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ORIGINAL PAPER

Renewable green hydrogen energy: performances amidst global disturbances

David Iheke Okorie[1,2,3,4]

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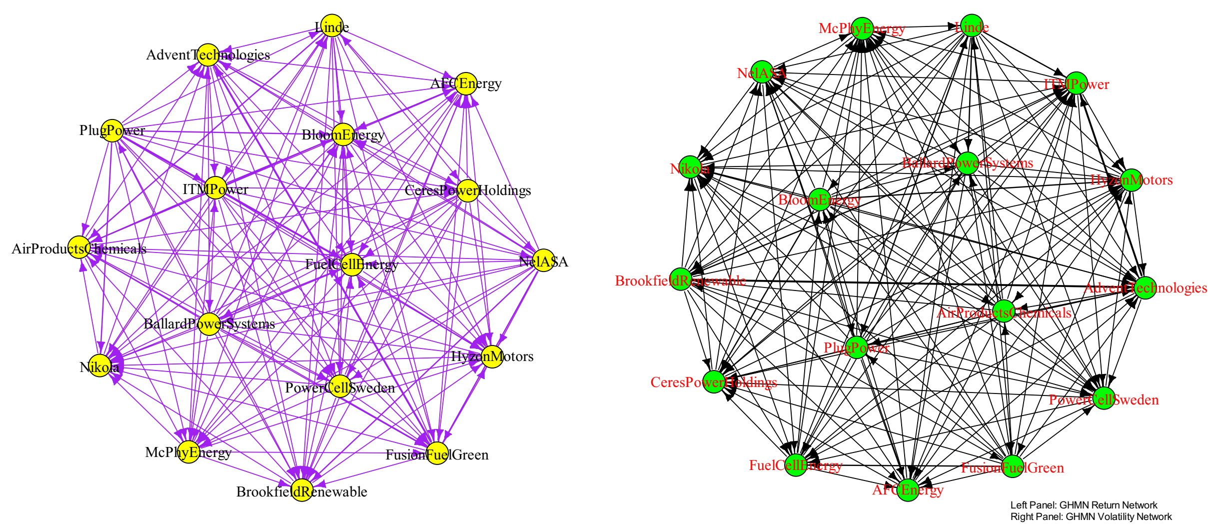
Abstract
Green hydrogen is a promising alternative towards the global target of mitigating greenhouse gas emissions. As such, attention is geared towards green energy hydrogen technologies and markets. Invariably, this also provides investment opportunities for both institutional and private investors. To this end, seventeen green hydrogen markets are studied using network modelling techniques. Among other key findings, Plug Power leads the industry's returns while Bloom Energy leads its volatilities as net transmitters. Intuitively, these markets serve as signals or yardsticks in identifying performances, developments, investment opportunities and prospects in the green hydrogen industry. Conversely, Fuel Cell Energy and Nikola are the leading net return and volatility receivers respectively. Nonetheless, the outbreak of the coronavirus altered the nature of connectedness existing in the renewable green hydrogen industry. This is further confirmed using the Welch (two samples) test. Besides, the outbreak of the COVID-19 pandemic strengthened and improved the industry's overall connectedness. Generally, vital evidence for understanding the green hydrogen industry is presented and discussed. Evidence-based Investment and portfolio management policy implications and recommendations are made.

Graphical abstract



Green Hydrogen Network

Keywords Green hydrogen energy · Renewables · Network modelling · Return · Volatility

JEL Classification Q29 · Q42 · C45

Extended author information available on the last page of the article

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Introduction

As the search for better, cleaner, and more renewable energy sources increases, (green) hydrogen renewable energy has been identified as a suitable and promising energy source alternative (Field and Derwent 2021). The just concluded COP27 (UN's 27th Conference of the Parties) at Sharm el-Sheikh, Egypt concluded that green hydrogen is the best and optimal energy source. This hinges on the urgent need to reduce the global emissions of greenhouse gases and avert the global warming consequences (Okorie and Wesseh 2023). It has also been shown that renewable energies can mitigate greenhouse gas emissions (Bilgili et al. 2023, 2021; Kuskaya 2022). The severe impact of greenhouse gases like carbon emissions has been explored in the literature (Kim et al. 2022; Jiang et al. 2021; Galdos et al. 2013). However, they support and justify the need to identify alternative energy sources globally. Therefore, the identification of renewable green hydrogen as the next best energy source alternative has engineered lots of interest in the green hydrogen industry. However, these increased interests have other implications for the green hydrogen energy industry. One of which is the demand for green hydrogen stocks for investment portfolio formation and management purposes, even in the decarbonization grid markets.

To this end this article takes a step further, in contribution to the existing body of studies, to firstly, investigate the nature of the connection among the green hydrogen energy markets. This is particularly important to understand the green hydrogen industry and its reactions and development path given new (external and internal) information in the industry. Secondly, this study identifies the key players in the green energy industry. These key players are more or less the leaders in the industry. They practically determine the development paths in the industry and can serve as indicators or signals while studying the green hydrogen industry. Thirdly, given the coronavirus pandemic, this article also investigates the alteration effects of the 2019 coronavirus outbreak in the green hydrogen energy industry. While several studies have shown the significant effects of the coronavirus pandemic on different markets (Okorie and Lin 2023, 2021a; Chit et al. 2022), no existing study have investigated or ascertained the effects of this pandemic on the green hydrogen industry. This is yet another contribution of this study. Last but not least, evidence-based policies and recommendations for the green hydrogen industry and its investors, are based on the results of the study. These summarize the key significance, relevance and importance of this study. Based on data availability, market information from a seventeen (17) renewable Green Hydrogen Markets Network (GHMN) is used for the analyses.

