumption positively impacts economic growth in non-OECD countries only after a certain threshold of renewable energy adoption. In developed countries, however, renewable energy consumption does not significantly affect economic growth. Additional studies by Dogan et al. [28], Madaleno et al. [29], and Ozcan et al. [30] emphasize the trade-offs between the economic benefits of renewable energy adoption and the ecological costs, highlighting the triangular relationship between energy consumption, economic growth, and environmental degradation. They argue that a "green economy" is essential for facilitating sustainable development. However, Zhironkin and Cehlár [31] note that transitioning to a green economy requires widespread adoption of green technologies in production and consumption, as well as the development of sustainable industries across all sectors.

Another key focus in energy-related literature is the impact of energy transition, often measured through the carbon footprint of various activities and its implications for sustainability. This relationship is often framed within the theoretical concept of the Environmental Kuznets Curve (EKC), which suggests that economic growth initially leads to environmental degradation but, after a certain threshold, results in improved environmental quality [32]. Some studies, such as Hassan et al., explore the potential for the EKC to operate in reverse, arguing that while economic growth may exacerbate environmental issues initially, sustainable practices and green growth can eventually reverse the negative trend in both developed and developing economies. Additionally, the intensity and shape of the relationship between energy transition and sustainability are influenced by catalyst factors, including financial regulation and policy stringency. Meo & Adebayo [33] and Meo et al. [33] explore how stringent regulatory frameworks can lead to long-term emissions reductions through investments in low-carbon technologies, highlighting the critical role of regulatory environments and energy uncertainties in shaping emissions outcomes.

Empirical studies have extensively examined the factors driving CO2 emissions across different sectors and regions, with a particular focus on the dynamic and asymmetric nature of emissions. In China, sectoral CO2 emissions have been analyzed in-depth, considering the time-varying relationships between economic growth and emissions. Fatima et al. [34] use advanced econometric techniques to study these dynamics, emphasizing the need for emission reduction strategies that account for sectoral differences. Similarly, research by Meo et al. [35] investigates the impact of temperature fluctuations on environmental degradation in Pakistan, finding that rising temperatures exacerbate CO2 emissions. Bridgman et al. [36] also highlight the role of temperature fluctuations in pollutant concentrations in the Czech Republic. Moreover, factors such as rural population growth, energy consumption, and economic growth are identified as key drivers of CO2 emissions across regions. Shaari et al. [37] explore these interrelationships in developing economies, identifying energy consumption as the most significant driver, especially in rural areas with lagging energy efficiency practices. Similarly, Bekhet and Othman [38] examine the effects of urbanization, energy consumption, and economic growth on CO2 emissions in Malaysia, finding that urbanization influences emissions in two distinct stages. Despite these insights, a significant gap exists regarding the effectiveness of green finance and technology adoption in reducing emissions. Afshan et al. [39] argue that green finance and stringent policies are essential for advancing sustainability, although their quantile-ARDL estimation suggests the benefits may differ based on levels of economic development. Some studies, however, contend that the impact of green technologies and finance may not be immediate, particularly in rapidly industrializing countries like China, where the transition to sustainability is hindered by competing priorities. Additionally, while much of the research has focused on the relationship between CO2 emissions and economic growth, there is limited empirical work comparing the drivers of emissions across different regions. This discrepancy is evident in the contrasting findings when comparing developing and developed countries, where the EKC is commonly observed in developed economies, yet its applicability to developing nations remains contested due to ongoing structural changes.

Previous studies often overlook the distinction between short-term market-driven effects and long-term structural impacts, limiting their relevance for policymakers. To address this gap, our study employs a time-frequency connectedness approach, offering a deeper understanding of how green energy influences sustainability across different timescales. While extensive literature exists on sustainability and energy sources, research exploring the direct link between them remains relatively scarce. In conclusion, although the body of work on the relationship between clean and dirty energy sources and sustainability is substantial, it remains fragmented. Frameworks like the EKC offer valuable insights into potential sustainability pathways, yet empirical findings vary considerably depending on regional context, policy frameworks, and economic structures. The contrasting results regarding the roles of green finance and energy use highlight the need for further investigation, especially into the cyclical relationships influenced by both short- and long-term dynamics. Addressing these gaps will provide stronger empirical foundations, enabling policymakers and academics to develop more effective sustainability strategies and emission reduction policies.

3. Methodology: time-frequency domain connectedness analysis

This study employs a Time-Frequency Domain Connectedness Model, as proposed by Chatziantoniou et al. [40] - which is based on Barunik and Krehlik [3]- to investigate the dynamic interactions between clean/dirty energy sources and global sustainability. This model is a significant extension of traditional time-domain connectedness measures, as it captures the interconnectedness of variables across both time and frequency bands (e.g., high-frequency, low-frequency), providing a richer understanding of the interactions. Moreover, it allows for time-varying connectedness, capturing the evolving nature of relationships between variables over time. Among its key features, the model decomposes the total connectedness into components associated with different time-frequency bands, enhancing the interpretation of the results. Overall, the model offers a more granular analysis of short-term and long-term spillovers.

