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A step forward on sustainability: The nexus of environmental responsibility, green technology, clean energy and green finance

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ABSTRACT

The literature lacks enough evidence on the nexus of green finance and clean energy although the terms 'green' and 'clean' have been eminent concepts in sustainable development. Therefore, the fundamental objective of this study is to carry out the causal relationship among green finance, clean energy, environmental responsibility, and green technology by applying the novel time-varying causality test (Shi et al., 2018, 2020) on the daily data spanning from July 31, 2014, to October 12, 2021. The data follow persistent upward and downward movements; thus, the application of a time-varying approach should be reliable and robust. The recursive evolving and rolling window algorithms show bidirectional causalities among green finance, clean energy, environmental responsibility, and green technology, but not for the entire period, and with a special decrease and loss of significance in the COVID-19 period. In addition, clean energy caused by green finance is less evident, except in specific periods, especially at the start of the pandemic. However, higher volatility and significance of causality are observed for the entire period running from clean energy to green finance. Thus, green finance investments are promoted and proportionated by the need for clean energy. This study exhibits the need to design a comprehensive policy for strengthening environmental responsibility and green finance through the funding of green technology to successful energy transition and sustainable development goals.

1. Introduction

The Inter-Governmental Panel on Climate Change (IPCC (Intergovernmental Panel on Climate Change), 2018) reported that the impacts of global warming to be over 1.5 °C above pre-industrial levels and noted the necessity of a global response to stabilize the greenhouse gas emissions and minimize the threat of climate change and poverty and ensure sustainable development. It is obvious that to revert the 1.5 °C increase, low carbon investments are of crucial importance, which requires a major shift of investment patterns towards green technology projects (McCollum et al., 2018). UN notes that (UN (United Nations), 2017) $1.5 trillion of green financing is necessary every year to fulfill the requirements discussed by Paris Agreement. Green financing is even more crucial following the COVID-19 outbreak, which posed significant challenges to finding sources to fund clean energy and green technology (Tu et al., 2021; Zhan and Santos-Paulino, 2021). Building on the finance-growth nexus, creating sources of green finance is the primary necessity to ensure sustainable economic growth. Green finance creates means to enable sources for environmental responsibility, fund green technologies, and initiate the production of renewable energy, which leads to sustainable growth.

Green finance has many definitions and is sometimes referred to as sustainable finance and climate finance. Green finance is the provision of financing to investments that brings in environmental benefits (IFC, International Finance Corporation, 2017). Climate finance, on the other hand, is financing that aims to support actions that are addressing climate change. Overall, all terms here are centered on one focus which points at financing tools to deal with sustainability development. Green finance is vital for financing renewable and clean energy projects to degrade the carbon emissions and their detrimental impacts on human health and environmental sustainability. It makes sustainability reflections a part of financial decision-making. So, it is expected that with green finance these sustainability reflections will improve the environmental and sustainability considerations through the financing of climate neutral, energy, and resource-efficient technologies.

Green financing is necessary to match sustainable development goals

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through the funding of green technology. The financial system allocates the pool of funds to productive projects and current financial markets are expected to allocate the savings to projects with green technology that helps to mitigate environmental degradation. Despite the fast degradation in the environment and the many efforts, it is seen that the pool of funds is still matched with projects that are environmentally harmful and aggravate the current conditions (Sachs et al., 2019). Despite the necessity of green finance in the advancement of green technologies, investments in those technologies still do not attract enough investors. Considering the huge investment needs in green industries, many governments lack the gigantic funding needs, requiring private sector interest in this area. However, private sector investment in green technologies is very limited, since initial investments in green technologies are immensely costly (Eyraud et al., 2011) and the associated risks are enormous, making the rate of return considerably very small (Yoshino and Taghizadeh-Hesary, 2019). Considering the risky nature of green investments, the banking sector is reluctant to provide financing to green technologies establishing a need for other forms of financial resources (Sachs et al., 2019). Zadek and Zhang (2014) also noted the necessity for stronger intervention in the financial system, which is a potential solution to the financing constraints faced by clean energy and green technology projects.

This paper aims to investigate the Granger causality relationship between clean energy, green finance, environmental responsibility, and green technology by adopting the novel time-varying methods proposed by Shi et al. (2018, 2020) for the period between July 31, 2014, to October 12, 2021. There are a few papers in the literature considering the relationship by focusing on only one aspect. Hammoudeh et al. (2020) investigate the green bonds and various other assets including US conventional bonds, WilderHill clean energy (equity) index, and CO_2 emission allowances prices. Their results of the time-varying Granger causality test (Shi et al., 2018) report a significant causality running from WilderHill clean energy index returns to the prices of green bonds. Shahbaz et al. (2021) examine the causal relationship between the energy market, stock market, and green stock returns using quantile-causality approaches. Their results suggest that clean energy markets react asymmetrically to crude oil and stock markets, depending on market regimes and extreme fluctuations in oil and stock market negatively impact clean energy markets. Liu et al. (2021) assess the dynamic dependence and spillover between green bond markets, several global and sectoral clean energy markets. Their results suggest that excessive movements in the clean energy markets spillovers to the green bond market. Nguyen et al. (2021) investigate the interaction between green bonds and several asset classes such as stocks, commodities, clean energy, and conventional bonds. Their results suggest a negative low correlation between green bonds, stocks, and commodities. Pham (2016) focuses on the green bond and equity market dependence by using frequency connectedness and a cross-quantile approach. The results advocate that the dependence between green bond markets and equity markets is comparatively small even after controlling for movements in general stock, fixed-income, and energy markets. The results also convert that they are more connected during times of extreme volatility in the markets.

The paper contributes to the literature in various aspects. This study for the first time in the literature analyzes the relationship between green finance, clean energy, green technology, and environmental responsibility. These variables are assumed to have a significant impact on each other. Environmentally responsible firms produce green technology and invest in renewable energy sources that provide clean energy and the responsible behavior of these firms may create more flows to the green finance industry. Clean energy pools funds from investors and given the inevitable dependency on clean energy; both from the environment and the energy security aspect, increases green financing, provides environmentally desired outcomes with providing limited harm to the environment, and triggers the development of green technologies. Green technologies, which are very appealing to the investors even in terms of profitability recently, despite their costs, impacts environmentally responsible projects and firms through enabling cleaner production processes and creating ways to ensure clean energy. With this paper, we aim to empirically verify the relationships between environmental responsibility, green technology, clean energy, and green finance. Second, this study uses a large daily dataset for seven years, which also coincides with the COVID-19 pandemic that substantially impacted the environment, financial markets, and energy sector. Investment in green technologies, clean energy investments, and environmental and social investments start to tremendously increase with the adoption of sustainable development goals in 2015. Yet, there is a huge gap in the investments with the funding requirements (UNCTAD, 2020a). The pandemic also pushed down the investments in green technologies and clean energy, with a major cut down by one-third in 2020 (UNCTAD, 2020b). Third, this research adopts the novel time-varying methodology proposed by Shi et al. (2018, 2020). This econometric technique relaxes the hypothesis that the causality between the variables under consideration is constant over time. Considering that markets are dynamic, and particularly the series under analysis, constancy is not a viable assumption, and dynamic effects are not captured by commonly applied and traditional causality methods. Furthermore, this novel approach helps to identify the times of emergence and collapse of any causality event.