Understanding the Green Hydrogen markets' nature of connectedness is imperative for several reasons such as identifying their performances, behaviours, opportunities, growths, information flows, developments, and industrial prospects. Other essential reasons may include the formation of investment portfolios, risk management, portfolio optimization and management, etc. Secondly, the effect of the COVID-19 pandemic on the GHMN system is another key area explored in this study. The contribution, significance, and rationale for this hinges on the survival of the green hydrogen markets after the COVID-19 pandemic. Aside from other factors like innovations, it has been shown that firms' or markets' connectedness is vital for surviving the COVID-19 pandemic (Chit et al. 2022). Therefore, it is essential to understand the strength and nature of connectedness in the green hydrogen industry in light of the coronavirus pandemic ex-post. This is because it is indicative of their post-pandemic survival traits in the industry. The survival of this industry is also paramount because its benefits transcend global environmental and economic wellbeing, given their roles in mitigating greenhouse gas emissions.

Green hydrogen is, therefore, the product of using renewable energies to power water electrolysis. That is, green hydrogen is an energy source generated from other renewable energies through water electrolysis. Thus, renewable energies and water mainly define the supply-side of the green hydrogen industry. More so, the main technologies used in this industry are electrolyzer technologies like Polymer Electrolyte Membrane (PEM) electrolyzers, Alkaline electrolyzers, High-temperature electrolyzers, etc. Other technologies used in green hydrogen production may include Methane pyrolysis tech, Photoelectrochemical water splitting tech, Photocatalytic water splitting tech, Biogasification tech, etc. These technologies are developed and supplied within the (green) energy industry and by high-technology companies. Green hydrogen energy substantially reduces greenhouse gas emissions (Field and Derwent 2021). This makes the heavy carbon industries the key customers of green hydrogen due to the urgent need to decarbonize these industries. Therefore, the users of green hydrogen include industries such as steel, transportation, cement, manufacturing, natural gas, etc.

Related studies

The global energy transition to renewable green hydrogen energies comes with a lot of benefits. These may include the decarbonization of the power system, carbon neutrality, emission abatements, hydrogen technology innovations, rapid electrification developments, cost-effectiveness, green hydrogen mix with other renewables, promising energy sources with potential, et cetera (Field and Derwent 2021; Oliveira et al. 2021; Owen 2004). Hydrogen can be green (from renewable electricity), grey or blue (from methane, coal, or natural gas), or turquoise (from methane). However, there are concerns since hydrogen (blue and/or grey and/or turquoise) is produced from fossil fuels, thereby emitting relatively more carbon (Squadrito et al. 2021). More attention is, therefore, geared towardss green hydrogen. Hence, green hydrogen is expected to play a key vital role in future clean energy targets. This is why this study focuses on and examines the connections existing among the renewable green energy markets.

Green hydrogen energies outperform other hydrogen energy sources. This is based on environmental quality, climate change, and global warming. These other hydrogen energies are Blue, Turquoise, and Grey hydrogen. This advantage is rooted in the production of hydrogen energies, including that of water electrolysis (Squadrito et al. 2021). While Blue, Turquoise, and Grey hydrogen energies are derived from fossil fuels and/or stored emissions, Green hydrogen is produced from renewable electricity energies. This makes Green hydrogen energies the preferred alternative. This has equally earned more attention enjoyed by the renewable green hydrogen energy markets given its promising prospects. As a result, more investments, research, and developments are channelled and seen in these markets. Due to these developments, both institutional and private investors pay serious attention to the stocks of these renewable green hydrogen markets for investment and profiteering purposes. Therefore, green hydrogen is seen as the enabler or driver of the transition to carbon neutrality prospects (zero emissions) and sustainable energy globally. Green hydrogen is a clean energy solution capable of tackling the global need and challenges of energy. It is promised to assist in decarbonizing heavy emitting industries (Oliveira et al. 2021), storing, and supplying clean energies. It is seen as a booster of the many advances in technology and renewable energy innovations achieved around the world today and their externalities (Owen 2004). Most economies have already keyed into the green hydrogen energy source developments and uses. In the end, investors see promising opportunities in the green hydrogen industry. Hence, a better and improved understanding of the performances, behaviours, and interrelations of these markets is essential. This is where this study comes in handy.

