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Are clean energy and carbon emission allowances caused by bitcoin? A novel time-varying method

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ABSTRACT

The bitcoin market has substantially grown in recent years. The researchers are exploring its various repercussions for socioeconomic and political matters; however, the literature still lacks clear evidence on how bitcoin interacts with energy and the environment. This study aims to explore the causal relationship between bitcoin, clean energy, and carbon emissions allowances by applying the novel time-varying Granger causality test on the daily data spanning from Sept 17, 2014, to October 12, 2021. The empirical findings confirm that both clean energy and emission allowances are causally associated with bitcoin. However, this causal relationship varies over time and the duration of causality is longer as suggested by the recursive evolving procedure. The outcome is robust when bitcoin is measured by the volume and the price. Furthermore, the results obtained from robustness analysis conducted through heteroskedastic consistent test also validate the findings that bitcoin causes clean energy and carbon allowance. The findings offer a platform for government officials and policy managers to improve clean energy and carbon allowance markets for sustainable development by managing and using the tools to control and regulate cryptocurrency markets.

1. Introduction

As cryptocurrency markets continue to grow, it is imperative to explore its associations with other markets particularly with clean energy and carbon emission allowances markets owing to the fact that cryptocurrency markets are associated with high energy consumption and release heat during the mining process. Among several cryptocurrencies, bitcoin is a digital currency and the best application of blockchain (Gallersdorfer et al., 2020) and least risky than other developing currencies (Gkillas and Katsiampa, 2018). Bitcoin being an important component of the fourth industrial revolution (Su et al., 2020) is a deflationary medium (only 21 million bitcoins will ever exist) and will increase in supply at a fixed but diminishing rate no matter how much the demand increases (Suazo, 2021). The bitcoin blockchain ("a digital ledger of transactions") application is based on Proof of Work (POW[1]; consensus mechanism to avoid double-spending and manipulation: Stoll et al., 2019) and mining (validation process) of bitcoin raises concerns about its role in environmental sustainability (Mora et al., 2018).

One potential link between bitcoin and environmental concerns serves through its association with energy consumption. Energy is required for ownership validation and transaction of bitcoin (Gallersdorfer et al., 2020) which is mainly based on fossil fuels, and it releases a vast amount of heat and emissions. In this respect, Corbet et al. (2021) pointed out: "*the energy footprint* per *Bitcoin transaction is estimated as 619 Kwt, which is equivalent to the power consumption of an average US household over 20.92 days*". Some researchers pinpoint the issue of electronic waste and the need for further energy to offset the heat released from the rigs (Leslie, 2020). Contrary to this, arguments for energy usage in mining are refuted by Vranken (2017). Since its amount is given, with its increasing popularity and mining efforts, its rival miners are increasingly finding ways and adopting new technologies such as modern and smart hardware with the lowest cost to enhance their profits. Thus, bitcoin and sustainability concerns turn out less serious issues.

Besides, the type of energy used in cryptocurrency mining also matters in determining its environmental concerns. Renewable energy supports the transition towards a cost-effective, secure, and environmentally friendly energy supply (IRENA, 2019). Considering an environmentally friendly approach, Ferreira et al. (2018) showed that

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renewable energy stocks help to diversify portfolios. Renewable energy certificates (REC) were created in the US to promote investment in renewable energy. One REC represents 1 MW/h renewable energy produced. *According to USA's National Renewable Laboratory, "the voluntary green power market grew to 77.9 million megawatt-hours (MWh), which were sold to 4.3 million customers in 2015"* (Kushch and Castrillo, 2017). However, the estimates of energy generation are based on projections and show a greater amount of energy produced than in reality. This problem was solved through the application of blockchain applications and the Internet of Things (IOT) which enabled solar panels to estimate energy generated and renewable energy certificates. Homeowners having their own power source can sell energy in the market and can trace the flow of electricity and money through blockchain (Kushch and Castrillo, 2017). The intermittent nature of renewable energy hinders its ability to fulfill peak demand but with use of blockchains technology in energy markets (renewable energy) can solve this problem and results in cost reduction (due to decrease in transaction costs and decline in transmission losses) and make transaction simpler and faster through the interaction of consumers and prosumers (Khatoon et al., 2019).

The existing literature on cryptocurrency and clean energy nexus has mainly focused on the calculations of energy requirements for sustaining cryptocurrency markets (Krause and Tolaymat, 2018; Li et al., 2019; Stoll et al., 2019). The estimates of these studies suggest that the mining of cryptocurrency is energy-intensive, and it has serious implications for environmental sustainability. Following this thread of the literature, some studies concluded that cryptocurrency markets are the source of carbon emissions (Mora et al., 2018; Krause and Tolaymat, 2018). In successive research, the literature also worked on the association between cryptocurrency and energy markets. Some researchers argued that cryptocurrency markets mainly rely on non-renewable energy sources which harm the environment (Stoll et al., 2019; Shojaei et al., 2021). Contrary to this, some studies negated this view and suggested that the cryptocurrency market is associated with the clean energy market (Corbet et al., 2021; Polemis and Tsionas, 2021). Some empirical studies consider the favorable role of financial development including cryptocurrencies for the clean energy sector (Anton and Nucu, 2020; Croutzet and Dabbous, 2021; Wang et al., 2021). In addition, to decarbonize the economies and combat climate change several market mechanisms are introduced through emission permit trading. In this regard "the cap-and trade system" places a limit on the level of CO_2 emission and the prices on emissions are determined by the market forces.

The above discussion suggests that the literature on bitcoin, clean energy, and carbon emission allowances nexus is quite limited and emerging in recent years. The literature highlights the sustainability concerns of cryptocurrencies. The literature does point out the importance of bitcoin for the environment, however, to the best of the authors' knowledge, no previous study is available that explores the causal association between bitcoin, clean energy, and carbon emissions allowances using a large data set. The present study attempts to answer the following research questions:

1) Is clean energy Granger caused by bitcoin (prices and volume)?
2) Is carbon emission allowance Granger-caused by bitcoin (prices and volume)?

Following the above-mentioned arguments and answering the research questions, this study contributes to the existing literature in the following ways: (1) This is the first study of its kind that explores the associations between bitcoin, and clean energy and carbon emission allowances utilizing the daily data spanning from Sept 17, 2014, to October 12, 2021. The study utilizes both prices and volumes of bitcoin for the causal analysis as robustness checks. (2) The study applies the novel time-varying Granger causality test proposed by Shi et al. (2018, 2020) based on the recursive evolving procedure which has the advantage of highlighting the date of origin and collapse of causality without the need of detrending or taking the difference of the data. Employing a time-varying approach is imperative as it counters the flaws of parametric analysis, which tends to disguise time-varying links between the selected indicators. For example, the episodes of significant positive and negative influences at various points in time can offset the net influence in the context of parametric estimation, revealing no significant association. Such outcomes do not aid effective policy formulation and in effect, they can mislead policymakers. Contrary to this time-varying associations can provide deeper insights into the associations between selected variables. (3) Unlike the earlier studies that attempt to understand the connection of clean energy and environment with short and yearly data, this study draws a picture on the nexus, using very long daily data, which should be more representative and reliable.

The findings of this study support the causality running from bitcoin (in volume and price) to clean energy and emission allowance. The study outcome implies that bitcoin energy consumption associated with bitcoin can be entertained by clean energy, thereby mitigating its environmental hazards. Furthermore, Bitcoin causes carbon allowance. The results are validated with heteroscedastic consistent test statistic. Finally, the additional analysis supports bidirectional causality between clean energy and carbon allowance.

The study is structured as; Section 1 provides an introduction, section 2 is based on the literature, section 3 explains the methods used. Section 4 provides empirical results, sensitivity analysis, and further analysis while section 5 concludes the study.