The paper proceeds as follows. Section 2 briefly explains theoretical background and literature review, Section 3 provides data and methodology, Section 4 presents the empirical results of the analysis and robustness checks, Section 5 discusses the empirical findings, and finally, Section 6 concludes the study.

2. Theoretical background and literature review

Previous literature has intensively discussed the role of finance on economic growth. The finance-growth nexus discusses the bidirectional relationship between economic growth and the financial sector. The earlier strand of research overlooked the impact of finance on economic growth and even exaggerate it by identifying finance as a significant factor as a determinant (Lucas, 1988). However, many other following papers reckon the importance of finance and assert that the finance industry might impact the long-run growth rates through influencing saving rates, investment decisions, and technological innovation (Levine, 2005). The finance sector identifies the best feasible technologies and escalates the technological innovation through the selection of technological projects with high success probabilities (King and Levine, 1993). Moreover, the finance industry pools savings from individuals and enables better savings utilization, thus improving resource allocation and triggering technological innovation. Beck and Levine (2004) proved the positive influence of finance on economic growth considering the impacts of banks and stock markets, suggesting that the finance industry fosters growth irrespective of the bank-based, market-based feature of the country.

The level of financial development however stands as a challenge for developing countries, since lower financial development can inhibit to reap benefits from technology transfers that will enable the countries to boost their growth (Menyah et al., 2014). The literature has discussed the role of finance on the economy in various time horizons and various contexts and it is not wrong to suggest that the literature has agreed upon a long-run impact of finance on growth (Pradhan et al., 2013; Jedidia et al., 2014; Peia and Roszbach, 2015; Samargandi et al., 2015; Pradhan et al., 2013; Nguyen et al., 2019; Afonso and Blanco-Arana, 2022; Ali et al., 2022) despite some contradictory views (Eng and Habibullah, 2011; Mukhopadhyay et al., 2011; Demetriades and Rousseau, 2016; Boikos et al., 2022). Since finance is expected to contribute to economic growth, it is expected that green finance will impact sustainable growth. Considering the previous literature this impact is fulfilled using various channels. Many papers note that achieving sustainable economic growth is possible through the usage of renewable energy (Sohag et al., 2019; Taşkın et al., 2020). Schmalensee (2012) note that the usage of non-renewable energy creates unchecked environmental degradation and curtails natural capital, which precludes sustainability.

Among different channels, green bonds stand as the most favorable source to finance green technologies, since they provide modestly priced long-term capital funds to finance (Natural Resources Defense Council, 2016). Green bonds fund only low-carbon projects that influence climate change mitigation or adaptation, natural resource, and biodiversity conservation and pollution inhibition (ICMA (International Capital Market Association), 2018). Fossil fuels are dominant in energy investments. Thus, shifting the investments from non-renewable energy to clean energies to mitigate carbon emissions is very significant (Mazzucatoa and Semieniukb, 2017). Green bond investments provide various advantages to their investments alongside the intrinsic environmental benefits. The introduction of green bonds is especially appealing to finance clean energy projects. Fixed-income assets are instruments that carry low-risk with stable returns. Those features of the bonds will make green financing appealing both to domestic and institutional investors. The issue of bonds allows funds to be pooled from an investor with a different risk appetite and expands the credit pool (Ng and Tao, 2016). Bonds also provide prospects for diffused ownership of the liability across different types of investors, which enables the indirect investment in clean energy or green technology projects. Lastly, the existence of a secondary market enables liquidity to the investors and provides them with an exit strategy. This feature also attracts those with short-term investment horizons. Given these facts, the promotion of green bonds is a good means to upsurge investments in clean energy and green technology projects (Ng and Tao, 2016).

Despite the attractiveness of green bonds, equity financing is another channel to finance clean energy and green technology investments. Recent years showed that many equity investors are reluctant to invest in sin-stocks that are harmful to the environment and human health or abuses societal well-being ignoring irrespective of the returns they provide. The last decades witnessed the rise of Environmental and Socially Responsible stocks investments that focus on the firms' alignment towards environmental, social, and corporate governance strategies, such as attitudes on climate change and human rights. Sustainable investments all around the globe reached USD 35.3 trillion, suggesting a growth of 15% in two years despite the COVID-19 pandemic (Global Sustainable Investment Alliance (GSRI), 2021). The evidence also suggests that these equities in the Environmental and Social Responsibility Index stand more resilient to downturns in the market such as the global financial crisis (Nofsinger and Varma, 2014; Leite and Cortez, 2015), commodity price shocks (Crifo and Forget, 2012) or COVID-19 pandemic (Broadstock et al., 2020). The financing of clean energy and green technology projects through equity markets provides various advantages. The disclosure requirements in this market provide a safe environment for investors and ensure higher fundraising through this market. Additionally, the dispersion of the ownership to shareholders postulates diverse perspectives from these owners that would enhance the evaluation of the projects.

3. Data and method

3.1. Data

This research study uses S&P Global Clean Energy Index as a proxy for clean energy (CENE), S&P Green Bond Index as a proxy for green finance (GFIN), S&P Environmental and Social Responsibility Index as a proxy for environmental responsibility (ERES), and S&P Renewable Energy & Clean Technology Index as a proxy for green technology (GTEC). The dataset is obtained from the official website of S&P Dow Jones Indices in which variables-related detailed explanations are available (www.spglobal.com). The range of all the daily datasets is from July 31, 2014, to October 12, 2021- yielding 1712 available days- which is the largest possible dataset given that S&P Green Bond Index was launched on July 31, 2014. The descriptive statistics are reported in Table 1. Furthermore, the trends of analyzed variables are presented in Fig. 1 which shows that the data follow upward and downward linear outcomes with volatile actions. Therefore, the application of a time-varying approach should be sense and preferred in this study.

It is noticed from Fig. 1 the upward trend in all the series from 2020 onwards, mostly due to the pandemic period. While environmental responsibility continued rising, clean energy and green technology indexes started decreasing recently. At the highest values, as well, green finance started from 2021 a more volatile period. The sudden drop is clear in both green technology and clean energy indexes.