This econometric approach has been effectively applied to study the interplay between sustainability and different markets. Among recent contributions to the topic, we find Rehman et al. [41] for the global energy market, Jiang et al. [42] for geopolitical risks and carbon markets, Su and Zhao [43] for clean energy and technology, Suleman et al. for sustainability markets, Wu et al. [44] for carbon and energy markets and Gao et al. [45] in the context of tourism market in relation to the energy market. Likewise, Jiang and Chen [46] employ the model to provide evidence of heterogeneous frequency horizons across carbon, traditional and new energy, and material markets.

The model starts with a vector autoregressive (VAR) model for the n-dimensional time series $y_t = (y_{1t}, y_{2t}, \ldots, y_{1n})$. The VAR model is given by:

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + \cdots + A_p y_{t-p} + \epsilon_t \tag{1}$$

Where y_t is an $n \times 1$ vector of endogenous variables, $A_1, A_2, \ldots, A_p$ are the autoregressive coefficient matrices, and ϵ_t is an $n \times 1$ vector of error terms.

In order to compute the connectedness measures, we derive the variance decomposition using the VAR model. For that, we define the variance decomposition from variable j to variable i over horizon H:

$$\theta_{ij}^H = \frac{\sum_{h=1}^{H} \left(e_i' \Phi_h \sum e_j\right)^2}{\sum_{h=1}^{H} \left(e_i' \Phi_h \sum \Phi_h' e_j\right)} \tag{2}$$

where Φ_h is the moving average coefficient matrix from the VAR representation. The matrix Σ is the variance-covariance matrix of the error terms; and e_i, e_j are selection vectors. Eq. (2) is the basis for connectedness measures.

Next, we define the directional connectedness measures as follows:

$$C_{i\rightarrow j} = \frac{\theta_{ij}^H}{\sum_{k=1}^{n} \theta_{ik}^H} \tag{3}$$

$$C_{j\rightarrow i} = \frac{\theta_{ji}^H}{\sum_{k=1}^{n} \theta_{ki}^H} \tag{4}$$

$$C_i^{net} = C_{i\rightarrow j} + C_{j\rightarrow i} \tag{5}$$

Eqs. (3) to (5) demonstrate, respectively, the directional connectedness from all other variables to variable i. from variable i to others, and the net directional connectedness **for** variable i. To analyze connectedness across different time horizons, we use the spectral density matrix $S(d)$ at frequency d:

$$S(d) = \lim_{T\rightarrow\infty} \sum_{t=1}^{T} y_t y_t' \, exp(-\, idt) \tag{7}$$

Then, the model decomposes the total variance-covariance matrix of the series into components that correspond to different time-frequency bands d. The connectedness between variables at frequency d is defined as:

$$C_{ij}(d) = \frac{\sum_{k=1}^{n} |Granger - causality\ matrix\ element_{ik}(d)|^2}{\sum_{k=1}^{n}\sum_{m=1}^{n} |Granger - causality\ matrix\ element_{km}(d)|^2} \tag{8}$$

where $C_{ij}(d)$ measures the connectedness between variable i and j at frequency d and the Granger-causality matrix elements represent the directional influence between variables in the frequency domain.

The total connectedness across all frequencies at time t is the sum of the connectedness across different frequency bands d:

$$C_{ij}(t) = \sum_{d=1}^{D} C_{ij}(d, t) \tag{9}$$

where D is the total number of frequency bands. The total connectedness C_{ij} can be decomposed into contributions from different time-frequency bands (d):

$$C_{ij}(d) = C_{ij}(d_{low}) + C_{ij}(d_{medium}) + C_{ij}\left(d_{high}\right) \tag{10}$$

which we denote as:

$$C_{ij}(d) = C_{ij}^{low} + C_{ij}^{medium} + C_{ij}^{high} \tag{11}$$

where C_{ij}^{low}, $C_{ij}^{medium}$and C_{ij}^{high} represent the connectedness from low, medium, and high-frequency components, respectively.

4. Data

To examine the connectedness between green and dirty energy sources and global sustainability performance, we utilize three indices in our empirical analysis: The Nasdaq (n.a., a,b) Future Global Sustainability Leaders Index (GSI), Nasdaq Clean Edge Green Energy Total Return Index (GEI) and Vanguard Energy Exchange-Traded Fund (DEI) which are used to proxy Global Sustainability Index (GEI), Green Energy Index (GEI) and Dirty Energy Index (DEI), respectively. These proxies for global sustainability are widely used in the literature due to their broad coverage and comprehensive nature ([43,47–49], etc.). Their combined use allows for a more nuanced analysis of the complex relationship between sustainability and alternative energy sources. These indices are constructed using equity market data, and as highlighted in the literature, their reliance on stock prices enables them to capture market dynamics and shifts related to energy sector developments [50–52]. Moreover, since these indices are composed of stocks that specifically reflect energy market trends within the broader framework of sustainability—including environmental, social, and governance considerations as well as clean and dirty energy transitions—they serve as reliable barometers of market dynamics in this domain.