Hydrogen energy sources can mitigate global emissions more than other alternative energy sources like natural gas (Field and Derwent 2021; Cooper et al. 2022). Other approaches examined to reduce carbon emissions include low and medium-temperature glide mixtures (Dai et al. 2020), carbon capture and storage (Withey et al. 2019), alternative energy sources for automobiles (Sagar 1995), disaggregated renewable energy consumption (Hu et al. 2021), research and development and technology transfer (Gu et al. 2021), etc. Aside from renewable electricity sources, alternative sources of producing green hydrogen have earned a lot of attention. For instance, the feasibility of sourcing green hydrogen from solar and wind energy (Colakoglu and Durmayaz 2022; Gerloff 2021; Armijo and Philibert 2020), hybrid production and storage of some energy mixes, including green hydrogen (Alirahmi et al. 2021), green hydrogen energy from water (Maggio et al. 2022; Nadaleti et al. 2021; Basheer and Ali 2019), green hydrogen energies from biogas steam (Minutillo et al. 2020), green hydrogen from wasted energy (Nadaleti et al. 2022), from surplus hydrogen energy (Thapa et al. 2021) etc. On the other hand, Rabiee et al. (2021) investigate the impact of green hydrogen on the power security system and scheduling whereas Hermesmann and Müller (2022) examine its environmental impacts. Likewise, green hydrogen storage shows promising environmental benefits (Razmi et al. 2022; Vuuren et al. 2010). While developing and harnessing green hydrogen has taken the leading interest of most economies (Gyanwali et al. 2022; Karayel et al. 2021; Drela 2021; Armijo and Philibert 2020). Similarly, other measures to mitigate carbon emissions include the optimization of the supply chain (Jiang et al. 2022).

The outbreak of the coronavirus in 2019 (COVID-19) has triggered thousands of studies that investigate its impact on several areas, fields, markets, industries, etc. Most, if not all of these studies arrive at similar conclusions. Their conclusion hinges on the fact that the COVID-19 pandemic has a significant effect on the markets, industries, fields, areas, etc. Just to mention a few, research studies have shown that the COVID-19 outbreak has substantial dampening effects on global levels of carbon emission (Ray et al. 2022). Generally, the effects of the coronavirus outbreak are visible and significant in several markets. These include the stock markets (Okorie and Lin 2021), oil and social responsibility stock markets (Rehman et al. 2022), etc. Aside from the studies on the impact of the pandemic on different markets, financial and otherwise, other studies investigate the environmental impact of the pandemic through the rapid increase in waste disposals as a result of the COVID-19 pandemic (Yuwen et al. 2022).

Based on the modelling approach, network modelling techniques have been used to study several forms of connectedness in different markets and systems. Examples include the oil and gas sector (Okorie and Lin 2022), cryptocurrency and electricity markets (Okorie 2021), financial markets (Mensi et al. 2022; Diebold and Yilmaz 2012), oil markets (Liu et al. 2022), futures markets (Kang and Lee 2019), bond markets (Umar et al. 2022; Gao et al. 2021), stock markets (Gong et al. 2019), green commodities (Khalfaoui et al. 2022), financial institutions (Qian et al. 2022), etc. It has several benefits relative to other spillover measures (Okorie and Lin 2020). These advantages include the identification of the net receiver or transmitter positions in the system, leading net transmitter or receiver, different connected measures, etc. These summarize the existing studies as they relate to the green hydrogen energies, the impacts of the coronavirus outbreak, and the network modelling applications.