4. Method

We apply the novel time-varying methods recently proposed by Shi et al. (2018, 2020) to detect changes in the Granger causal relationship between clean energy, green finance, environmental responsibility, and green technology. Shi et al. (2018, 2020) present three time-varying causality tests: forward recursive causality, rolling causality, and recursive evolving causality. Suppose y_t is a k-vector time series, which is deduced with the following model:

$$y_t = \alpha_0 + \alpha_1 t + u_t \tag{1}$$

where u_t follows a *VAR(p)* process

$$u_t = \beta_1 u_{t-1} + \ldots + \beta_p u_{t-p} + \varepsilon_t \tag{2}$$

where ε_t represents the error term. If we substitute u_t using Eq. (2) $u_t = y_t - (\alpha_0 + \alpha_1 t)$ into Eq. (1) we get

$$y_t = \gamma_0 + \alpha\gamma_1 t + \beta_1 y_{t-1} + \ldots + \beta_p y_{t-p} + \varepsilon_t \tag{3}$$

where γ_i represents the function of α_i and β_j in which $i = 0{,}1$ and $j = 1, \ldots,$ p.

The lag augmented VAR of Dolado and Lütkepohl (1996) and Toda and Yamamoto (1995) advocate to undertake causality test for a possible integrated variable, y_t can be denoted as

$$Y = \tau\Gamma' + X\Theta' + B\Phi' + \varepsilon \tag{4}$$

where $Y = (y_1, \ldots, y_T)_{T\times n'}$, $\tau = (\tau_1, \ldots, \tau_T)_{T\times 2'}$, $\tau_t = (1,t)_{2x1'}$, $X = (x_1, \ldots, x_T)_{T\times np'}$, $x_t = (y_{t-1'}, \ldots, y_{t-p'})_{np\times 1'}$, $\Theta = (\beta_1, \ldots, \beta_p)_{n\times np}$, $B = (b_1, \ldots, b_T)_{T\times nd'}$, $b_t = (y_{t-1'}, \ldots, y_{t-p-d'})_{nd\times 1'}$, $\Phi = (\beta_{p+1}, \ldots, \beta_{p+d})_{n\times nd}$ and $\varepsilon = (\varepsilon_1, \ldots, \varepsilon_T)_{T\times n'}$ with d is the maximum order of integration for y_t. The Wald statistics for testing the null hypothesis, $H_0 = R\theta = 0$, is as follows:

$$w = [R\widehat{\theta}]' \left[R\left(\widehat{\Omega} \otimes (X'QX)^{-1}\right)R'\right]^{-1}[R\widehat{\theta}] \tag{5}$$

in which $\widehat{\theta} = vec(\widehat{\Theta})$ stands for the row vector, $\widehat{\Omega} = \frac{1}{T}\widehat{\varepsilon}'\widehat{\varepsilon}$ and $\otimes$ is the Kronecker product. $\widehat{\Theta}$ is the OLS estimator being $\widehat{\Theta} = (X'QX)^{-1}$ and R is a $m \times n^2p$ matrix with m being the number of restrictions. Toda and Yamamoto (1995) and Dolado and Lütkepohl (1996) present that the Wald statistics in the model has the usual ${\chi_m}^2$ asymptotic null distribution. In the Shi et al. (2018, 2020) approach, a real time-varying causality test is generated from supremum (sup) Wald statistic sequences are generated by using a forward recursive (Thoma, 1994), a rolling window (Swanson, 1998), and a recursive evolving methodology

Table 1
Descriptive statistics.

Variables	Max	Min	Mean	Std. dev.
CENE	2113.52	492.81	764.92	333.58
GFIN	158.99	121.78	136.95	9.48
ERES	4150.5	1586.03	2403.54	637.56
GTEC	316	99.12	148.91	41.78

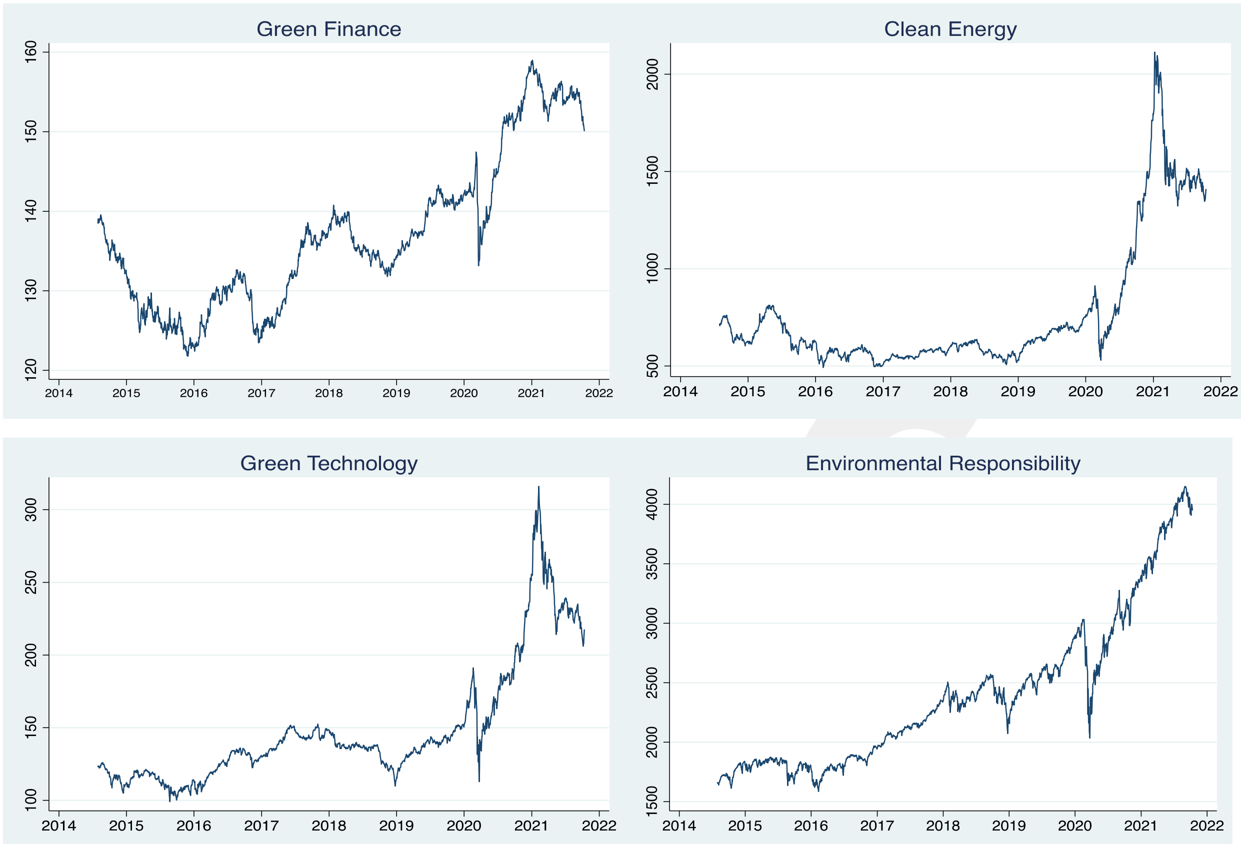

Fig. 1. Time plots of analyzed variables.