The analysis period is from 25.11.2016 to 17.11.2022. The first index, GSI, is introduced by Nasdaq aims to track stock price performance of firms which are considered as climate leaders. The criteria imposed in eligibility of the companies are as follows: having minimum two billion dollars of market capitalization, being recognized by the Responsible Investment Committee as a “climate leader” and passing particular restrictions to eliminate companies which are either directly or considerably exposed to fossil fuel market developments. The index initiated in 2016 and possesses a base value of 1000. The second index, GEI, tracks the price performance of selected clean energy companies. Those businesses have operations mainly in manufacturing and developing clean energy technologies and hold the standards of "Clean Edge". The index was introduced in 2006 and has a first data point of 250. Finally, the last index, DEI, is a product of investment advisor company Vanguard Group, Inc. and displays the performance of shares in the energy sector that mainly operates in oil, natural gas and coal. The index depicts the performance of its constituents since 28.02.2013. Empirical analyses are conducted through E-views and R.

Table 1 populates the results of descriptive statistics. As seen, approximately each return series has an average return of zero. Median values also depict a similar image. According to the standard deviation statistics, GEI and DEI variables display a similar extent of fluctuations. Their variability is almost twice larger than GSI variability. As shown by skewness and kurtosis statistics, each series demonstrates departures from normal distribution. Negative values in skewness test statistic indicate that the frequency of above-mean returns is greater than below-mean returns in each variable. The greater kurtosis statistics than the reference number of three reveals that return series incorporate fat tails, namely, possess high probabilities for less likely expected events. The departures from normal distribution are confirmed by the statistically significant Jarque-Bera test results. Finally, to check the stationarity of the variables we employ ERS test of Stock et al. [53]. Results show that all variables are stationary in their levels as the test statistics suggest rejecting the null hypothesis of possessing unit root.

Fig. 1 demonstrates the price and return series of the variables. As seen, GSI and GEI variables follow similar price developments across the years. We observe a comparable reaction to the global pandemic which emerged in [55]. Both indices illustrate a plunge in this period. However, a quick recovery occurs this plummet. On the other hand, these indices decouple toward the end of 2020 and divergence is maximized in Q3–2021. While GSI reach its historical high, GEI test its support levels of 1000 just before its new rally. When it comes to DEI, its pattern is quite different than the path followed by the other two indices. While the index experiences a sharp decline during the pandemic, subsequent years illustrate mostly a steady climb compared to other variables. We observe these reactions also in return series. The extent of fluctuations in returns is considerably larger during the pandemic period. These variations keep sustaining in following years in GEI variable. Other two variables, GSI and DEI, show relatively smaller uncertainties in returns, except for the case occurred in DEI at the end of 2020.

5. Empirical analysis

Green energy is an essential component in achieving the goals for sustainable development. Since by their nature dirty energy sources have already a finite lifespan and harmful impacts on nature, the climate-resilient energies have become the interest of governments and academia. Thus, policies imposed in the transition from dirty energy to green sources have a great importance for the future of human beings and all stakeholders. To that end, in this study, we seek evidence regarding the current status of return spillovers between energy sources and global sustainability. By providing evidence, we aim to reveal the extent of interactions that may vary across the years and events occurred in global economy and society such as pandemic and financial turbulence.

The preferences of investors might be impactful on their investment horizon and frequencies enable us to consider this notion. To examine the transmission mechanism of spillovers through a virtue of frequency, here we employ time-frequency connectedness methodology of Barunik and Krehlik [3] and Chatziantoniou et al. [40]. Barunik and Krehlik [3] show that lower frequencies incorporate higher sensitivity to shocks; thus, we decompose the components of the system and split the connectedness analysis into three parts. This approach allows us to gauge the financial connectedness at any frequency band of interest. The time-frequency connectedness analysis results are presented in Table 2. The results are estimated through a VAR model that has an optimal lag length of two days, 200 days of window size and 100 days forecast horizon. In analysis, the first model presents the total dynamic connectedness. Frequency bands one, two and three roughly correspond to one to five days, five to thirty days and thirty days to infinity, respectively. In results, we mainly focus on spillovers received by GSI from other two variables.