2. Literature review

The cryptocurrency markets are growing in recent years. The sustainability of these markets has attracted the attention of academic researchers as these markets require high energy consumption, creating environmental concerns across the globe. In this perspective, some studies have estimated the energy need for sustaining cryptocurrency markets (Krause and Tolaymat, 2018; Foteinis, 2018; Li et al., 2019; Stoll et al., 2019). For example, Krause and Tolaymat (2018) calculated the energy consumption of four cryptocurrencies including bitcoin between January 2016 and June 2018 and stated that mining of these ("Bitcoin, Ethereum, Litecoin and Monero") cryptocurrencies is based on higher energy consumption when compared to conventional mineral mining while producing same market value and results in 3–15 million tons of carbon emissions. Similarly, the study of Foteinis (2018) also reported the carbon footprint of bitcoin and Ethereum mining to be more than 43.9 million tons of CO_2 equivalent. The study of Li et al. (2019) analyzed the power consumption of 9 digital currencies and their mining efficiency. They focused on Monero mining, its electricity consumption, and related carbon emissions in China. According to their analysis, the electricity consumption of Monero may stand at 30.34 GWh with 19.12e 19.42 thousand tons of emission between April–December in 2018 in China while 645.62 GWh at the global level. *According to the authors although blockchain technology and cryptocurrency mining is promising however their linkages between energy conversation and sustainable development should be examined.* Similarly, Stoll et al. (2019) estimated the energy consumption by bitcoin blockchain and translated it into CO_2 emissions. Their findings suggest that it consumes electricity of 45.8 TWh as of November 2018 and lead to CO_2 emissions of 22.0–22.9 MT CO_2. According to their findings, these emissions are equal to the emissions caused by Jordan and Sri Lanka.

Some studies link cryptocurrency markets with carbon emissions (Mora et al., 2018; Krause and Tolaymat, 2018). According to Mora et al. (2018) at the current rate of technological use, the emission generated from electricity use in bitcoin will lead to 2 °C of global warming within a few decades. The mining will shift to economies with cheaper energy. They suggested that mitigation of bitcoin carbon footprint is possible through electricity decarbonization but at places where renewable energy is cheaper than conventional energy sources. The authors also suggested modification in the system and the addition of more transactions per block to reduce the difficulty and time required for resolving proof-of-work (PoW). These measures will reduce the energy consumption of bitcoin. Krause and Tolaymat (2018) also reported bitcoin is among four cryptocurrencies that are responsible for almost 3–15 million tons of carbon emissions from 2016 till 2018, due to being energy intensive while producing the same level of value when compared to the mining of metals. They also suggested that the energy requirement of these currencies will continue to increase. Some authors view the role of blockchain as favorable in handling frictions and inefficiency of the clean energy market (Nassiry, 2018; Mengelkamp et al., 2018; Rusovs et al., 2018; Khatoon et al., 2019). In this regard, blockchain technology is used as a verification mechanism for cryptocurrencies, decentralized consensus procedure (a mechanism), resolution of conflicts, remove information asymmetries leading to a transparent and valid record of transactions. Blockchain technology can introduce a user-friendly application for energy consumption and is cost-efficient (due to the removal of intermediaries). In spite, of the absence of intermediaries, the blockchain systems depend on improvement in predefined rules that ensure the security, reliability, and accuracy of the information and have limited transaction loads (Mengelkamp et al., 2018). Blockchain application in the decentralized energy system can help in the facilitation of contracts between energy suppliers and consumers to be made automatically and achieve sustainability outcomes. Blockchain can enable the participant to trade electricity which use to be expensive or time-consuming previously (Nassiry, 2018). Blockchain enables dis-intermediation (*decentralization)* (Nassiry, 2018)*, digitalization, and democratization of the energy sector* and enable energy consumer to monitor and control their energy requirements along with monetization of excess energy resulting from either energy saving or generation (Khatoon et al., 2019). Mengelkamp et al. (2018) demonstrated that the interaction of consumers and prosumers (consumers who are producers as well) of renewable energy through private blockchain in a decentralized manner (without the need of central authority) can lead to balance in energy demand and supply. They concluded that a blockchain-based smart grid leads to sustainable and efficient local energy markets. Rusovs et al. (2018) consider blockchain mining of cryptocurrencies as a problem as well as an opportunity for renewable energy. They examined different parameter to check at what point mining support bioenergy generation in Latvia and suggested using levelized cost of bitcoin. Furthermore, they also suggested that bitcoin or other cryptocurrencies result in support of distributed bio-generation only in the absence or decline in feed-in tariff.

Some studies link cryptocurrency markets with the clean energy market (Li et al., 2019; Suazo, 2021; Corbet et al., 2021; Polemis and Tsionas, 2021). Li et al. (2019) emphasize that the clean energy market is expected to be reshaped by blockchain applications, Similarly, Suazo (2021) asserts that instead of focusing on how much energy is consumed by bitcoin, the focus should be on clean energy usage to assess that how much bitcoin is mined from clean energy sources. Likewise, Corbet et al. (2021) argued that the conventional energy used in the process is to be blamed for emissions, not the digital currency. Therefore, the carbon footprint and environmental impact of cryptocurrencies can be controlled through the transition to clean energy. Corbet et al. (2021) analyzed the data of China, Japan, and Russia to investigate the linkages between bitcoin's price volatility and dynamics of cryptocurrencies (Bitcoin) mining characteristics and trading volume using DCC-GARCH model. They reported positive linkages between bitcoin returns and price volatility of Chinese and Russian electricity companies. Energy companies benefit from an increase in bitcoin prices and lack the incentive to boost the use of renewable energy for the sustainability of its usage. They also report that evidence lack on the impact of the expansion of the cryptocurrencies market and its positive impact on renewable energy increase to decrease carbon footprints. They concluded that investment in cryptocurrencies is unsustainable due to the positive linkage between bitcoin price and electricity volatility and the lack of positive linkages between clean energy and investment in cryptocurrencies. The study of Polemis and Tsionas (2021) analyzed the impact of bitcoin on environmental quality using quantile cointegrated vector autoregression (CQVAR). By using the daily panel data of 50 economies during 2016–2018, they reported a causal relationship between bitcoin and CO_2 emissions resulting from increased energy use. They reported a negative association between bitcoin miners' revenue and carbon emissions. They suggested the use of renewable energy and energy-efficient mining hardware to decline the carbon footprint associated with bitcoin. Some studies link cryptocurrency markets with carbon credit market allowances (Best, 2017; Ashley and Johnson, 2018; Di Febo et al., 2021). Financial credit supports energy transition from conventional sources to renewables especially wind in developed economies while in developing economies decreases the use of biomass and increases the use of coal (Best, 2017). According to Ashley and Johnson (2018), blockchain technology can alleviate problems associated with conventional credit management. Blockchain is a distributed ledger technology that can support renewable energy credits and carbon credits systems (clean energy production and certification) and stored in owners account, transfer digital credits quickly and securely, decreasing time and costs associated with manual works. The purpose is to make clean energy accessible and incentivize production not only to benefit this generation but the future as well. Di Febo et al. (2021) used the multivariate-quantile conditional autoregressive (MVQM-CAViaR) model to capture risk spillovers between the carbon credit market and bitcoin. They reported asymmetric risk spillover from bitcoin to carbon credits. The results from Granger causality also support the influence of bitcoin on carbon credit markets in the lower quantile. A decline in bitcoin returns initiate a negative response in carbon market.

One strand of empirical literature supports the favorable role of financial development including cryptocurrencies for the clean energy sector (Anton and Nucu, 2020; Croutzet and Dabbous, 2021; Wang et al., 2021). According to Anton and Nucu (2020), financial development contributes to renewable energy consumption in 28 European Union (EU) economies over 199–2015 using the fixed-effects model. Similarly, Croutzet and Dabbous (2021) used the panel of 21 Organization for Economic Cooperation and Development (OECD) economies over 2005–2018 and reported that FinTech (financial technologies; Cryptocurrencies) increases renewable energy consumption using the fixed-effects model with Driscoll-Kraay standard errors. Thus, financial technologies support carbon neutrality using clean energy. Wang et al. (2021), also supported the positive role of financial development towards renewable energy for China at the regional and national level during 1997–2017 using pooled mean group estimation. They reported unidirectional causality from financial development to renewable energy, respectively.