(Phillips et al., 2015a, 2015b).

The Wald statistic over $[f_1, f_2]$ that has a sample size fraction of $f_w = f_2 - f_1 \geq$ is represented by $W_{f2}(f_1)$ in the recursive evolving algorithm. The supremum Wald statistic is presented as

$$SW_f(f_0) = \frac{sup}{(f_1, f_2) \in \wedge_0, f_2 = f}\{Wf_2(f_1)\} \tag{6}$$

where $\wedge_0 = \{(f_1, f_2) : 0 < f_1 \leq f_2 \leq 1\}$ and $0 < f_1 \leq 1 - f_0$ and $f_0 \in (0,1)$ represents the minimum number of observations necessary to estimate the VAR system. Forward procedure (Thoma, 1994) requires the statistic sequences to be as follows:

$$\widehat{f}_e = \frac{inf}{f \in [f_0, 1]}\left\{f : W_f(0) > cv \text{ and } \widehat{f}_f = \frac{inf}{f \in [\widehat{f}_e, 1]}\left\{f : W_f(0) < cv\right.\right. \tag{7}$$

The rolling procedure of Swanson (1998) requires the statistic sequences to be as follows:

$$\widehat{f}_e = \frac{inf}{f \in [f_0, 1]}\left\{f : W_f(f - f_0) > cv \text{ and } \widehat{f}_f = \frac{inf}{f \in [\widehat{f}_e, 1]}\left\{f : W_f(f - f_0) < cv\right.\right. \tag{8}$$

The recursive evolving procedure of (Phillips et al., 2015a, 2015b) requires the statistic sequences to be as follows:

$$\widehat{f}_e = \frac{inf}{f \in [f_0, 1]}\left\{f : SW_f(f_0) > scv \text{ and } \widehat{f}_f = \frac{inf}{f \in [\widehat{f}_e, 1]}\left\{f : SW_f(f_0) < scv\right.\right. \tag{9}$$

where $\widehat{f}_e$ and $\widehat{f}_f$ represent the first of estimated observations that exceed or fall below, respectively below the critical values in the causality; cv is the critical value of W_f and scv is the critical value of SW_f statistics.

5. Empirical results

The purpose of this paper is to detect the changes in the causal relationship between clean energy and green finance, green technology, and environmental responsibility. The proposed recursive evolving methods allow the identification of the causal change in the clean energy and precise episodes of causality and instability in this relationship with green finance, environmental responsibility, and green technology. Thus, we relax the hypothesis in which the causality between clean energy and these variables is constant over the sample period. In this sense, we contribute to the literature by examining the evolving causality between clean energy and other economic, environmental, and financial variables. To follow our goals, first, we apply three different unit root tests; namely, Augmented Dickey-Fuller (ADF) proposed by Cheung and Lai (1995), Phillips-Perron (PP) proposed by Phillips and Perron (1988) and Zivot-Andrews (ZA) proposed by Zivot and Andrews (2002), to determine the order of integration of clean energy, green finance, green technology, and environmental responsibility. According to the results reported in Table 2, all the analyzed variables are concluded to be stationary at their first differences, i.e., I(1).

To know the order of integration is essential to correctly set up the time-varying Granger causality model for which we conclude that lag parameter d = 1 is the more suitable. The next step is to run the causality test among the variables under investigation. Initially, the time-varying causality based on the forward, rolling, and recursive evolving algorithms are obtained from a lag augmented VAR model with d = 1. The time-varying Wald test statistics and their bootstrapped critical values are shown in Figs. 2 and 3. If the Wald statistic sequence exceeds its corresponding critical value during a period, then a significant causality is detected. Results for the forward algorithm, considering the assumption of homoscedastic residual error terms for the VAR, are not presented. The reason is simple. Starting with the clean energy-green

Table 2
Results from unit root tests.

	Levels			First-differences			Outcome
	ADF	PP	ZA	ADF	PP	ZA	
CENE	−1.50	−1.48	−3.38	−18.99*	−35.15*	−13.93*	I(1)
GFIN	−3.31	−3.15	−3.95	−17.66*	−37.62*	−16.82*	I(1)
ERES	−1.56	−1.72	−5.24	−19.46*	−48.16*	−16.41*	I(1)
GTEC	−2.05	−2.03	−3.46	−18.28*	−39.61*	−14.99*	I(1)

Note: *Represents a 1% level of significance.

finance causal relationship, we observe that green finance exerts causal effects on clean energy which are very limited, considering forward algorithms, mainly observed during the end of 2019 and until September 2020. The main explanation for this period's strongest causality is undoubtedly the COVID-19 period.

Recursive evolving and rolling window algorithms evidence other periods of significant causality from the green finance to clean energy, at both 10% and 5% significance levels, from 2016 until 2020. Given the limited capacity of the forward procedure, we skipped the presentation of its results. Moreover, we are using time series to perform the analysis, and heteroscedasticity is commonly observed in this type of series. Thus, homoscedastic errors results have also been left aside, and we concentrate the analysis in the following looking at the heteroscedastic errors. Even so, the sequences of test statistics were obtained from the forward recursive procedure. In all plots, we have long periods where the test statistic of the predictive power of green finance, green technology, and environmental responsibility, for clean energy, are always below their critical values. The only exceptions are for green technology at the beginning of 2014 and the end of 2019 and environmental responsibility at the start of 2014. Thus, the null hypothesis of no Granger causality from the green finance, green technology, and environmental responsibility to clean energy over the whole sample period cannot be rejected. Even so, this stronger result is provided by the forward recursive Wald test of causality to the effect that there is no causal relationship or significant change in the causal relationship, both under homoscedastic and heteroscedastic residual error terms.