The results indicate that in the first group, the lowest and highest own-variance share spillovers are observed in GEI (60.75 %) and DEI (72.00 %), respectively. Short-term own variance spillovers appear to dominate these total values. For instance, for the DEI, frequency bands one, two and three possess the following values 59.07 %, 10.89 % and 2.04 %, respectively. Likewise, for the GSI, of 64.39 %, 55.55 % stem from shorter components in frequency bands. Therefore, GEI and DEI account for 35.61 % of the forecast error variance spillovers of GSI. The contribution of GEI (25.2/10.41=2.42 in total spillovers) appears to be as twice as greater than that of DEI in every frequency band. Thus, from averaged dynamic connectedness analysis results we conclude that although green and dirty energy sources impacts are relatively weak, spillovers transmitted to GSI from GEI are considerably greater than that of DEI. This result can be considered as an encouraging and motivating finding for the policy makers to promote green energy initiatives.

Fig. 2 displays dynamic total connectedness in respective frequency bands across the years. As the results indicate, total connectedness reaches its record high in emergence of the pandemic in [55], the COVID-19 crisis slowed down the global economy, resulting in a decrease of global CO_2 emissions by about 5 % [56]. As a result of lockdowns and reduced economic activity, global demand for energy decreased considerably [55]. In spite of this, it must be noted that this reduction of CO_2 emissions was accompanied by enormous economic losses worldwide [57]. It is evident that short-term components become more pronounced than their long-term counterpart over the analysis period. During 2021, the index has a smooth downward trend and declines up to 10 %. Unlike the steep rise due to the COVID-19, in 2022 the total connectedness gains momentum and starts climbing. The Russian-Ukraine war may account for this increase in total connectedness. In the global energy market, Russia is considered the second-largest producer of oil and the largest producer of natural gas. Due to its vital role in global energy markets, Russia's economy plays a major role in global energy markets. As a result, any changes in Russian energy policies, production policies, export policies, as well as geopolitical events can have an impact on energy prices.

In Fig. 3, we present the net pairwise dynamic directional connectedness. In discussing the findings, we use the zero line as a reference point. The values above this line indicate that the first variable in each

Table 1
Descriptive statistics.

	Mean	Median	Std. Dev.	Skewness	Kurtosis	Jarque-Bera	ERS
GSI	0.0006	0.0011	0.0113	−0.5393	15.868	10,833*	−18.0*
GEI	0.0009	0.0013	0.0222	−0.4063	8.5570	2049*	−18.0*
DEI	0.0002	0.0000	0.0212	−0.8650	17.252	13,388*	−16.0*

* denotes significance at the 1 % level. GSI: Global Sustainability Index, GEI: Green Energy Index, DEI: Dirty Energy Index, ERS: Elliott, Rothenberg, and Stock [54] Unit Root Test.

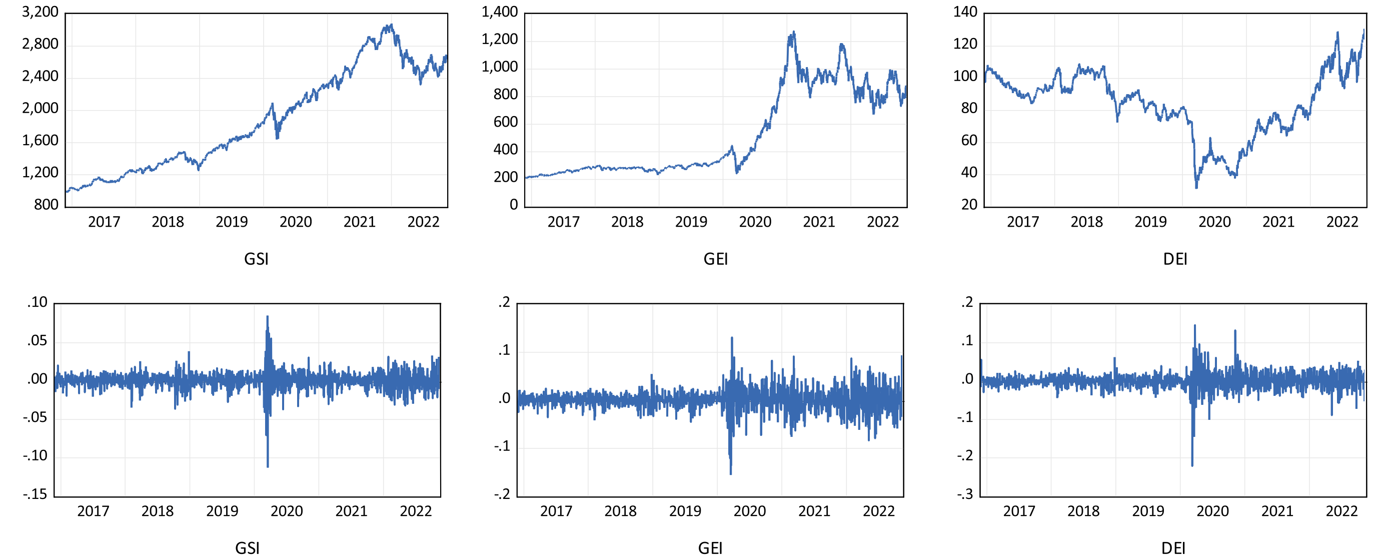

Fig. 1. Price and return series of the variables.