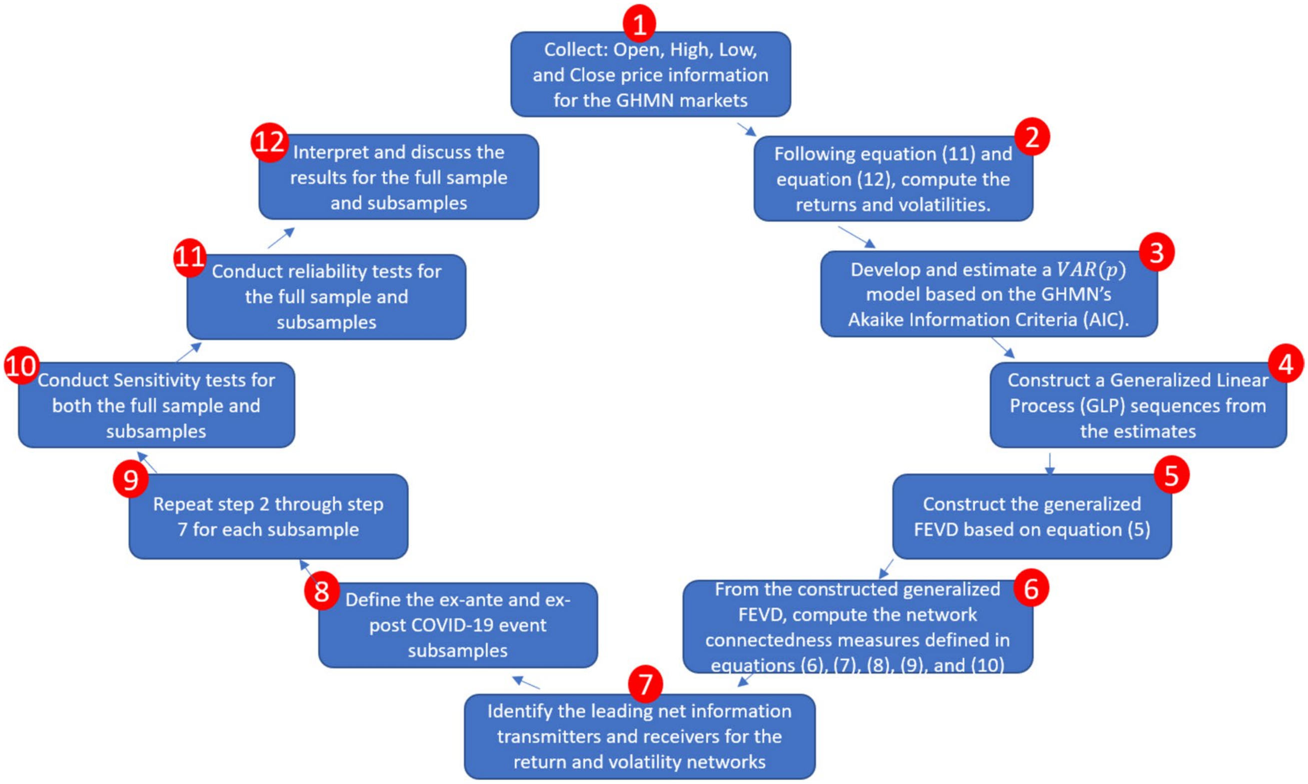

Fig. 1 Analyses procedures

Pertaining to the green hydrogen industry, several gaps are identified in the body of existing studies. These identified gaps are filled by this study. Firstly, existing studies on green hydrogen have neither examined the strength nor the nature of connectedness in the green hydrogen industry. Secondly, the survival of the green hydrogen industry after the outbreak of the coronavirus has not been investigated by any existing study. Thirdly, the key markets that can serve as indicators and yardsticks for the green hydrogen industry have not been identified in the existing body of literature for the green hydrogen industry. As such, this study goes a step further to evaluate the green hydrogen markets' connectedness, identify the leading markets, net transmitters and receivers, and investigate the alteration impacts of the coronavirus outbreak on their connections. Suffice it to say that this study is different from every other existing study by investigating the green hydrogen industry's connectedness, identifying the industry's key players or markets, and ascertaining the effects of the coronavirus pandemic on the green hydrogen industry.

Empirical strategy

The entire analysis, from data collection down to the interpretation and discussion of results, is summarized in Fig. 1. This is down in 12 chronological steps. For instance, step 1 shows the specific market information needed and collected for constructing the GHMN. Based on these markets' information, the required series are constructed for each GHMN market in step 2. Step 3 identifies and estimates the best model for the constructed network. Step 4, Step 4 and Step 6 are based on the estimated results or outputs of Step 3 using the definitions in "Model" section. Based on the results in Step 6, the positions of all the GHMN markets are identified and the leading net information transmitter and receiver are determined in Step 7. Step 8 develops two subsample periods due to the outbreak of the coronavirus while Step 9 repeats the full sample analysis for the subsamples. To support the results or output of this study, sensitivity and reliability tests are conducted for both the full and subsamples in Steps 10 and 11 respectively. Finally, the results are interpreted and discussed in Step 12.

Model

Different approaches have been adopted to study markets' connectedness or information spillover. This ranges from the conditional heteroscedastic models (Okorie and Lin 2020) to network models (Diebold and Yilmaz 2012; Okorie and Lin 2022; Okorie 2021). The benefits of the network models over the conditional heteroscedasticity models include their ability to map the levels of information spillover from one market to the other, identify the information transmitters or receivers, identify the leading transmitter or receivers, and define different connectedness measures, et cetera (Diebold and Yilmaz 2012). This is why the network modelling tools are employed in this analysis. These are the Information Inflow (II), Information Outflow (IO), Net Connectedness (NC), Net Pairwise Connectedness (NPC), and the Total System Connected (TSC). It begins with a Vector Auto-Regressive (VAR) system of equations in Eq. 91) with lag indicator L and lag order p.

$$\boldsymbol{\varphi}(L,p)\boldsymbol{R}_t = \boldsymbol{a}_0 + \boldsymbol{u}_t \quad (1)$$

$$\boldsymbol{R}_t = \boldsymbol{\mu}_t + \boldsymbol{u}_t \quad (2)$$

$$\boldsymbol{\mu}_t = E\left(\boldsymbol{R}_t|\mathbb{F}_{t-1}\right) \text{ and } \boldsymbol{u}_t|\mathbb{F}_{t-1} \sim \text{MG}(0,\Sigma)$$

The choice of the optimal lag length order for the system of equations, p, is made following the Akaike Information Criteria (AIC). The series $\boldsymbol{R}_t = \{r_t\}_{17\times1}$ is a 17×1 series vector at time t and $\boldsymbol{a}_0$ is a vector of the intercept terms. The aim of the VAR(p) model is to disintegrate the series, $\boldsymbol{R}_t$**,** into explained, $\boldsymbol{\mu}_t$**,** and unexplained variations, $\boldsymbol{u}_t$, as shown in equation (2). The explained variations of $\boldsymbol{R}_t$ is based on the past information set $\mathbb{F}_{t-1}$ (markets' information up to time $-\,t$), while the unexplained variations follow the multivariate gaussian distribution of zero-mean and Σ homoscedastic variance–covariance matrix. Using the Generalized Linear Process (GLP) sequences, Sim (1980) developed the flow of information among the series in a system of equations, which is later called the basic Forecast Error Variance Decomposition (FEVD) and the Impulse Response Function (IRF). It was discovered that this model fails to capture the contemporaneous information connected but for n-steps ahead. To solve this, the Cholesky decomposition of the system variance–covariance matrix is used to update the model, this leads to the Orthogonal FEVD and IRF. As more advances are made, scholars show that both the Basic and Orthogonal FEVD and IRF suffer from what is generally called the ordering problem. This led to the introduction of the Generalized FEVD and IRF (Pesaran and Shin 1998; Koop and Pesaran 1996). Furthermore, Diebold and Yilmaz (2012) developed network connectedness measures based on the generalized FEVD to study markets' information spillover networks. Information spillover is defined as the transmission or flow of market information from one market to another in a network or system of markets. This is carried out in the following steps, starting from the GLP in equation (3) with white noise $\boldsymbol{\varepsilon}_t$.