To decarbonize the economies numerous market mechanisms are introduced through emission permit trading. In this respect "the cap-and trade system" places a limit on the level of CO_2 emission and the prices on emissions are determined by the market forces. The three most adopted emission trading systems include "EU emission trading system (EU ETS), California's AB-32 cap-and-trade system, and the US Regional Greenhouse Gas Initiative". These carbon pricing systems promote and provide an incentive for energy-saving and innovation of clean energy (renewable energy) and decline in the cap with time. The emission trading system plays an important role in controlling emissions (Di Febo et al., 2021). Furthermore, the market of carbon credits is supporting green energy through an increase in renewable energy options and a decline in fossil fuel energy sources to promote carbon neutrality (low carbon economy) (Mathews, 2008). According to Khatoon et al. (2019) frictionless energy trading across borders is possible through standardized global blockchain infrastructure. On the empirical front, recently some studies have found evidence on cryptocurrency markets with carbon credit market allowances nexus (Ashley and Johnson, 2018; Di Febo et al., 2021). According to Ashley and Johnson (2018), blockchain technology can alleviate problems associated with conventional credit management. Di Febo et al. (2021) reported asymmetric risk spillover from bitcoin to carbon credits. The results from Granger causality also support the influence of bitcoin on carbon credit markets in the lower quantile.

The literature on bitcoin, clean energy, and carbon allowance nexus has emerged in recent years. Although the studies have investigated the links between cryptocurrencies and environment, carbon footprints of digital currencies, energy demand, and energy transition (from conventional to clean energy). However, no prior study has examined the potential linkages between bitcoin, clean energy, and carbon allowances. Furthermore, the literature is silent on the varying impact of time on the association between bitcoin, clean energy, and carbon allowances.

The studies have provided estimates for the energy required to mine cryptocurrencies. Some studies have linked cryptocurrency markets with clean energy and carbon credit allowances markets mostly from pure engineering points of view. The literature so far is silent on the causal association between bitcoin, clean energy and carbon allowances; especially, looking from an economics perspective. Particularly, time-varying causal analysis is missing in the existing literature which the current research paper aims to fulfill.

3. Data and methods

3.1. Data

This research study uses S&P carbon emissions allowances (GSCE), S&P global clean energy index (GCEN), and bitcoin is denoted by the volume traded (BTCV) and price of bitcoin in US$ (BTCP), separately. The dataset is obtained from the official website of S&P Dow Jones Indices and Datastream in which detailed explanations related to variables are available (www.spglobal.com & www.refinitiv.com/en). The range of all the daily dataset is from Sept 17, 2014 to October 12, 2021 (1681 observations) which is the largest dataset given that bitcoin data are not available prior to the above-mentioned date. In this study, we propose to analyze Bitcoin as a major cryptocurrency, based on its market capitalization and data availability. Costa et al. (2019) find that Bitcoin and Ripple seem to behave as efficient financial assets as compared to other cryptocurrencies. Besides, they also found out that all the cryptocurrencies have statistically significant correlations with Bitcoin.

The trends of analyzed variables are presented in Fig. 1 which shows that the data on emission allowances and clean energy follow upward and downward linear outcome, and volume and price of bitcoin are very volatile over the study period of time. Therefore, it should be a reliable choice to employ a time-varying approach in this respect.

4. Methods

We apply the novel time-varying methods recently proposed by Shi et al. (2018, 2020) to detect whether clean energy and carbon allowances are Granger caused by BTCV and BTCP. The test examines the joint significance of a subset of model parameters against the alternative of parameters being significant over the whole or a fraction of time. The procedure provides three causality results including forward, rolling window, and recursive evolving causality. The recursive evolving procedure is based on subsample of sup Wald statistics while forward and rolling window algorithms are based on subsamples of Wald statistics. The purpose of the test is to determine change points within the sample data endogenously (Shi et al., 2018). According to Shi et al. (2018), the recursive procedure is based on the recursive calculation of the related test statistics ("Wald test of Granger causality"), in backward expanding sample sequence in which the observation of interest is the final observation. The inference about the existence of causality is based on that observation which depends on "supremum taken over the values of all the test statistics in the entire recursion, therefore, this procedure is called a recursive evolving algorithm" (Shi et al., 2018).

Furthermore Shi et al. (2020) proposed three methods that examine the causal relationship and provide information about the point of change in the relationship without the need of detrending the data. These methods include forward recursive, rolling window and recursive evolving algorithm and are based on "lag-augmented vector autoregressive framework (LA-VAR)". The results obtained from the recursive procedure are reliable followed by rolling window while the forward algorithm has the worst performance (Shi et al., 2020). The advantages of the recursive procedure include detection of date of origination and collapse of causality, detection of a possible change in direction of causal

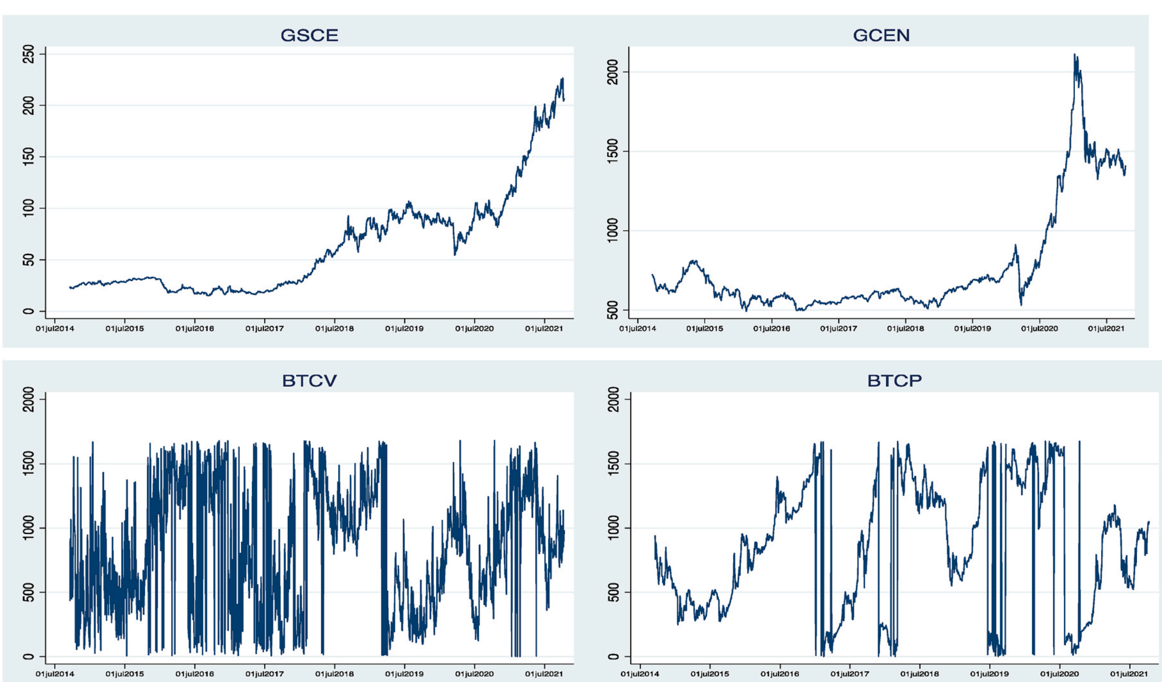

Fig. 1. Time plots of variables under investigation.

relationship originating from economic fluctuations, and this method does not require differencing or detrending of data (Hammoudeh et al., 2020).

The three time-varying causality tests are 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 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 Yamamoto (1995) and Dolado and Lütkepohl (1996) present that the Wald statistics in the model has the usual χ^2_m 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 (Philips 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 $W_{f_2}(f_1)$ in the recursive evolving algorithm. The supremum Wald statistic is presented as

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

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:

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

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

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

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

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

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.