Table 2
Averaged time-frequency connectedness analysis.

		GSI	GEI	DEI	FROM			GSI	GEI	DEI	FROM
Total	GSI	64.39	25.2	10.41	35.61	FB1	GSI	55.55	21.84	9.13	30.97
	GEI	23.34	60.75	15.91	39.25		GEI	19.52	49.9	13.72	33.24
	DEI	10.10	17.90	72.00	28.00		DEI	8.75	14.62	59.07	23.37
	TO	33.44	43.1	26.33	102.9		TO	28.26	36.46	22.85	87.58
	Net	−2.17	3.84	−1.68	51.43		Net	−2.71	3.23	−0.52	43.79
		GSI	GEI	DEI	FROM			GSI	GEI	DEI	FROM
FB 2	GSI	7.46	2.82	1.08	3.9	FB3	GSI	1.37	0.53	0.21	0.74
	GEI	3.22	9.11	1.85	5.07		GEI	0.61	1.73	0.35	0.95
	DEI	1.15	2.77	10.89	3.91		DEI	0.21	0.51	2.04	0.72
	TO	4.36	5.59	2.92	12.88		TO	0.82	1.05	0.55	2.42
	Net	0.46	0.52	−0.99	6.44		Net	0.08	0.09	−0.17	1.21

FB: Frequency Band. The frequency bands d_1 (3.142 ~ 0.628), d_2 (0.628 ~ 0.105) and d_3 (0.105 ~ 0) corresponds to one to five days, five to thirty days and thirty days to infinity, respectively.

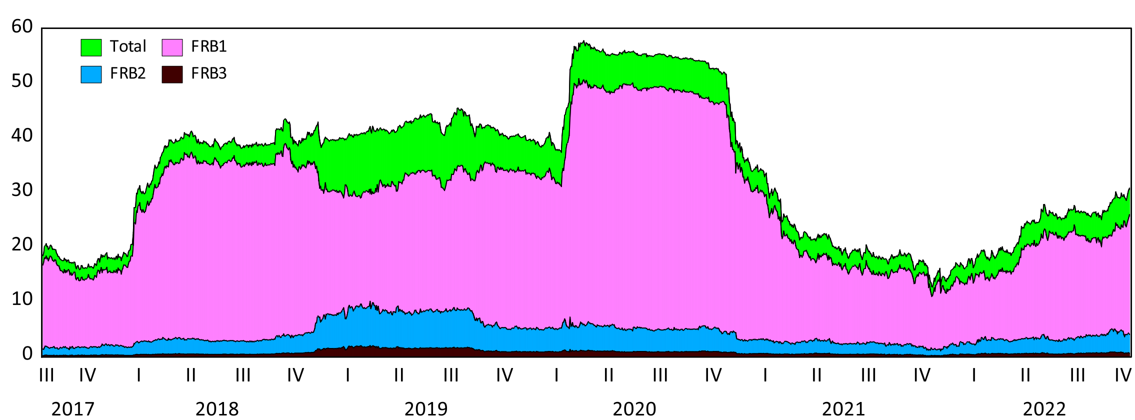

Fig. 2. Dynamic total connectedness.

pair is the transmitter of the return spillovers. Likewise, points below zero line illustrates the variable which is receiver of return spillovers. Accordingly, results depict that GEI is a net transmitter of spillovers to GSI especially in total and frequency band one. Unlike this persistent pattern, we observe varying interactions between GSI and DEI across the years in each frequency band utilized. Q4–2017 – Q3–2018 and [55] – Q1–2021 show pronounced and persistent spillovers from DEI to GSI predominantly in total and frequency band one.

When it comes to the last pair, GEI and DEI, it is evident that GEI illustrates a dominance on DEI. Across the years GEI becomes mostly a net transmitter of returns in all components, except for impersistent and temporal spillovers received from DEI during 2021. Results attained in time-varying domain reveal the stronger and more persistent impact of GEI on GSI than that of DEI. This influence is also can be monitored through the network structure of the averaged spillovers as demonstrated below. The GEI appears to be source of spillovers both in total