$$\boldsymbol{R}_t = \sum_{i=1}^{\infty} \boldsymbol{A}_i \boldsymbol{\varepsilon}_{t-i} \quad (3)$$

$$\{\boldsymbol{A}_i\}_{i=1}^{\infty} = \sum_{j=1}^{p} \boldsymbol{\varphi}_j \boldsymbol{A}_{i-j} \quad (4)$$

$$\boldsymbol{A}_0 = I_n; \text{ and } \boldsymbol{A}_{i-j|\langle j\rangle i} = \boldsymbol{\varphi}_{j|\langle j\rangle k} = 0$$

$$\omega_{ij}(H) = \sum_{h=0}^{H-1} \left(I_i{\prime}A_h\Sigma I_j\right)^2 \Big/ \sigma_j \sum_{h=0}^{H-1} I_i{\prime}A_h\Sigma A_h{\prime}I_j \quad (5)$$

The 17×17 matrix of coefficient, $\boldsymbol{A}_i = \{A\}_{17\times17,i}$, follows the recursive process modelled in equation (4). $\boldsymbol{\omega}_{ij}(H)$ is the information variance contribution of market j to market i, $\forall i,\ j\varepsilon$ GHMN. The n-steps ahead frequency is H. The Green Hydrogen Market Network (GHMN) directional information spillover is captured in $\boldsymbol{\omega}_{ij}(H)$, from which the following five (5) information spillover network measures are defined. Chronologically, these are the Inflow $\left(N_{i\leftarrow}\right)$ and Outflow $\left(N_{j\rightarrow}\right)$, Net Connectedness $\left(N_{i|i=j}\right)$, Net Pairwise Connectedness (NPC), and the Total System Connected (TSC) as shown in equations (6)–(10). More detailed explanations of these measures are in Diebold and Yilmaz (2012), Okorie and Lin (2022), and Okorie (2021).

$$N_{i\leftarrow} = \sum_{\substack{j=1 \\ j\neq i}}^{n} \omega_{ij} \quad (6)$$

$$N_{j\rightarrow} = \sum_{\substack{i=1 \\ j\neq i}}^{n} \omega_{ij} \quad (7)$$

$$N_{i|i=j} = N_{j\rightarrow} - N_{i\leftarrow} \quad (8)$$

$$\omega_{ji} > \omega_{ij} \quad (9)$$

$$\mathbb{C} = {}^{1}\!/_{n} \sum_{\substack{j=1 \\ j\neq i}}^{n} \sum_{i=1}^{n} \omega_{ij} \quad (10)$$

The market price information extracted from these 17 green hydrogen markets includes their open, high, low, and closed prices. All these prices are used to compute the unconditional markets' volatility while the markets' returns are solely from the close price. Based on these information sets, the markets' returns and volatilities are computed. It has become a common practise for researchers to use the natural logarithmic difference as markets' return. However, this is only an approximation of a market's return and this conditional approximation works better when the return is very close to zero. That is; $\lim_{x_t \to 0} \ln\left(1 + x_t\right) \to x_t$. Notwithstanding, based on the empirical stylized facts from the basic summary statistics of the dataset, most market green hydrogen returns are not that close to zero for this approximation to work well. Therefore, this approach is often unhealthy (misleading, inconsistent, and incorrect) since it is a conditional approximation technique that works only on a certain limiting condition. Secondly, most studies used latent market volatilities. The problem with this is that these latent volatilities greatly depend on the choice of the conditional heteroscedasticity model adopted. That is to say that different conditional heteroscedasticity models will produce different unobserved volatilities for the same market. Alternatively, unconditional market volatilities are computed from the observed market's information set (Okorie and Lin 2022; Okorie 2021). Therefore, the return $\left(r_t\right)$ and volatility $\left(v_t\right)$ series used in this paper are derived following equations (11) and (12). Where c_t is the closing price at time t. $\boldsymbol{I}_{\boldsymbol{\alpha}}$ is a $3 \times 3\,\alpha$ - identity matrix.[1] and $\boldsymbol{C}$ and $\boldsymbol{D}$ are symmetric matrices for the differences between the normalized high (X), closing (M), and low (Z) prices from the normalized open price respectively.

$$r_t = {c_t - c_{t-1}}/{c_{t-1}} \tag{11}$$

$$v_t = \mathrm{trace}\left(\boldsymbol{I}_{\boldsymbol{\alpha}} \mathbf{C}_t \mathbf{D}_t\prime\right) \tag{12}$$

$$\mathbf{C} = \begin{bmatrix} Z - X & 0 & 0 \\ 0 & \Delta & 0 \\ 0 & 0 & M \end{bmatrix},\ \mathbf{D} = \begin{bmatrix} Z - X & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & M \end{bmatrix},$$
$$\text{and } \Delta = Z(M - X) + X(M - Z)$$