This methodology is superior to previous methodologies as highlighted by Shi et al. (2020) that previous research ignored the way lags were selected and used arbitrary number of lags between 6 or 12, however only a few researchers have used information criteria for lag selection, ignoring the fact that Granger causality was sensitive to lag-selection. Another methodological issue with the previous methodologies is the role of trend (deterministic and stochastic). In this perspective, the authors emphasized on the two lessons derived from the evidence are that methods which does not use detrending or differencing are preferred to those that do, and causal linkages changes over time which makes it sensitive to the time period. Their methodology allows treatment of both deterministic and stochastic trend in a manner that does not require prior detrending. Furthermore, they allow for possible heteroscedasticity in the testing procedure which is also ignored in the literature. Furthermore, the VECM can handle trends in causal testing, however, pretesting for cointegration rank leads to size distortions *and "Granger causality test suffer from nuisance parameter dependencies and nonstandard limit theory*". The lag-augmented VAR (LA-VAR) has size control properties (size stability). If structural changes occur during the time under consideration it can lead to instability in the dynamic relationship between the variables (Zhang et al., 2021).

4. Empirical results

First, we apply two different unit root tests; namely, Zivot-Andrews test with a structural break (ADF) proposed by Zivot and Andrews (2002) and Phillips-Perron (PP) proposed by Phillips and Perron (1988), to determine the order of integration of clean energy, emission allowances, the volume of bitcoin and price of bitcoin. According to the results reported in Table 1, GSCE and GCEN are concluded to be stationary at their first differences, i.e., I (1), while BTCV and BTCP are found to be stationary at levels. It is essential to know the order of integration to correctly set up the time-varying Granger causality model for which we conclude that possible maximum lag parameter d = 1. It is noteworthy hereby that this methodology does not require differencing or detrending the data as it adopts robust econometric methods for different integration and cointegration properties of variables. The next step is to run the causality test among the variables under investigation.

The time-varying Wald test statistics and their bootstrapped critical values are shown in Fig. 2 and Fig. 3, respectively. If the Wald sequence exceeds its corresponding critical value during a period, then a significant causality is detected. Initially, in Fig. 2 we examine whether GCEN is caused by BTCP, and BTCV. The left panel of Fig. 2 shows the causal relationship between BTCP and GCEN. The forward procedure (a) only shows a single point (between April 2016 and June 2016) above the critical value for BTCP and GCEN relationship while rolling and recursive evolving procedure show volatility in the relationship suggesting

Table 1
Results from unit root tests.

	Levels		First-differences		Outcome
	ZA	PP	ZA	PP	
GSCE	−3.27	−2.42	−17.41*	−43.94*	I (1)
GCEN	−3.41	−1.54	−13.81*	−34.80*	I (1)
BTCP	−8.18*	−20.54*	–	–	I (0)
BTCV	−6.75*	−8.26	–	–	I (0)

Note: * represents 1% level of significance.

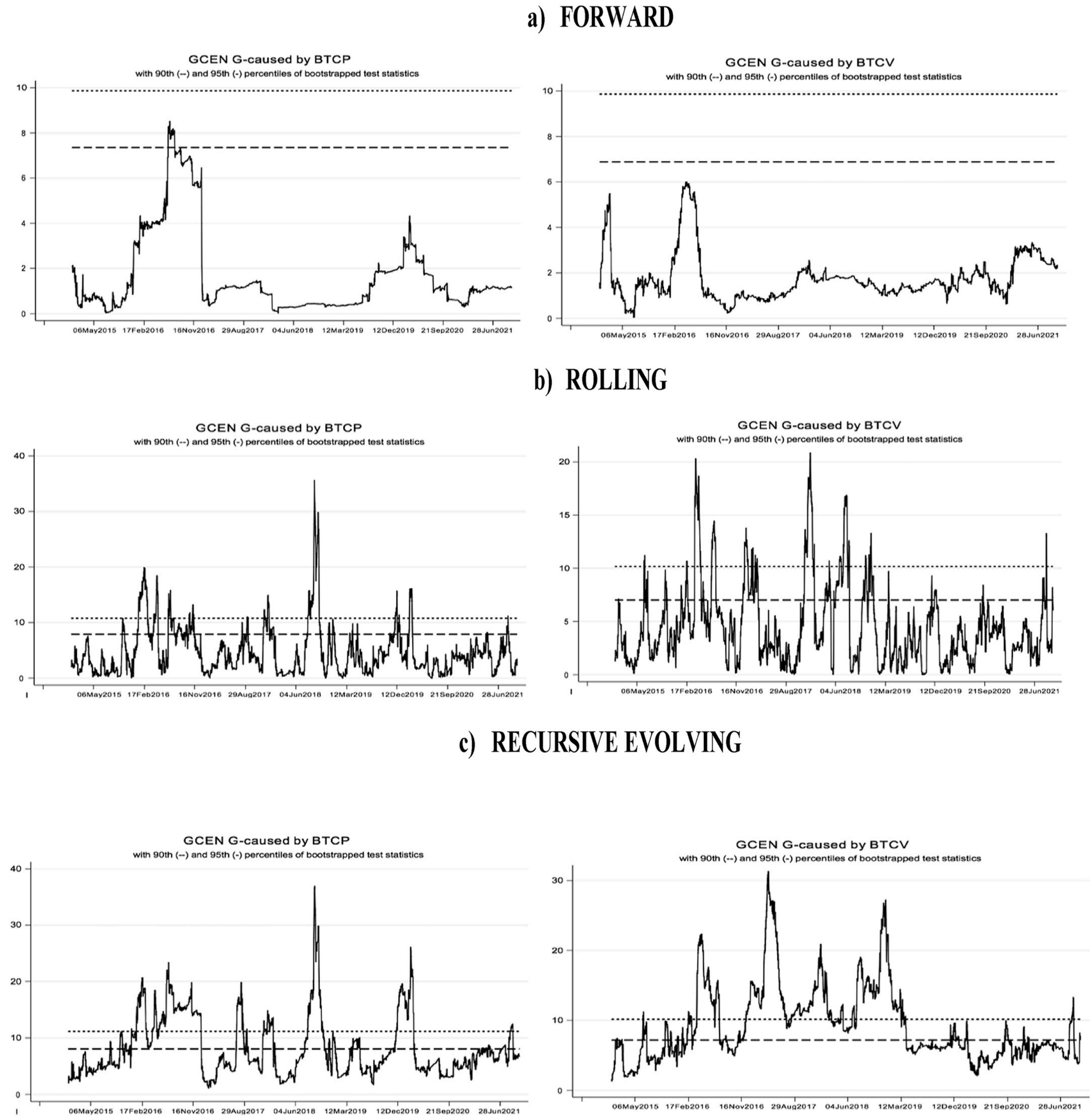

Fig. 2. Is clean energy Granger-caused by bitcoin?.

episodes of a causal relationship. The performance of recursive approach in a finite sample is better than rolling and forward recursive procedure (Shi et al., 2018). Therefore, it can be concluded that GCEN is Granger caused by BTCP.

It is quite interesting to observe that during 2014 when the largest cryptocurrency exchange in the world collapsed resulting in the loss of 850,000 bitcoin (Leath, 2019) no causal relationship is observed between bitcoin prices and clean energy. The absence of causal linkages may be attributed to higher geopolitical risk during 2014:12 to 2015:03 resulting from advancement in renewable energy technologies that caused decline in oil revenues (Su et al., 2021). The influx of capital of about 1 billion dollar (Leath, 2019) in bitcoin and blockchain between 2015 and 2016 led to its success in 2017 that had an impact on the relationship as strong evidence of causal relationship between bitcoin prices and clean energy is observed at the start of 2017 while no causal relationship is observed at the end of 2017 till mid of 2018 after which the evidence suggests a causal relationship. The rise in bitcoin price can be attributed to high oil price in following ways (Su et al., 2020). First, the high oil price may trigger inflation, decrease real income of residents and the profit margins of companies, as well as the public confidence, especially in oil-importing countries. In such a situation, preferences for holing bitcoin can drive its higher price. Second, the falling USDX not only causes oil price to rise but also increases bitcoin price owing to its denomination in U.S. dollars. Third, the geopolitical events in the