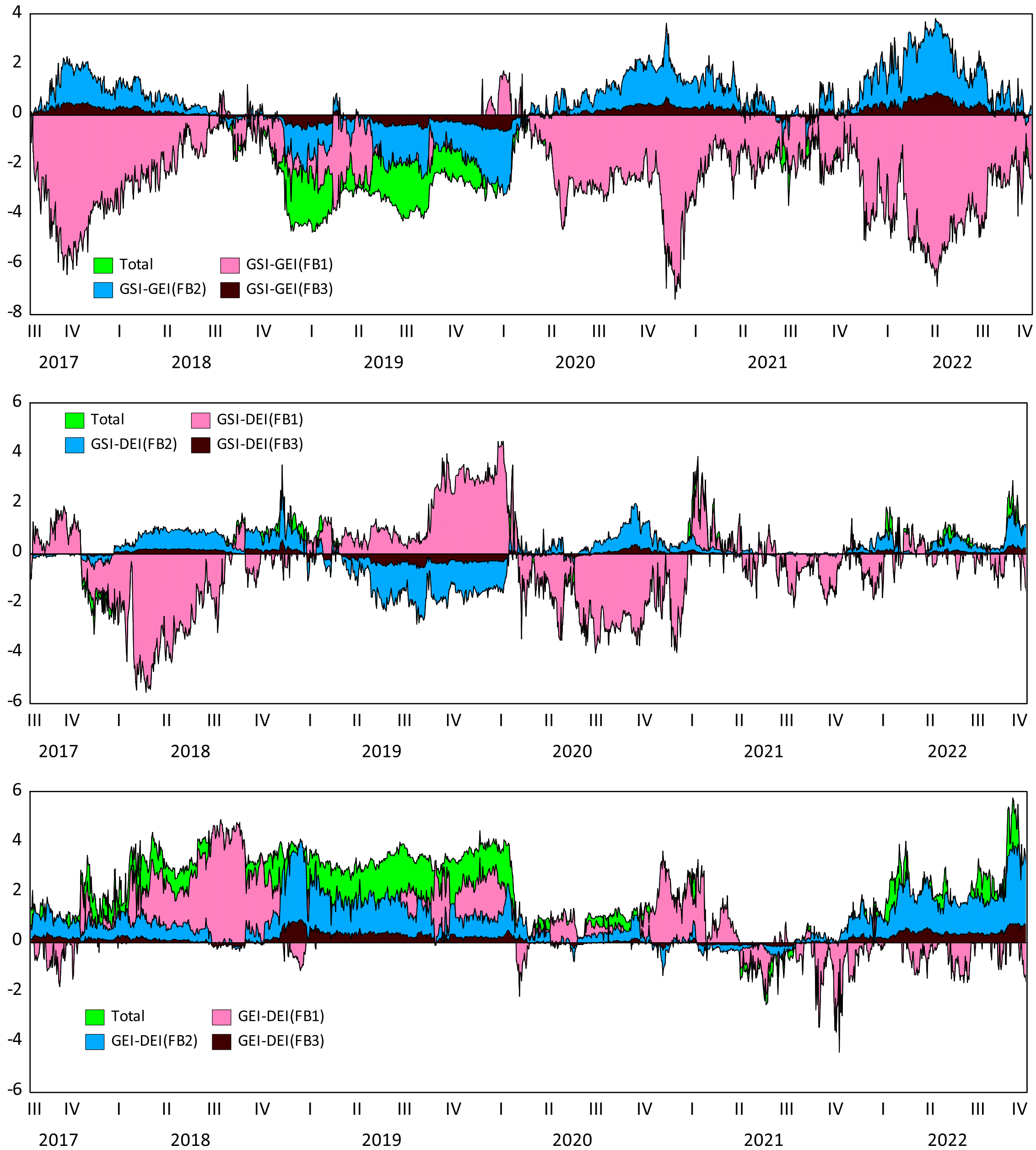

Fig. 3. Net pairwise dynamic directional connectedness.

and short-term component. In both cases it propagates the spillovers to GSI and DEI. Only in frequency bands two and three this finding is partially violated and GSI turns into net transmitter of spillovers to GEI with a low intensity. The dominance of GEI is a promising finding both for policy makers and all stakeholders as it represents the overall developments and performance of green energy sector.