Identification strategy

The estimation of the VAR(p) system of equation parameters is the basis of this network model. Therefore, they have to be properly estimated from the sampled data from these 17 green hydrogen markets. Methods like the maximum likelihood, ordinary least squares, etc. Can be used to estimate the VAR(p) model parameters. However, this study adopts that of the ordinary least square, in equation (13), due to its BLUE (Best Linear Unbiased Estimates) properties over the other methods

$$\widehat{\boldsymbol{\varphi}(L,p)}_{.} \epsilon \arg\min_{\boldsymbol{\varphi}} \sum_{t=1}^{T} \boldsymbol{u}_t \boldsymbol{u}'_t \tag{13}$$

[1] $\alpha_1 = 0.511, \alpha_2 = -0.019$, and $\alpha_3 = -0.383$. These parameter values are the best analytic scale-invariant estimators of unconditional volatilities proposed by Garman and Klass (1980) as cited in Okorie (2021).

Results and discussions

Data

Data from the seventeen (17) top-performing green hydrogen markets are sampled from the platform investing.com. The full sample covers the period from August 30th 2017 to March 3rd 2022. The full sample is further divided into two sub-samples to analyse how the COVID-19 pandemic altered the connection in the GHMN system. These are the ex-ante and ex-post samples. Following Okorie and Lin (2021), the 1st of January 2020 is set as the cutoff period between the two subsamples (ex-ante and ex-post). The full sample has 1,109 observations from the markets while 550 and 557 observations are recorded for the ex-ante and ex-post subsamples respectively. The top 17 green hydrogen markets, based on their market capitalization, employed in this analysis are Advent Technologies (AT), AFC Energy (AFCE), Air Products Chemicals (APC), Ballard Power Systems (BPS), Bloom Energy (BE), Brookfield Renewable (BR), Ceres Power Holdings (CPH), Fuel Cell Energy (FCE), Fusion Fuel Green (FFG), Hyzon Motors (HM), ITM Power (ITMP), Linde (LN), McPhy Energy (MPE), Nel ASA (NASA), Nikola (NK), Plug Power (PP), and Power Cell Sweden (PCS).

Table 1 presents the basic summary statistics information of the green hydrogen markets. These are the simple average (A), and the standard deviation SD of the percentage return and volatility series. For the markets' returns, these statistics are presented for the full and subsamples (ex-ante and ex-post COVID-19 pandemic) while the full sample statistics are presented for the volatilities of the market. For instance, the average return for Advent Technologies before the pandemic was about 0.003% while it increased to 1.93% during the COVID-19 pandemic. Based on the overall samples, their average return and volatility are 0.97% and 0.0004 respectively. Their standard deviations are equally reported in the same Table 1. A similar interpretation can be made for the rest of the green hydrogen markets in Table 1. For some of the markets, it appears that their average return level increased after the coronavirus outbreak while the reverse is the case for the other markets. This suggests alterations in the green hydrogen markets system as a result of the COVID-19 pandemic. Besides, the pre-estimation diagnostic stationarity tests for the return and volatility series are reported in Table 1. The tests are conducted using the Augmented Dickey-Fuller (ADF) test statistics with the null hypothesis of unit-root in the series. The reported values in Table 1 are the p-values from the ADF test statistics. The results confirm that these series (full and sub-samples) are stationary at level form, $I(0)$, and thus, they can be used for the VAR(p) model parameter estimations. The pairwise correlation coefficients among these markets are reported in Table 2. The results

Table 1 Data statistics

Markets	Ex-ante return			Ex-post return			Full return			Full volatility		
	A	SD	ADF	A	SD	ADF	A	SD	ADF	A	SD	ADF
1. AT	0.003	0.29	.01***	1.93	25.00	.01***	0.97	17.75	.01***	0.0004	0.001	.02**
2. AFCE	0.23	6.80	.01***	0.29	5.96	.01***	0.27	6.40	.01***	−0.04	0.32	.01***
3. APC	0.08	1.20	.01***	0.02	2.14	.01***	0.05	1.74	.01***	0.0002	0.001	.01***
4. BPS	0.14	3.75	.01***	0.20	5.18	.01***	0.18	4.54	.01***	0.001	0.001	.01***
5. BE	−0.07	4.61	.01***	0.43	6.94	.01***	0.18	5.90	.01***	0.004	0.005	.01***
6. BR	0.00	0.00		0.09	1.98	.01***	0.05	1.41	.01***	0.0005	0.0002	.01***
7. CPH	0.16	2.43	.01***	0.29	4.61	.01***	0.23	3.69	.01***	−0.02	0.48	.01***
8. FCE	0.09	11.15	.01***	0.50	7.72	.01***	0.28	9.59	.01***	0.01	0.03	.01***
9. FFG	0.00	0.00		−0.08	3.91	.01***	−0.04	2.77	.01***	0.02	0.01	.08*
10. HM	0.00	0.00		−0.01	4.15	.01***	−0.01	2.94	.01***	0.001	0.002	.01***
11. ITMP	0.16	3.83	.01***	0.46	6.32	.01***	0.32	5.25	.01***	0.002	0.003	.01***
12. LN	0.08	1.37	.01***	0.09	1.98	.01***	0.09	1.70	.01***	0.0002	0.0003	.01***
13. MPE	−0.03	2.48		0.44	5.47	.01***	0.21	4.26	.01***	0.001	0.003	.01***
14. NASA	0.00	0.00	.01***	0.004	3.36	.01***	0.002	2.38	.01***	0.001	0.0004	.01***
15. NK	0.01	0.17	.01***	0.27	8.33	.01***	0.15	5.91	.01***	0.002	0.01	.01***
16. PP	0.10	3.69	.01***	0.55	5.95	.01***	0.33	4.96	.01***	0.002	0.002	.01***
17. PCS	0.37	4.24	.01***	0.13	4.95	.01***	0.25	4.61	.01***	0.001	0.002	.01***