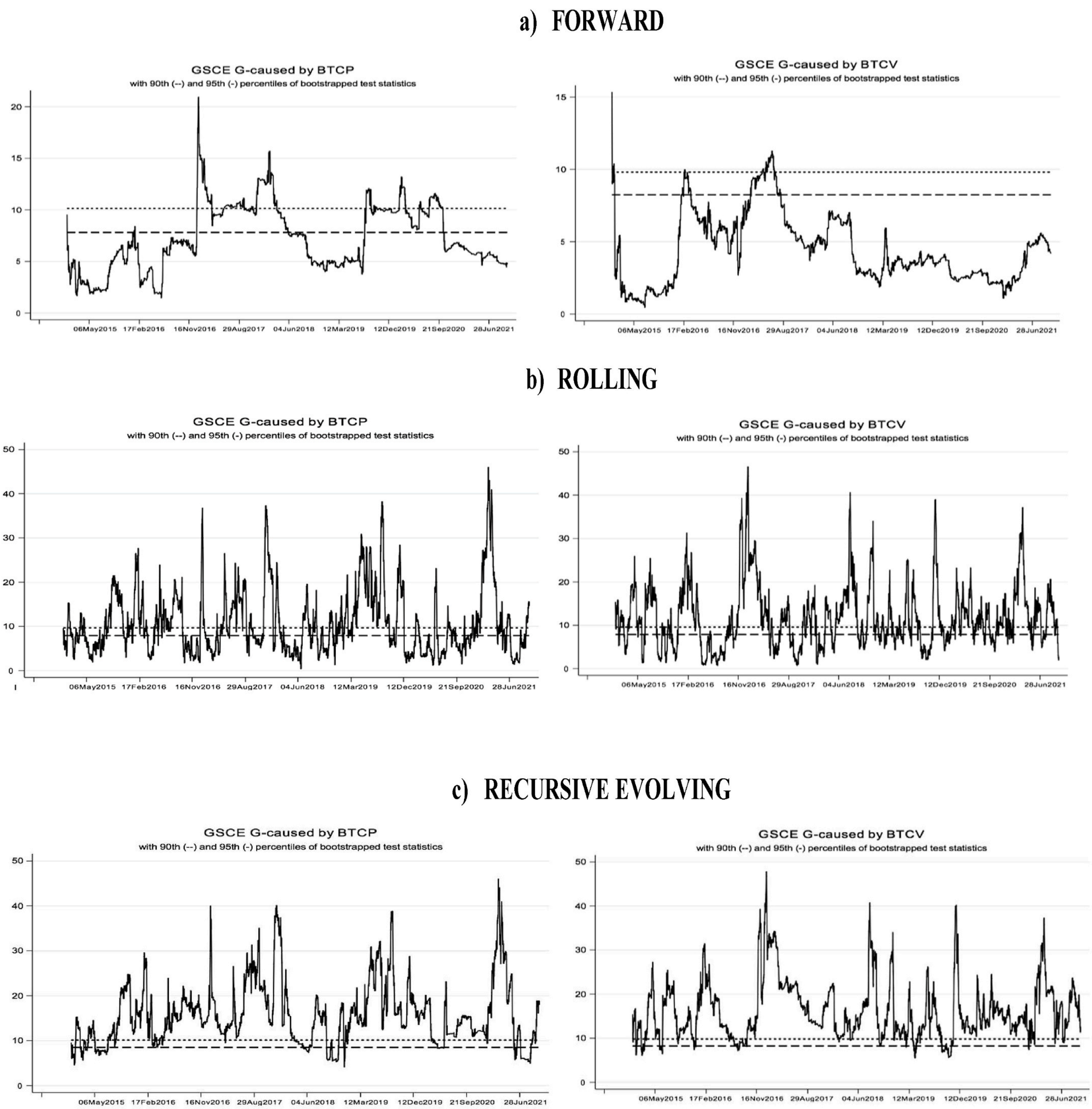

Fig. 3. Is emission allowances Granger-caused by bitcoin?.

Middle East increased oil price, and shacked consumer confidence and investor sentiment. In such a situation, people tend to store assets with hedging ability to reduce losses, increasing the demand for Bitcoin. Also, the Brexit and the U.S. presidential election created global uncertainty, which further increased the demand for bitcoin. Fourth, the rising trend of bitcoin price has attracted more investors to invest, especially in China, Japan and South Korea, further prompting bitcoin price in 2017. Thus, we can evidence that oil price positively affected bitcoin price during the period of 2016:M8–2017:M6. Furthermore, a strong causal relationship can be seen between bitcoin prices and clean energy in December 2019 when Covid-19 pandemic was reported. In this regard, Bejaoui et al. (2021) reported that Covid-19 outbreak increased bitcoin prices because of massive investment in cryptocurrencies (Bitcoin). Moreover, changing economic conditions such as production, financial burden on corporate sales, change in consumer behavior, and unemployment over this period contributed to cryptocurrency prices. Particularly, Huynh et al. (2020) reported that bitcoin act as a better hedging instrument when compared to other digital currencies. Likewise, Johnson (2020) pointed out that the use of Bitcoin increased due to a lack of intermediaries (decentralized nature) during the pandemic. Goodell and Goutte (2021) also reported a positive association between the pandemic and Bitcoin prices.

The right panel of Fig. 2 shows causality between BTCV and GCEN. The forward recursive procedure does not provide evidence of a causal relationship; however, rolling and recursive evolving procedures suggest causality from BTCV to GCEN. The duration of a causal relationship is longer as suggested by recursive evolving procedure when compared to rolling window. Thus, bitcoin (volume traded and prices) Granger causes clean energy. The same results are reported by Croutzet and Dabbous (2021), as they reported an increase in renewable energy consumption resulting from FinTech (cryptocurrencies). Rusovs et al. (2018) reported that using levelized costs of bitcoin support bioenergy generation in Latvia along with a decline in feed-in tariff. Anton and Nucu (2020) also supported the positive role of financial development in renewable energy consumption. Similarly, Wang et al. (2021) also reported financial development causes renewable energy. It is observed that during the crash of the cryptocurrency market in 2014 no causality is observed from bitcoin volume traded to clean energy. However, a high investment in bitcoin between 2015 and 2016 led to episodes of a causal relationship between the two variables. This causal relationship remained significant till December 2019 when Covid-19 pandemic cases were reported. During the Covid-19 pandemic period, no strong evidence of causal relationship is evident, though some weak episodes of causality are observed. Our findings contrast with Corbet et al. (2021) as they reported that increases in bitcoin prices benefit energy companies, and they lack the incentive to deploy renewable energy for the sustainability of cryptocurrency.

Fig. 3 demonstrates the causality between BTCP and GSCE (left panel), and BTCV and GSCE (right panel), respectively. The left panel of Fig. 3 supports the causal relationship of BTCP and GSCE suggesting GSCE is Granger caused by BTCP as suggested by forward, rolling, and recursive evolving procedures. However forward recursive procedure provides evidence of weak Granger causality as the value is above the critical value at different points (February 2015, before February 2016, between December 2016 till June 2018, and between June 2019 till September 2020) in time, in contrast to this rolling and recursive