Considering previous authors' results, also Ng and Tao (2016) conclude that green finance is good to promote clean energy and green technology projects. We find that there is significant causality from the green finance index to the clean energy index. Additionally, Hammoudeh et al. (2020) found no causality running from green bonds to all other variables, concluding for no predictive power for this asset. As we present next, a far more dynamic causal relationship between green finance, green technology, and environmental responsibility, with clean energy is revealed by our results, making us contradict the findings that green finance has no predictive power.

Looking now at the green technology causality impact over the clean energy (under the forward algorithm there is only significance, with a huge spike, at the end of 2019, from March 2019 onwards), this significant causal relationship between both indexes is more visible under the rolling and recursive evolving algorithms, especially in the latter where the Wald statistic sequence always exceeds its corresponding 5% significance value except during the end of 2015 and February 2016, in specific periods. Considering the environmental responsibility causality impact over clean energy, once again specific periods of highly significant causal relationships can be identified under the forward algorithm, which is more noticed and frequent when both rolling and recursive algorithms are applied. High volatility is even observed under the rolling algorithm, and huge significance between February 2016 and the end of 2019 is detected for these two series., in Fig. 3, applying the recursive evolving algorithm.

Fig. 2 presents the results of the time-varying Granger causality considering the rolling window algorithm among all series, whereas Fig. 3 the recursive evolving algorithm results. The recursive evolving procedure (Fig. 3) highlights significant values for almost all periods, whereas it is demonstrated higher volatility among causalities between series under the rolling window procedure. By opposition, the rolling and recursive evolving procedures of Figs. 2 and 3 paint a different picture from that of an unequivocal failure to reject the null hypothesis of no predictability. Instead, a far more dynamic causal relationship between green finance, green technology, and environmental responsibility, with clean energy is revealed. Furthermore, the difference between the homoscedastic and heteroscedastic tests is not very obvious for the rolling and recursive evolving procedures. The main distinction is that significant causality episodes are more frequent from green finance to clean energy, being less frequent from green technology and environmental responsibility causal effects over clean energy. Even so, the duration and findings of stronger evidence of causality are stronger and longer under the recursive evolving algorithm than those suggested by the rolling procedure, where more volatility is evident for these causal relationships. Still, the clear spikes observed for the rolling algorithm where causality is stronger are predominant in the mid-2016, around May 2019, and at the beginning of 2020 for both green technology and environmental responsibility indexes (Granger-causality) over clean energy. Again, causality among the studied series seems to vanish from the beginning of 2020 onwards, raising great concern about the disinvestment caused by the pandemic in the green fields.

Analyzing deeply the results presented in Fig. 2, it is observed that environmental responsibility causality over clean energy presents only one big spike at the start of the pandemic while presenting an even higher spike over green finance in 2018. Significant spikes are even more noticed from environmental responsibility on green technology and are bidirectional. It is also clear that extreme jumps are more common at the beginning of the analyzed period when green technology Granger causes environmental responsibility (Fig. 2, continued). Clean energy Granger-cause over green technology is more frequent and volatile than in the other way around, but still, we can talk about bidirectional causalities. As stated previously, the green finance causality over clean energy is less evident, with significance, except in specific periods, especially at the start of the pandemic. However, higher volatility and significance, in causality terms, is observed for the entire period running from clean energy to green finance. Thus, green finance investments are promoted and proportionated by the need for clean energy (Fig. 2). No significant causality impacts running from green finance to green technology are noted until 2016, whereas during the pandemic almost all causality movements are significant. On the other way around, significant volatile causalities are evidenced from green technology to green finance and for the entire period.

Turning now attention to the recursive evolving algorithm (Fig. 3) results, even if there is evidence of highly significant bidirectional causality between clean energy and green finance during the pandemic period, for the rest of the period analyzed, the causality runs from clean energy to green finance. The opposite happens between environmental responsibility and clean energy because it lost its significance at both the beginning of the period and during the pandemic. Even so, there is unidirectional significant causality running from environmental responsibility to clean energy during the entire period of February 2016 and until the beginning of 2020. On the other way around, causality running from clean energy to environmental responsibility is significant for the entire period analyzed. In fact, under the recursive evolving