AT = Advent Technologies, AFCE = AFC Energy, APC = Air Products Chemicals, BPS = Ballard Power Systems, BE = Bloom Energy, BR = Brookfield Renewable, CPH = Ceres Power Holdings, FCE = Fuel Cell Energy, FFG = Fusion Fuel Green, HM = Hyzon Motors, ITMP = ITM Power, LN = Linde, MPE = McPhy Energy, NASA = Nel ASA, NK = Nikola, PP = Plug Power, and PCS = Power Cell Sweden. Also A stands for the simple average, SD stands for the standard deviation, ADF stands for the Augmented Dickey-Fuller test p-values. Full Return (Volatility) stands for Full Sample Return (Volatility)

***p value < 0.01; **p value < 0.05; *p value < 0.1

Table 2 Markets' association tests

Returns	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. AT	1.00	0.05*	−0.01	0.03	0.05*	0.03	0.07**	0.04	−0.06**	0.05	0.03	−0.001	−0.02	0.17***	0.02	0.05	0.03
2. AFCE		1.00	0.11***	0.22***	0.16***	0.09***	0.27***	0.09***	0.08***	0.06***	0.28***	0.13***	0.18***	0.20***	0.03	0.18***	0.21***
3. APC			1.00	0.24***	0.18***	0.08***	0.18***	0.14***	0.03	0.02	0.20***	0.75***	0.18***	0.04	0.04	0.22***	0.20***
4. BPS				1.00	0.42***	0.26***	0.30***	0.38***	0.27***	0.22***	0.39***	0.30***	0.27***	0.30***	0.22***	0.63***	0.36***
5.BE					1.00	0.20***	0.25***	0.27***	0.19***	0.16***	0.27***	0.22***	0.20***	0.20***	0.20***	0.44***	0.22***
6. BR						1.00	0.26***	0.13***	0.25***	0.21***	0.20***	0.14***	0.19***	0.33***	0.13***	0.29***	0.19***
7. CPH							1.00	0.15***	0.17***	0.16***	0.50***	0.25***	0.35***	0.42***	0.12***	0.29***	0.41***
8. FCE								1.00	0.18***	0.14***	0.22***	0.15***	0.15***	0.17***	0.15***	0.42***	0.18***
9. FFG									1.00	0.32***	0.16***	0.06**	0.16***	0.37***	0.18***	0.29***	0.15***
10. HM										1.00	0.13***	0.08***	0.11***	0.29***	0.18***	0.22***	0.14***
11. ITMP											1.00	0.24***	0.35***	0.34***	0.10***	0.32***	0.50***
12. LN												1.00	0.24***	0.11***	0.04	0.27***	0.22***
13. MPE													1.00	0.28***	0.15***	0.25***	0.33***
14.NASA														1.00	0.17***	0.32***	0.34***
15. NK															1.00	0.27***	0.07***
16. PP																1.00	0.28***
17. PCS																	1.00

AT = Advent Technologies, AFCE = AFC Energy, APC = Air Products Chemicals, BPS = Ballard Power Systems, BE = Bloom Energy, BR = Brookfield Renewable, CPH = Ceres Power Holdings, FCE = Fuel Cell Energy, FFG = Fusion Fuel Green, HM = Hyzon Motors, ITMP = ITM Power, LN = Linde, MPE = McPhy Energy, NASA = Nel ASA, NK = Nikola, PP = Plug Power, and PCS = Power Cell Sweden