6. Discussion

The extent to which global sustainability is connected to relevant market parameters plays a crucial role in shaping future policies and assessing the effectiveness of those already in place. Within this framework, one of the most critical components is the energy sector. Energy is not only vital for global sustainability, but it also drives international relations and economic development, and has the potential to exacerbate geopolitical risks. As a result, policymakers, investors, academics, and entrepreneurs closely monitor its interactions with other economic and political indicators. For example, Uçan et al. [58], Chen et al. [59], Rezitis, and Ahammad, [6], Dritsaki and Dristaki [60], Apergis and Payne [61] provide compelling evidence of energy's influence on economic growth. Similarly, Qin and Zhang [62], Apergis, N., & Fahmy, H. (2024), Qin et al. [55] highlight the significant connection between energy sources and political tensions and risks at the domestic, regional, and global levels. While economic and political events are of immense importance to countries and societies, the welfare of future generations warrants particular attention. In this context, this study provides valuable evidence regarding both the frequency and time-domain interactions between energy sources and global sustainability. Šević et al. [63] also examined the relationship between sustainability indices and clean energy. However, their approach primarily emphasizes a static, aggregate perspective, potentially overlooking the frequency-specific dynamics that our time-frequency connectedness methodology captures. Our results align with existing literature, offering new insights from a different perspective. For example, the evidence presented by Du and Xu [4], Ha et al. [5], and Rezitis and Ahammad [6] focus on the time domain, while our findings are based on both time and frequency domains. This distinction allows us to provide valuable insights for both short- and long-term horizons, informing investment decisions and policy applications across different time frames. For instance, significant, stable, and long-term interactions between green energy sources and global sustainability would indicate the potential leading and governing role of green energy in driving global sustainability, further encouraging efforts toward this transition, as suggested by the theory (see [24,61,64–66]). Moreover, uncovering the cyclical patterns in both the short and long run allows for more flexible strategy adjustments, as strategic planning objectives can differ across time horizons. For instance, the European Commission has set climate change objectives for 2030 through Horizon Europe, while the EU's long-term goals, as outlined in the Paris Agreement, aim for a climate-neutral continent by 2050. Our study indicates that the policies introduced so far may lack the robustness necessary to achieve these ambitious goals. The connectedness between green energy sources and global sustainability appears volatile, often influenced by daily market developments, speculative information, and noise traders. We present the empirical findings that support this conclusion in the following section. Additionally, we offer meaningful implications for various market stakeholders, urging them to consider these insights in their decision-making processes.

7. Conclusion

7.1. Empirical findings

Green energy, such as solar energy, wind power and hydropower, is one of the drivers of sustainable development, a subset of renewable energy sources and alternative to their conventional or dirty counterparts, namely, coal, gas, and oil. As green energy is mostly naturally replenished, it does not necessitate operations that harm the ecosystem through drilling and mining. Recent international protocols and raised awareness of green energy have dramatically decreased the carbon footprint in many countries and made significant contributions to the progress of global sustainability.

Considering these developments, in this study, we aim to make empirical contributions regarding the role of green energy to global sustainability by comparing its influence with its dirty counterpart. To that end, we employ three indices that represent developments in global sustainability (The Nasdaq Future Global Sustainability Leaders Index, GSI), green energy (Nasdaq Clean Edge Green Energy Total Return Index, GEI) and dirty energy (Vanguard Energy Exchange-Traded Fund, DEI). In empirical analysis we utilized time-frequency connectedness analysis that allows us to examine the spillovers among the variables across time and frequency bands of interest. We executed the analysis for three frequency bands; roughly corresponds to one to five days, five to thirty days and finally thirty days to infinity Fig. 4

The results indicate that the GSI accounts for 64.39 % of its own variance, while the GEI and DEI account for 60.75 % and 72.00 %, respectively. This means that 35.61 % of the forecast error variance spillovers of GSI can be accounted for by green and dirty economy indices. Regarding the selected frequency bands, we see that short-term own-variance spillovers appear to be governing total spillovers. We found that of 64.39 %, 55.55 % stem from the shortest-term component in GSI variable. The role of the green economy index appears to be significantly greater than dirty economy index. The coefficients for GEI and DEI are found as 25.20 % and 10.41 % in the total connectedness, respectively. This ratio does not change in short- and long-term components and under each frequency band the return spillovers from GEI to GSI seem approximately two times greater than that of DEI. When it comes to the pairwise spillovers, in all frequency bands we witness the dominance of GEI on GSI. Over the years GEI becomes the net transmitter of returns to the GSI and short-term component plays an active role in this interaction. On the other hand, DEI shows an inconsistent pattern by generating varying spillovers in their extent and duration. The return spillovers from GEI to GSI occur pronounced and persistent in the periods of Q4–2017 – Q3–2018, [55] – Q1–2021 and Q1-Q4 of 2022.

7.2. Policy implications

Our findings suggest that the connectedness between global sustainability and clean/dirty energy sources is primarily associated with higher frequencies, which correspond to short-term spillovers. The characteristics of high and low frequencies are linked to investor horizons, with short-term horizons relating to high frequencies and long-term horizons to low frequencies. The high-frequency effects indicate that spillovers from green energy sources to global sustainability are