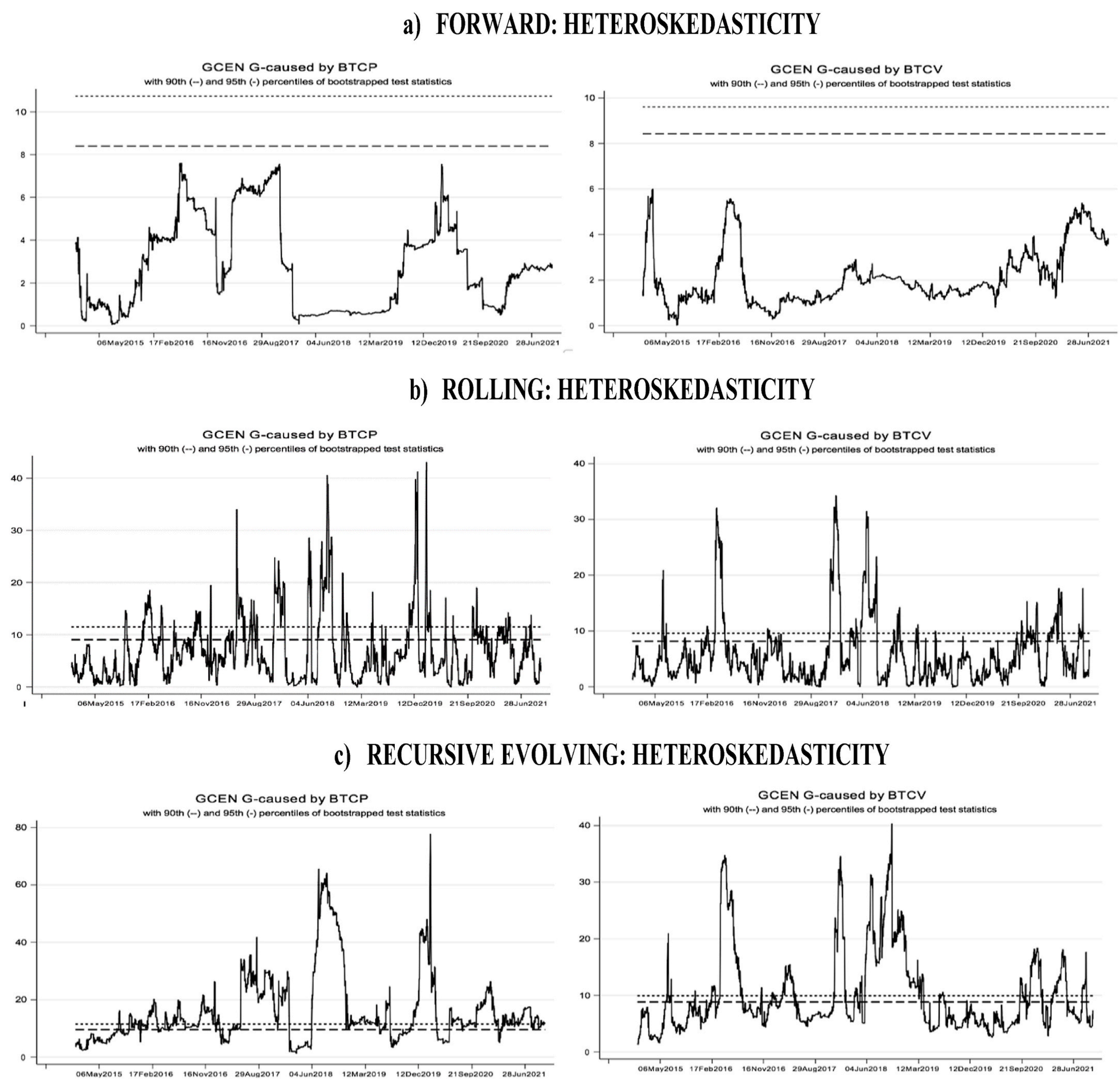

Fig. 4. Granger-causality between clean energy and bitcoin with heteroskedastic consistent test statistics.

evolving procedures supports a strong causal relationship between BTCP and GSCE the value of test statistics is above the critical value during most of the period.

The right panel of Fig. 3 highlights the causality between BTCV and GSCE. Although forward recursive procedure provides evidence of 3 episodes of causal relationship while rolling and recursive procedure suggests the presence of a causal relationship between BTCV and GSCE over a longer period of time. Therefore, the null of no causal relationship is rejected for the whole period as evidence of a strong causal relationship is provided by recursive evolving algorithm suggesting that the relationship between BTCV and GSCE varies with time. Our results coincide with the findings of Di Febo et al. (2021) as they reported an influence of bitcoin on carbon credit market. They supported causality from bitcoin to carbon market. Furthermore, they also depicted that both the markets (bitcoin and carbon) move in the same direction as fall in bitcoin returns lead to a negative impact on carbon market. Polemis and Tsionas (2021) reported a negative association between bitcoin miners' revenue and carbon emissions.

4.1. Robustness checks

To double check the robustness of the outcome on Granger causality presented in Figs. 2 and 3, an additional analysis is carried out by estimating the heteroskedastic consistent test statistics. The results are

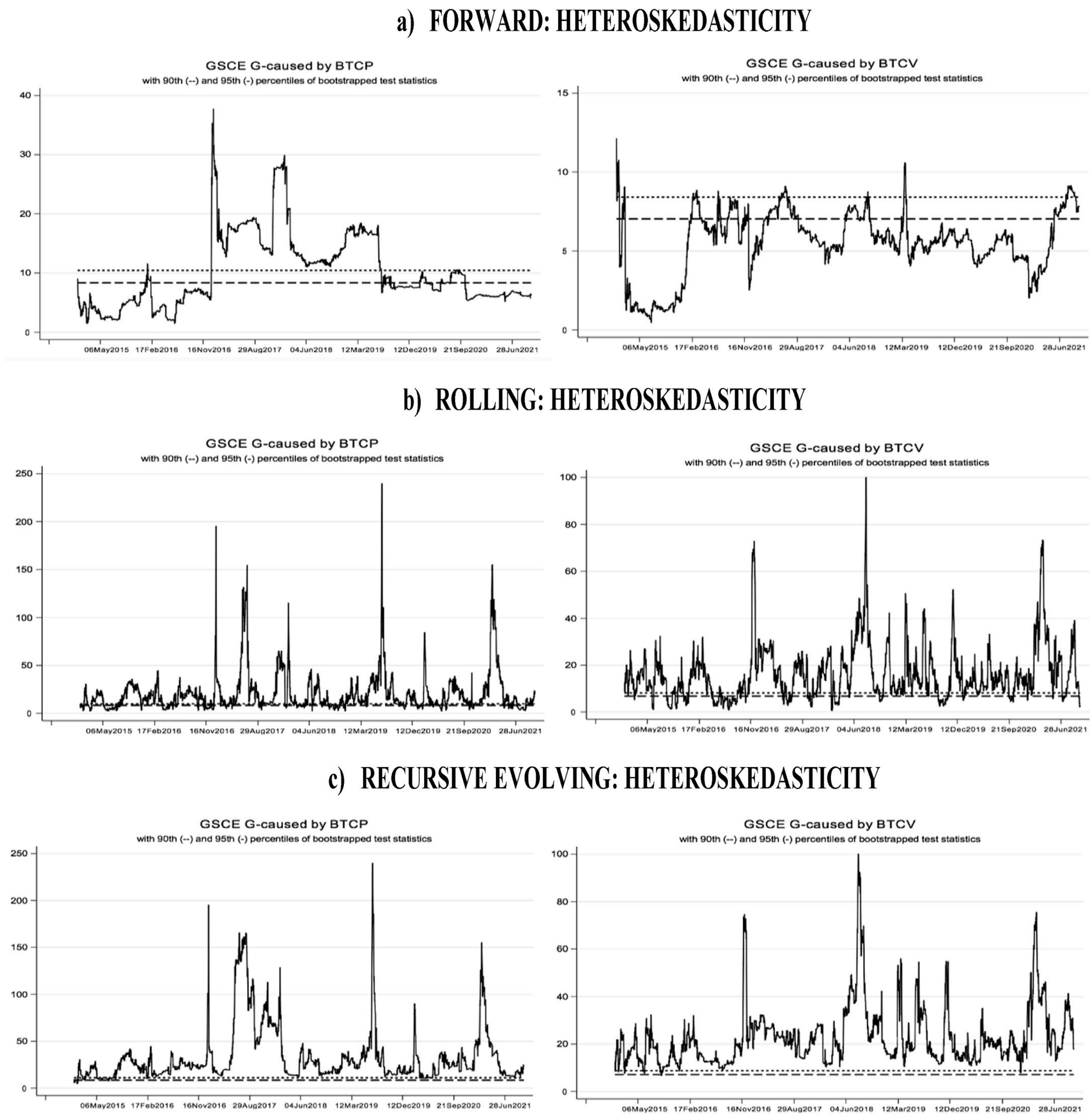

Fig. 5. Granger-causality between emission allowances and bitcoin with heteroskedastic consistent test statistics.

reported in Fig. 4 and Fig. 5. Fig. 4 panel a) shows the result of the forward recursive Wald test (heteroskedastic) of BTCP to GCEN and BTCV to GCEN. The test statistics sequence is below the critical value sequence for the whole sample period suggesting the acceptance of null of no Granger causality between BTCP and GCEN, and BTCV and GCEN. In contrast to the forward recursive, the rolling window procedure supports the existence of a causal relationship between BTCP and GCEN, and BTCV and GCEN as value of the test statistics is above the critical value at several time periods. Similarly, the recursive evolving procedure (panel c) also indicates test statistics is above the critical value suggesting a causal relationship among the variables and the duration is longer in the case of recursive evolving procedure when compared to the rolling procedure. The heteroscedastic consistent test statistics provide evidence of additional episodes of a causal relationship between BTCP and GCEN and BTCV and GCEN when compared to homoscedastic test statistics. Thus, highlighting the importance of heteroscedastic test statistics when using Granger causality. Our results are similar to Croutzet and Dabbous (2021) and Wang et al. (2021).