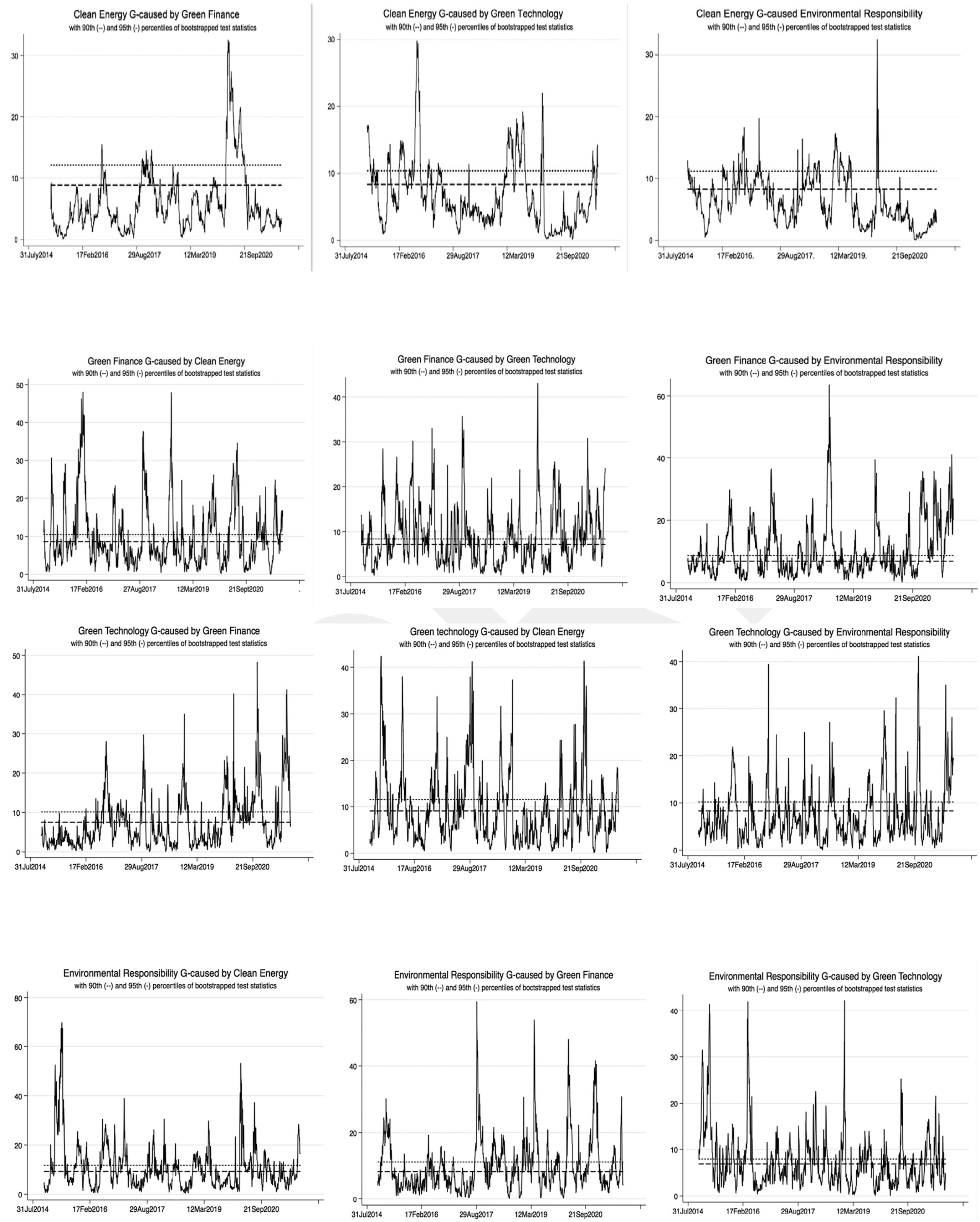

Fig. 2. Time-varying Granger causality with heteroskedastic-robust specification: Rolling window.

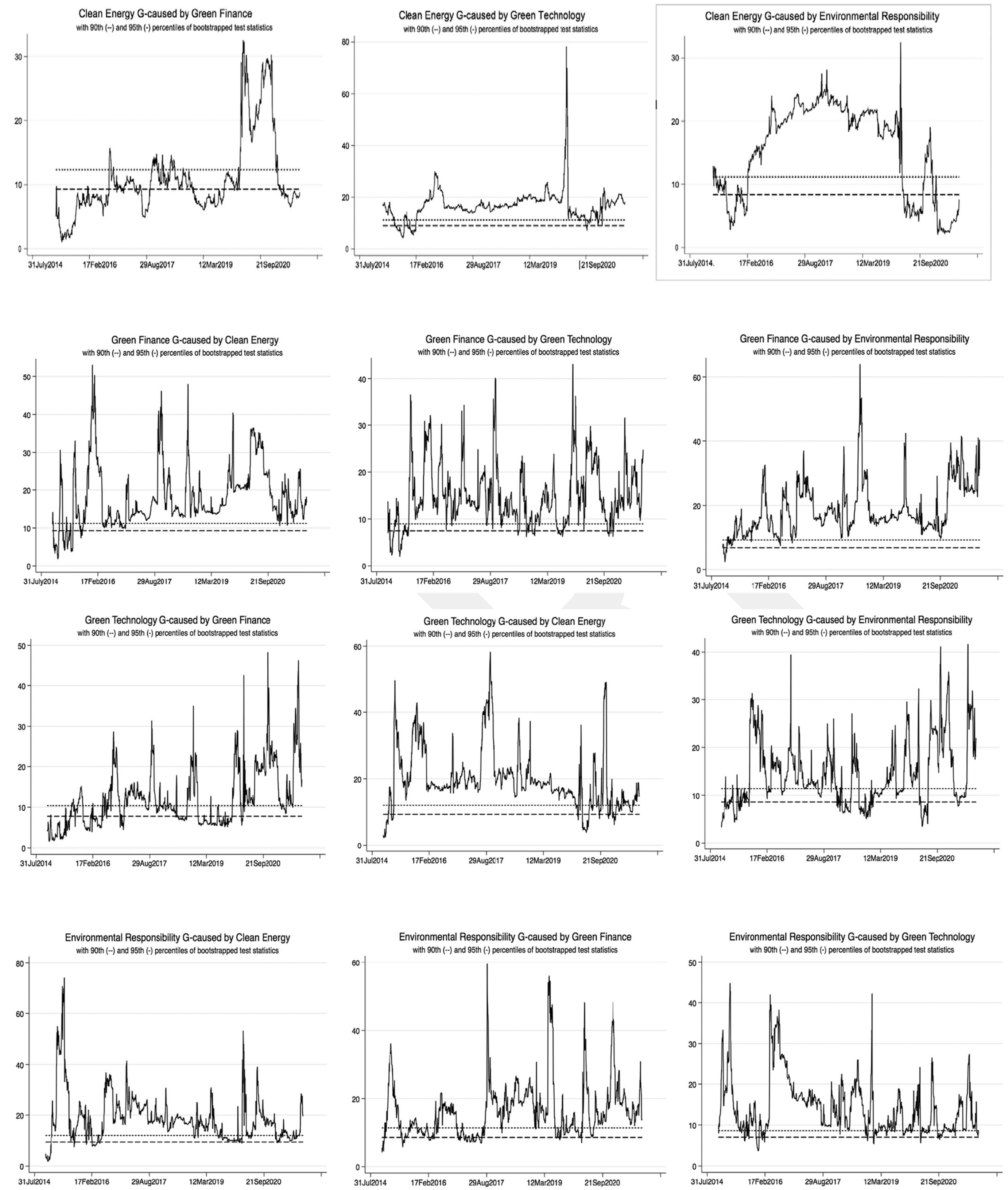

Fig. 3. Time-varying Granger causality with heteroskedastic-robust specification: Recursive evolving.

algorithm, significance is highlighted among series most of the time, and for longer than those revealed by the rolling window, showing higher evidence of bidirectional causalities, although, lower volatility is denoted. The same is true between environmental responsibility, green finance, clean energy, and green technology, as well as vice versa, except for the already highlighted differences. The recursive evolving procedure detects more episodes of causality than the forward and rolling algorithms, turning the recursive evolving algorithm the most suitable procedure in this setting. By looking at the green finance plots (pairs), except for the initial period, results reveal a significant causality running from clean energy to green finance, from green technology to green finance, and from environmental responsibility to green finance, even in the covid period. Environmental responsibility is also significantly caused for the entire period by clean energy, green finance, and green technology (Fig. 3).

The most significant period in G-causality terms is the pandemic from green finance to green technology, but it changes when we look at the causality running from clean energy to green technology provided in the COVID-19 period the high volatility does not reveal a complete unidirectional significance. Thus, we cannot talk about bidirectional causality between green finance and clean energy, nor between green finance and environmental responsibility. Except between 2016 and 2017, we cannot talk about significant causality as well between green technology and environmental responsibility. But we have bidirectional causality (except during the pandemic) with significance between clean energy and green technology, unidirectional from clean energy to environmental responsibility during the entire period of analysis, and bidirectional between clean energy and environmental responsibility during 2016 and the end of 2019. These different periods' causalities and significances have also been highlighted by Hammoudeh et al. (2020) whose results point out that the US 10-year Treasury bond causes green bonds from 2016 until 2020, being limited the causality from clean energy index and CO2 emission allowances to green bonds.