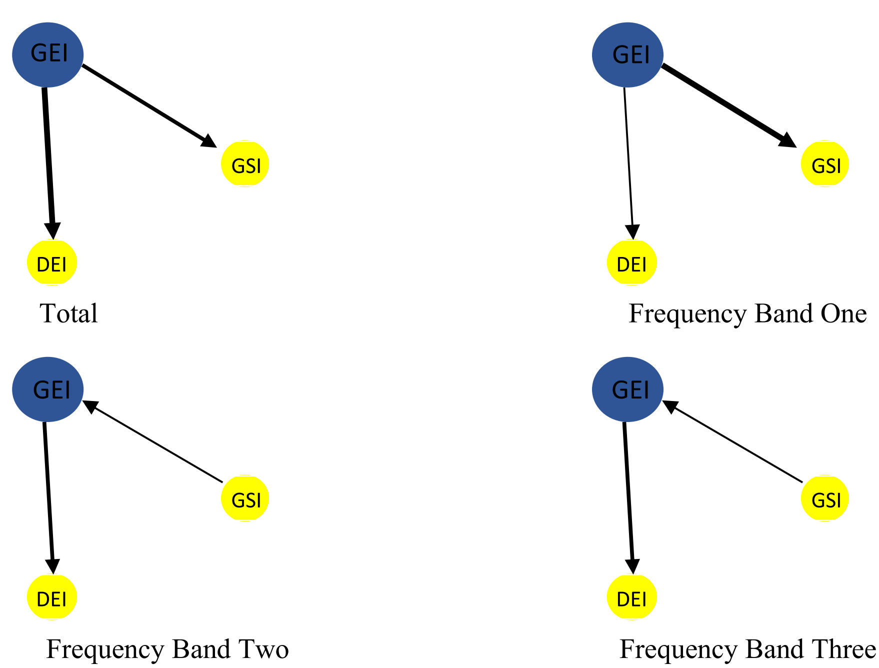

Fig. 4. Network structure of spillovers.

more closely tied to speculative price movements, rather than long-term fundamental economic trends. Although we identify more significant interactions between clean energy sources and global sustainability, their dependence on short-term market fluctuations signals a greater presence of speculative behavior. This finding highlights an unhealthy connectedness between global sustainability and green energy. Despite global efforts to coordinate on climate change and carbon emissions, it appears that policymakers need to implement more robust measures to create a more stable, long-term relationship between these variables, one driven by fundamental economic indicators rather than short-term speculation. Encouraging investments in renewable energy, offering incentives such as tax advantages, and promoting initiatives within this framework could help foster a more stable relationship in the eyes of the public and investors. These measures would likely contribute to a steadier and more established connection between the variables. Considering investor sentiment in financial markets, it is clear that the current progress is insufficient to establish lasting, robust relationships. This cannot be achieved through equity market regulations alone. Therefore, policymakers may need to introduce more ambitious and transformative initiatives to guide and influence investor sentiment in the financial markets.

Our findings in the time-domain further support the arguments presented above. Considering equity markets as barometers of economic developments and investor sentiment, which vary depending on market efficiency, the increased connectedness of variables during periods of market turbulence suggests potential weaknesses in the alignment of goals between green energy utilization and global sustainability. This relationship appears to be highly sensitive to market developments and struggles to maintain a stable, long-term equilibrium. Our results show that both during the COVID-19 pandemic and the Russia-Ukraine war, global sustainability and green energy indices reacted sharply to market events, with spillovers spiking—particularly at higher frequencies—indicating a fragile, market-phase-dependent connectedness. This reinforces concerns about the insufficiency of global coordination and effort. The [67] statistics, showing a success rate of only 17 % in achieving the 2030 SDGs, align with this observation. Furthermore, the U.S. withdrawal from the Paris Climate Agreement in 2025 under the Trump administration may have exacerbated the negative dynamics between green energy and global sustainability. Policymakers should focus on creating more binding agreements and fostering collaborations between states, independent of individual political preferences. Such an approach could help establish more predictable market conditions, which are essential for entrepreneurs in estimating cash flows and budgeting for projects. This, in turn, could drive positive developments in green and renewable energy sources, contributing to global sustainability.

7.3. Limitations

As discussed, this study aims to provide evidence from different time horizons (frequency domains) through spillover analysis. Future research could expand on this by incorporating frequency-domain causality analysis at various lag levels to explore the predictive power of lead-lag relationships between variables. This approach would provide valuable insights for investors in identifying leading variables in price developments across different time horizons. Due to data limitations, our study focuses on global-scale evidence and does not offer findings from a regional perspective. This limitation could be addressed by utilizing regional indices once they become available. Such region-specific findings could help policymakers design tailored measures for sustainability-related developments in different geographic contexts.

List of acronyms

GSI: Global Sustainability Index
GEI: Green Energy Index
DEI: Dirty Energy Index

CRediT authorship contribution statement

Samet Gunay: Conceptualization, Data curation, Formal analysis, Writing – original draft. **Selma Kurtishi-Kastrati:** Conceptualization, Validation, Supervision, Writing – original draft. **Mohamed M. Sraieb:** Methodology, Conceptualization, Validation, Supervision, Writing – original draft. **Gadaf Rexhepi:** Validation, Supervision, Writing – original draft.

Declaration of competing interest

All authors declare that there are no financial and personal relationships with other people or organizations that could inappropriately influence their work.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work didn't had any funding!

Data availability

All data generated or analyzed during this study are included in this article.

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