Fig. 5 highlights the result of the forward recursive Wald test (heteroskedastic) of BTCP to GSCE and BTCV to GSCE. Panel a) shows the result of forward heteroscedasticity of BTCP and BTCV to GSCE. The value of test statistics is above the critical values for BTCP and GSCE relationship for almost 3 years (November 2016 to mid-2019) and fluctuates afterward and below the critical value after September 21, 2020. Thus, the alternate null of the existence of a relationship over a fraction of time is accepted as evidence exists about the causal relationship between BTCP and GSCE. Similarly, peaks above the critical value are also observed in the forward procedure for BTCV and GSCE relationship, thereby suggesting the existence of the time-varying causal relationship. In contrast to the forward recursive, the rolling and

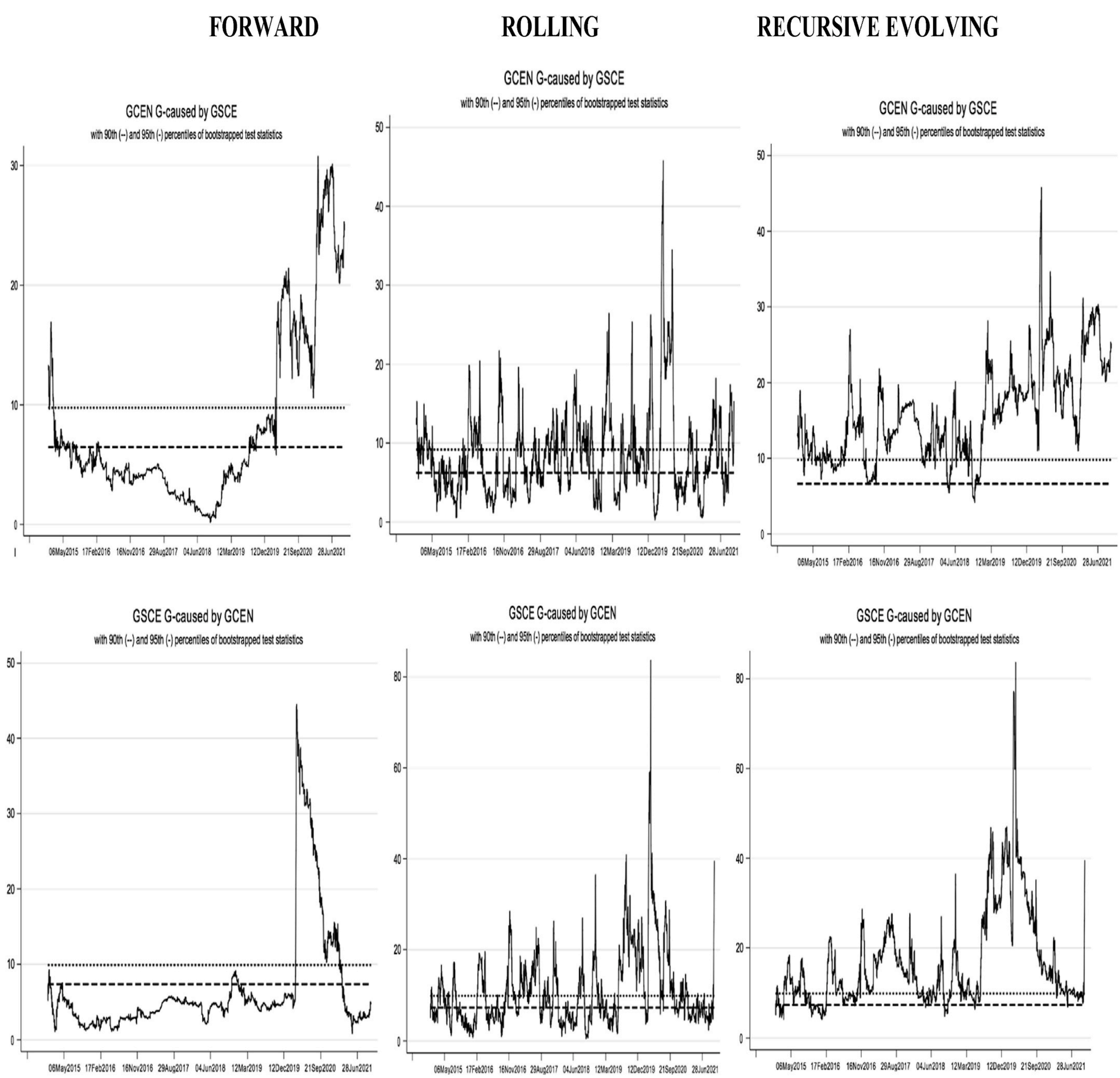

Fig. 6. Granger-causality between emission allowances and clean energy.

recursive evolving procedure also show the values of test statistics being above the critical value during most of the time period which is, in contrast, to forward recursive procedure thereby highlighting the presence of a causal relationship between BTCP and GSCE and BTCV and GSCE, respectively. The heteroscedastic consistent test statistics provide evidence of additional episodes of a causal relationship between BTCP and GSCE, and BTCV and GSCE when compared to homoscedastic test statistics. Thus, supporting the use of heteroscedastic test statistics while examining Granger causality. Similar findings have been reported by Di Febo et al. (2021).

4.2. Further analysis

An additional analysis is carried out by looking at the nexus of carbon allowances and clean energy. The results are reported in Fig. 6 and Fig. 7. In Fig. 6 the causality between GSCE and GCEN is examined. At first, the causality from GSCE to GCEN is reported with the help of forward, rolling, and recursive evolving procedures. The forward procedure suggests only a few episodes of causal relationship from GSCE to GCEN before May 2015 and after mid of 2019. The forward procedure does not provide evidence of a causal relationship between GSCE and GCEN between April 2015 Mid of 2019 however rolling and recursive procedures support the causal relationship between GSCE and GCEN throughout the period under consideration. In the case of the rolling procedure, the causality is more volatile than the recursive evolving procedure. Even the duration of the relationship is longer in the case of recursive evolving suggesting that GCEN is caused by GSCE.