6. Synthesis and discussions of empirical findings

During the latter section, it is revealed a strong and significant causality running from green technology to clean energy and as well from environmental responsibility to clean energy for the entire studied period while using the recursive evolving algorithm. As well, it is observed greatest volatile periods in these causality relationships when the rolling algorithm is applied. Also, these causal relationships are observed considering both homoscedastic and heteroscedastic residual error terms, and so we skip to present the former and present only the results associated with the latter. As well, we skipped the presentation of the forward algorithm results application. Therefore, only the causal relationships in the Granger sense between clean energy, green finance, green technology, and environmental responsibility are deeply analyzed and results presented considering heteroscedastic error terms.

For all studied relationships, it was visible huge and significant spikes starting in the pandemic period which becomes natural if we consider all the economic, financial, and environmental impacts emerging. Our results regarding the causal relationship of green finance on clean energy contradict those of Hammoudeh et al. (2020) who observed that green bonds do not exert any causal effects on clean energy. At least, green finance exerted a huge significant causality over clean energy during the pandemic and specific periods in time. As well, results reveal significant causality running from clean energy to green finance for the entire period of analysis under both rolling and recursive algorithms. The authors attribute this lack of causality to the fact that energy projects were probably financed by stock issues and commercial debt instruments. Thus, we can argue in favor of the higher consciousness of investors and firms in trying to finance clean energy through less traditional instruments, namely, using green bonds which was more specifically observed for the pandemic period. Unfortunately, results also indicate that more recently when markets are returning to the possible normality, this increased awareness decreased. This can be explained by the efforts being done by the markets to quickly and fully recover from the damages caused in economic and financial terms. Even so, green technology and environmental responsibility have been a constant effort through time to reach the desired goals related to clean energy and environmental performance. But, during the pandemic and except for the spike observed at its start, it is noticed a decrease in the causality of both S&P Renewable Energy & Clean Technology and S&P Environmental and Social Responsibility indexes on clean energy. It is therefore urgent to raise awareness to policymakers that economic and financial recoveries cannot be done at the expense of more environmental degradation.

The outcomes from this study are expected to easier carbon neutrality goals, enabling countries to understand how to comply with commitments from both the Paris Agreement (re-discussed at the end of 2021) and the Sustainability Development Goals defined by the United Nations, with special emphasis on those focused on sustainable environmental improvements. Following the results presented here, green finance investments are promoted and proportionated by the need for clean energy. Although our results point to a highly significant bidirectional causality between clean energy and green finance during the covid-19 pandemic, in the previous periods the causality runs from clean energy to green finance.

As stated earlier, through the funding of green technology, green finance is vital in reaching sustainable development goals. Green investment requires high amounts of financing, and governments by themselves are not enough, requiring more private investment, although these might become unbearable (Eyraud et al., 2011). Other forms of financial resources become necessary (Sachs et al., 2019), and the financial system has an essential role in this regard (Zadek and Zhang, 2014). Green bonds provide advantages and are appealing for the financing of clean energy projects (Hammoudeh et al., 2020; Ng and Tao, 2016) and green technologies are a "must-have" in this process (Ng and Tao, 2016). Although the investment in Environmental and Socially Responsible stocks was strongest in the last year and stood more resilient to market downturns like the global financial crises, as pointed out by Nofsinger and Varma (2014) and Leite and Cortez (2015), our results indicate that at the beginning of the covid pandemic, in fact, the causality between green finance, green technology, and environmental responsibility, with clean energy indeed was relevant, but that during March 2020 and up to October 2021, this significance lost relevance, thus contradicting the findings of Broadstock et al. (2020). Additionally, we analyzed the evolving causalities from green finance, green technology, and environmental responsibility to clean energy, and found as well strong bidirectional causalities for the entire period, whereas strong causal relationships were not detected previously by other authors in the other sense (Shahbaz et al., 2021; Liu et al., 2021; Pham, 2016; Nguyen et al., 2021).

Moreover, our results highlight the evidence reported in UNCTAD (2020b) that the COVID-19 pandemic has pushed down investments in green technologies and clean energy. However, it is critical for green bond investors to effectively invest their capital in economic activities able to promote a low-carbon economy (Liu et al., 2021). It should be highlighted that among the studied indexes, the S&P Renewable Energy and Clean Technology index measures the performance of companies whose core business is related to green technologies and sustainable infrastructure solutions, which we concluded to be highly important in explaining the evolution of clean energy. Results pointed for a long and consistent causal relationship of both indexes considering the recursive evolving algorithm for heteroscedastic error assumptions. However, the highest significant and stronger causal relationship identified during estimations was between green finance and clean energy. Green technology causal effects over clean energy are more dispersed and volatile, especially if the rolling procedure is followed in the novel time-varying methods proposed by Shi et al. (2018, 2020) and employed in this study. Following these results, it should as well be highlighted the superior advantage of recursive evolving algorithms, over rolling procedures, and of both over the forward recursive causality, when inferring the causal relationships between clean energy, green finance, green technology, and environmental responsibility.

The debate between environmental and financial performance received higher attention recently (Abban and Hasan, 2021), although no significant results were achieved, once they remain inconclusive and inconsistent. Our results allow us to agree with the literature stating that equity investments in the environmental, social, and corporate governance index stand more resilient to downturns in the markets such as the global financial crisis (Nofsinger and Varma, 2014; Leite and Cortez, 2015) or the covid-19 pandemic (Broadstock et al., 2020). As well, but using constant and traditional causality methods, Lu et al. (2022) detect a bidirectional causal relationship between the S&P Global Clean Energy Index and the S&P GSCI Carbon Emissions Allowances Index. Our results point to a highly significant causality impact of environmental responsibility for clean energy, promoting the urgent need to promote the substitution of the fossil by non-fossil energy, non-friendly by environmentally friendly products, and promoting green consciousness on consumers, and investors in financial markets. Finally, for the Johannesburg Stock Exchange, Worae and Ngwakwe (2017) found a unidirectional causality between environmental responsibility (measured through emissions intensity) and equity returns, but bidirectional with the market value of equity.

The green bond market has evolved sharply lately given its superior role in financing environmentally friendly projects as evidenced by Hammoudeh et al. (2020). Green bonds function like regular bonds, except for the fact that the money raised from investors should be used exclusively to finance projects that have a positive environmental impact. A clear example of these types of projects is renewable energy and green buildings. Our results evidenced a clear bidirectional causality between environmental responsibility and green finance but under the recursive evolving algorithm. Under the rolling window procedure, the bidirectional causality is revealed more unstable, and not significant during the COVID pandemic period. Thus, is as if investments with environmental benefits were relaxed, especially those able to promote clean energy. As Sartzetakis (2021) highlights, financing through green bonds is one of the main pillars backing the global transition to clean energy, but also broad low-carbon economic activities. Still, a lot more development is necessary to have these strictly financing clean energy, and probably it can only be fully reached under green technology development. Therefore, policymakers should also be aware of these facts and promote green investments, considering that there is empirical evidence regarding the straight connection between financial markets and economic growth.

Our results point to a failure in the bidirectional causality between environmental responsibility and clean energy in the pandemic period, and green technology can play an important role in these causal relationships. For this effect, technological and innovative models can be applied to promote sustainable investment, being results recognized and compensated. One such example is digital green finance by offers novel solutions for the fight against climate change. For now, policymakers should promote green financing through changes in countries' regulatory frameworks as a way to promote clean energy (Luo et al., 2019). Green financing should also be promoted by harmonizing public financial incentives, increasing its availability for different economic activity sectors, and increasing investment in clean and green technologies (Shan et al., 2021; Ren et al., 2020). That will be the only possibility to ensure alignment of public sector financing decision-making with the desirable reach of the environmental dimension of the Sustainable Development Goals. For that effect, governments should promote higher financing for sustainable natural resource-based green economies and climate-smart blue economies, which may be achieved through the increased use of green bonds, and similar assets.

Green finance as a financing source should be developed further and credit possibilities enlarged in this respect. Investors would win as well since they are increasing their awareness of environmental problems and the need to reach the desired sustainability development goals. It should be noticed that awareness of the climate change urgency is necessary (Grolleau et al., 2022). Only with the increased returns of green finance and lower risks would investors be tempted to invest more in this field and increase environmental responsibility. For that companies also need to participate in both environmental, social, and governance areas to guarantee that green finance and green technology would be the promoters of a better sustainable future, with less pollution, in the fight against climate change and enhancing environmental responsibility further.

The results also provide significant information from the viewpoint of the investors. During the COVID-19 pandemic, it is evident that almost all causality movements among the asset groups are significant. Despite the safe-haven properties of environmental and sustainable portfolios noted in the literature (Nofsinger and Varma, 2014; Leite and Cortez, 2015), the findings point to the fact that these instruments do not provide diversification benefits when combined in the portfolios of investors during turmoil. However, many data points under the observed period could not attach a Granger causality relationship suggesting investors holding a combination of these funds would enable them to eliminate non-systematic risk. Governments should also address carbon price risk that is intrinsically added to the risks of the investors while holding green portfolios. The carbon risk arises due to technological backdrop or change of the carbon-related policies of the governments. The uncertainty regarding the carbon risk increases the risk of the investors even more over the long term (Gianfrate and Lorenzato, 2018), thus the increased transparency regarding the environmental policies of the governments all around the world is a necessity to attract more funds to the financing of green projects.

7. Conclusions

This study intended to analyze the bidirectional and unidirectional causality relationships between clean energy, green finance, green technology, and environmental responsibility. For the effect, longer time series were used from July 31, 2014, to October 12, 2021, and the novel time-varying Granger causality test of Shin et al. (Shi et al., 2018; Shi et al., 2020) is used. Bidirectional causalities are among all series, but not for the entire period, and with a special decrease and loss of significance in the time-evolving of the covid-19 pandemic period. It is as if the benefits promoted by the environmental quality increases, were left aside in the period. This may as well be easily explained by the fact that during this specific period, governments, individuals, and companies were more aware of recovering both economically and financially than concerned with environmental responsibility continued growth. As such, green technology and green finance as promoters of clean energy should be the strongest bet even during crisis moments to help the continued promotion of clean energy and green technology. The results of our analysis indicate that progress to cut down emissions through clean energy and reach sustainable development goals is highly vulnerable, especially during turbulent times. Accordingly, governments and central banks should also consider financial governance policies to promote sustainable finance (Dikau and Volz, 2018).

This paper helps the policymakers to design a comprehensive policy for strengthening environmental responsibility through green technology innovation, clean energy, and green finance. Sustainable development goals can be achieved through green technology innovation, promoting additionally the reduction of the negative consequences on the natural environment (Luo et al., 2019). During the pandemic, our results pointed to a decrease in the causality of green technologies with all the other variables (clean energy, environmental responsibility, and green finance). Thus, although environmental quality increased during that period and pollution decreased, the development of green technology was not the priority. These effects were mainly explained by the Corfu and mandatory isolation to prevent propagation, reducing air, water, and road transport, whereas alleviating the environmental pollution (leading to historical and necessary decreases). Shan et al. (2021) used common Granger causality approaches with Turkish data to find that both renewable technology and renewable energy minimize carbon dioxide emissions both in the short and long run. Also, Ren et al. (2020) found that green finance and new energy use reduce carbon intensity, whereas the latter if increased, inhibits green finance and non-fossil energy use in China. Thus, it is urgent to promote green finance investments to increase clean energy use, whereas the necessary conditions should be promoted by policymakers to ensure that during crisis investments in green technology, through green finance, and clean energy would not decline, being as urgent as other traditional investments to promote sustainable economic growth and enhance environmental responsibility.

Despite those already pointed out here, in a previous section, we have highlighted the main policy implications of our study. However, some limitations also deserve to be pointed out and could provide valuable suggestions for future research. One of the major limitations of this study is the fact that we do not perform a country and cross-country analysis. As more data becomes available, this should be interesting research to follow. The empirical evidence and theory also, point out that different markets are likely to have different degrees of sensitivity, as well as different levels of macroeconomic reactions to shocks. Additionally, no macroeconomic variables, like economic growth nor trade, were included in the analysis despite the literature pointing for a positive connection between finance and economic growth (Beck and Levine, 2004; Pradhan et al., 2013; Ali et al., 2022) and also the opposite, where no impact is found (Demetriades and Rousseau, 2016; Boikos et al., 2022). Moreover, sustainable economic growth is only possible through the use of renewable energy (Sohag et al., 2019; Taşkın et al., 2020). A final limitation of the study that might be pointed is the use of daily frequency data in the causality context. Higher data frequencies could be affected by both drifts and noise, able to mask dependencies and hardening marginal distributions modeling. This happens if we are in the presence of nonstationary variances, long memory, sudden jumps, or high volatility using daily data. For robustness check it could also be used weekly or monthly data, although we believe a lot of information regarding causality could also be lost, justifying the use of daily data in the present work.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2022.105945.

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