Fig. 6 also presents the causality between GCEN and GSCE. The

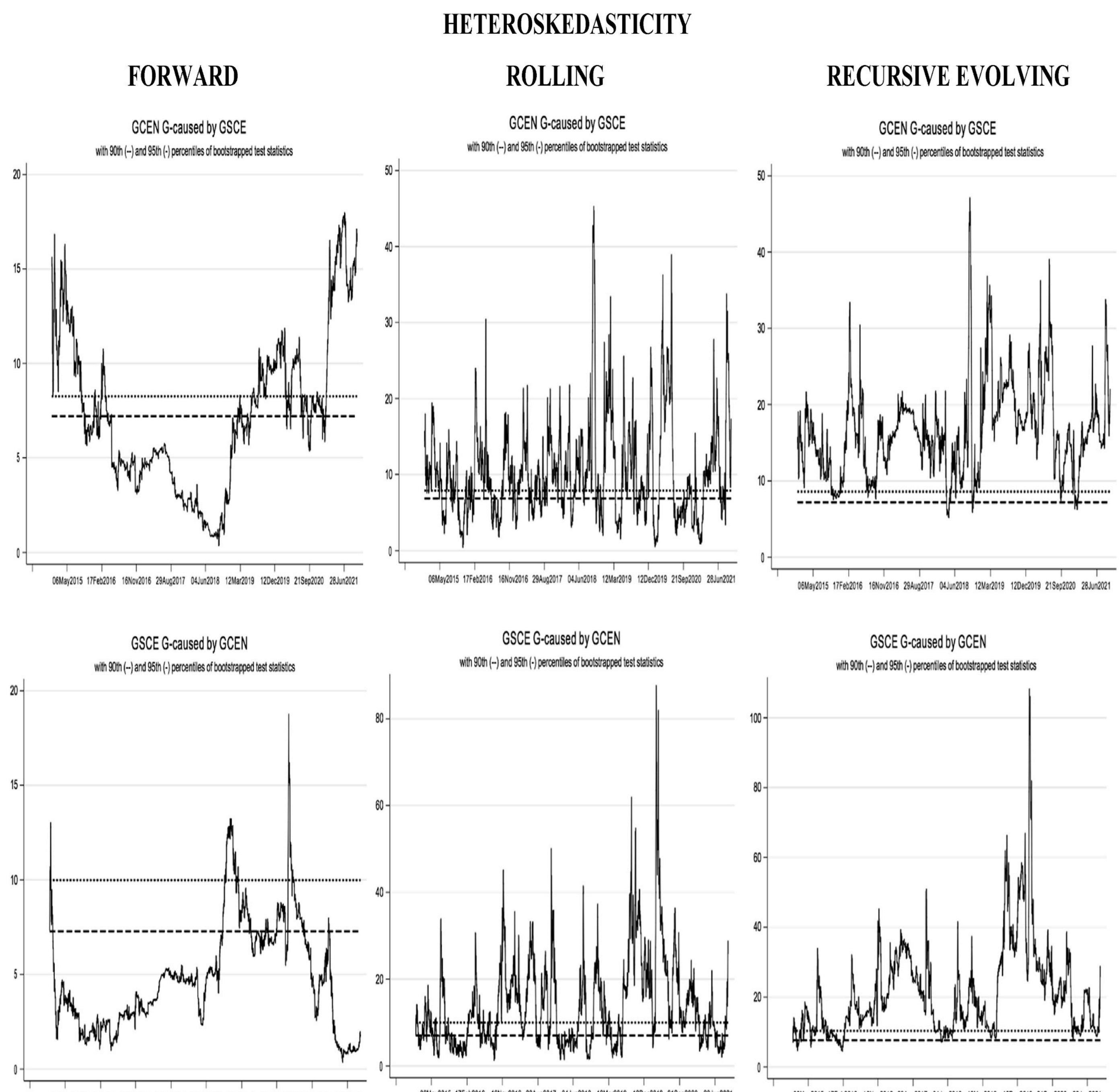

Fig. 7. Granger-causality between emission allowances and clean energy with heteroskedastic consistent test statistics.

forward procedure suggests 3 periods of a causal relationship in contrast to the rolling and recursive evolving procedure which provides evidence of multiple episodes of causal relationship over the period. The duration of a causal relationship between GCEN and GSCE is longer in the case of recursive evolving procedure supporting that GSCE is caused by GCEN. Fig. 7 presents the result of forward, rolling, and recursive heteroskedastic consistent test statistics of Granger causality between GSCE and GCEN. The recursive evolving procedure provides evidence of a strong causal relationship from GSCE to GCEN when compared to the forward and rolling procedure. The heteroscedastic consistent test statistics provide evidence of more episodes of a causal relationship between GCEN and GSCE and GSCE and GCEN and over a longer period of time as evident from the causality suggested by the recursive evolving procedure.

5. Conclusions and policy suggestions

With the increasing popularity of cryptocurrency its role in sustaining environmental quality raises concerns. The excessive use of conventional energy not only endangers ecosystem sustainability but undermines the measures taken to combat climate change and global warming. Therefore, it is important to examine that how cryptocurrency such as bitcoin can shape clean energy and carbon credit markets. This study investigated the causal association between bitcoin, clean energy, and carbon emission allowances by applying the novel time-varying Granger causality test (Shi et al., 2018, 2020) on the daily data spanning from Sept 17, 2014, to October 12, 2021. The results obtained from the forward recursive, rolling window, and recursive evolving procedure are reported and compared to highlight the causal relationship of bitcoin (volume traded and price), clean energy, and carbon allowance. The robustness is checked through heteroskedastic consistent test statistics. The nexus between carbon allowance and clean energy is also examined. The results support time-varying causality running from bitcoin return and volumes to clean energy consumption and carbon emission allowances. Although forward recursive procedure provides limited evidence of causal relationship the findings contrast with the rolling window and recursive evolving algorithm. The rolling window and recursive evolving procedure provide strong evidence of a causal relationship. Furthermore, the performance of the recursive evolving algorithm is better as it provides evidence of causal relationship over a longer period of time when compared to forward and rolling window procedures which the other two procedures fail to capture. Similarly, the results obtained from heteroskedastic consistent test statistics also validate our findings supporting the causality from bitcoin (in volume and price) to clean energy and from bitcoin to emission allowance. The findings imply that global initiatives to decarbonize cryptocurrencies need to be complimented with the use of clean energy in mining of cryptocurrencies. The effect of bitcoin on emission allowance implied that bitcoin miner's revenues are negatively associated with emissions.

The expanded analysis through the examination of carbon allowance and clean energy nexus also suggests a bidirectional relationship between the variables analyzed. Similar to previous findings the performance of the forward algorithm is weak as it only supports causality at the beginning and end of time period while the recursive procedure supports causality over the whole time period (although varying). Heteroskedastic consistent test also supports bidirectional relationship emission allowance and clean energy respectively. Thus, exploring the relationship with the time-varying approach is a reliable choice. These findings suggest that the return and volumes can be used to predict its influence on clean energy and carbon emission allowances.

This study suggests that the increasing use of renewable energy in bitcoin mining and the digitalization of the energy sector (with the help of blockchain technology) can bring sellers and buyers together, therefore, increasing cost efficiency and lowering the losses related to transmission and distribution of energy along with decreasing bitcoin carbon footprint. Besides, to overcome the negative impacts of bitcoin mining, novel, and sustainable solutions need to be developed. For example, reusing the waste heat deriving from mining, heating a multifamily dwelling, or designing a heat generator relying on bitcoin mining. Developing alternative algorithms which are efficient for digital transactions as well for energy use, therefore reducing energy usage. Similarly, mining can be shifted to colder areas where less energy use is required. This research further suggests a balance-seeking approach while devising policies for clean energy and carbon emission allowances market by taking of the adoption and support of the cryptocurrency markets.

Our research proposes different future research avenues. We focus on the time-varying causality between bitcoin, clean energy, and carbon emission allowances. Since it can influence this market through different socioeconomic and political mechanisms, future studies can explore other potential links to provide a deeper understanding of these markets. Furthermore, it can be useful to analyze the importance of bitcoin in influencing the energy mix. We emphasized the causality between bitcoin and clean energy, whereas future studies can investigate the contribution of bitcoin and other cryptocurrencies in determining the trade-off between renewable and non-renewable energy consumption. This study does not account for the possible causality from clean energy and carbon allowance to bitcoin (volume and prices) which can be focused by future research. The existence of potential non-linearities can also be the focal point of future studies. Finally, this study mainly focused on bitcoin whereas future research can conduct a comparative analysis to explore the impact of several cryptocurrencies on clean energy deployment and carbon allowances.

Note 1: The proof-of-work (PoW) consensus mechanism requires participating nodes to solve a numerical problem. Thus, it creates (computational) costs for adding new information, i.e. the next block. The probability that a miner finds a solution and, thus, creates the next block, depends on his use of computational resources. In combination with all nodes approving the new block, this prevents the dissemination of corrupted information and ensures the database's correctness without the need for a central authority.

Note 2: The term, blockchain, refers to a chain of blocks where each block stores a group of information about its past, present, and future. Each block plays a key role in connecting with the previous block, and with the following block, as soon as it comes into the system, to be a part of the chain. The main role of each block is to record, validate, and distribute the transactions among other blocks. This means that a block in the chain cannot be removed or altered as this would change every subsequent block. (pp-2) (Khatoon et al., 2019)

CRediT authorship contribution statement

Eyup Dogan: Writing – original draft, writings, model, Supervision. **Muhammad Tariq Majeed:** Methodology, Writing – original draft, writings. **Tania Luni:** introduction, literature review.

Declaration of competing interest

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

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