***p value < 0.01; **p value < 0.05; *p value < 0.1

Table 3 Full sample return network

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Inflow
1. AT	87.39	0.18	0.33	0.43	0.59	0.59	0.35	0.32	4.28	0.67	0.20	0.90	0.61	1.83	0.50	0.61	0.21	12.61
2. AFCE	0.17	68.81	1.07	3.51	1.86	0.72	4.65	0.89	0.73	0.48	4.98	1.49	2.34	2.90	0.05	2.19	3.17	31.19
3. APC	0.18	1.01	52.45	2.90	1.85	0.43	1.85	0.85	0.07	0.07	2.05	29.52	1.67	0.11	0.31	3.03	1.65	47.55
4. BPS	0.56	2.19	1.90	38.27	5.69	2.21	3.61	4.91	2.77	1.62	5.67	3.28	2.94	3.82	1.60	14.24	4.73	61.73
5. BE	0.57	2.95	1.38	7.79	52.12	1.59	3.61	3.24	1.88	0.93	2.98	2.22	2.39	2.76	1.73	9.22	2.66	47.88
6. BR	0.99	0.96	0.38	3.40	1.74	59.97	4.07	0.82	3.93	2.26	2.14	1.48	2.45	7.91	0.80	4.32	2.38	40.03
7. CPH	0.55	3.05	2.36	3.55	2.48	2.99	44.04	0.93	1.78	1.03	10.37	2.87	5.21	7.98	0.75	3.29	6.77	55.96
8. FCE	0.35	1.48	0.89	7.88	3.65	0.72	1.20	60.55	1.92	1.11	3.07	1.04	1.21	1.73	0.87	9.94	2.38	39.45
9. FFG	0.96	0.66	0.16	3.70	1.78	2.99	1.90	1.75	60.03	6.07	1.39	0.44	1.69	8.88	1.63	4.77	1.19	39.97
10. HM	0.83	0.30	0.05	2.89	1.31	2.72	1.52	1.25	6.55	68.37	0.83	0.53	1.18	5.65	2.07	2.60	1.35	31.63
11. ITMP	0.32	3.52	1.98	6.11	2.47	1.82	9.99	2.13	1.34	0.51	42.72	2.57	4.93	5.13	0.34	3.83	10.27	57.28
12. LN	0.08	1.26	27.51	4.12	2.06	1.12	2.65	0.93	0.32	0.36	2.56	47.94	2.65	0.59	0.27	3.49	2.09	52.06
13. MPE	0.12	2.35	2.65	3.89	2.27	1.88	6.28	1.15	1.56	0.69	6.77	3.58	52.28	4.40	1.07	3.39	5.67	47.72
14. NASA	1.69	1.95	0.05	3.58	1.70	5.05	8.04	1.18	6.58	3.80	5.35	0.56	3.78	46.18	1.21	4.36	4.94	53.82
15. NK	0.43	0.31	0.17	3.43	2.60	0.92	1.17	1.36	2.29	2.28	0.75	0.12	1.51	2.13	75.04	5.16	0.33	24.96
16. PP	0.47	1.41	1.78	14.33	6.88	2.93	3.02	6.48	3.51	1.51	3.33	2.71	2.58	4.09	2.72	39.29	2.96	60.71
17. PCS	0.39	2.30	1.82	5.24	1.83	1.89	7.36	1.26	1.15	0.80	11.54	2.19	5.17	5.18	0.24	3.59	48.05	51.95
Outflow	8.67	25.89	44.47	76.75	40.78	30.56	61.29	29.46	40.64	24.21	63.95	55.50	42.32	65.10	16.16	78.03	52.74	**756.53**
NC	−3.95	−5.30	−3.08	15.02	−7.10	−9.47	5.33	*−9.99*	0.67	−7.42	6.67	3.44	−5.40	11.27	−8.80	***17.32***	0.79	**44.50**

The 17×17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17×17 matrix, inflow, outflow, and the NC values are in percentages confirm substantial and moderate levels or degrees of association between each pair of green hydrogen markets. Hence, this is suggestive of a substantial connectedness in the Green Hydrogen Market Network (GHMN) system.

Static analysis of returns and volatility

Static analyses on the full sample returns are conducted and presented in Table 3. The first 17×17 matrix in Table 3 is the directional return information variance contributions from the column, market $-j$ to the row, market $-i$. That is to say that the Advent Technologies market receives about 0.18 and 4.28 information spilt over from AFC Energy (AF) and Fusion Fuel Green (FFG) respectively. However, this does not appear very intuitive. A better way of interpreting this same result is that both AFC Energy and Fusion Fuel Green, respectively, account for about 1.43% and 33.94% of the total information received by Advent Technologies from the GHMN. That is to say that Fusion Fuel Green is the major or key return information giver to Advent Technologies. Conversely, Advent Technologies controls about 87.39% of their return information while the rest 12.61% comes from the rest of the markets in the GHMN. Similarly, information spillover from Advent Technologies to the other markets in the GHMN can be analysed. About 1.96% and 19.49% of the total return information spilt over from Advent Technologies goes to AFC Energy and Nel ASA markets respectively. Ironically, while Advent Technologies spills over about 8.67% of return information to the other markets in the GHMN, it receives about 12.61% of return information from the other markets in the GHMN. This typically makes Advent technologies a net return information receiver in the GHMN system. Intuitively, the performance of Advent technologies' market returns is greatly dependent on the performances of the other markets in the GHMN system, or the green hydrogen markets, at large. The overall information shared among these markets in the GHMN is about 756.53 and 44.50 on average. This goes to say that Advent Technologies contributes about 1.15% while receiving about 1.67% from the overall GHMN. Thereby, making Advent Technologies an overall net return information receiver in the GHMN system. On average, markets contributing at least 44.50 to the overall GHMN are key return contributors. Therefore, the key return contributors in the GHMN include Air Products Chemicals (APC), Ballard Power Systems (BPS), Ceres Power Holdings (CPH), ITM Power (ITMP), Linde (LN), Nel ASA (NASA), Plug Power (PP), and Power Cell Sweden (PCS). Among these key return contributors, the leading GHMN return contributor is Plug Power, accounting for about 10.31% of the overall GHMN system volatility information and receiving about 8.02% from the GHMN. This makes Plug Power the leading net transmitter of return information in the GHMN. On the other hand, Fuel Cell Energy (FCE) contributes about 3.89%

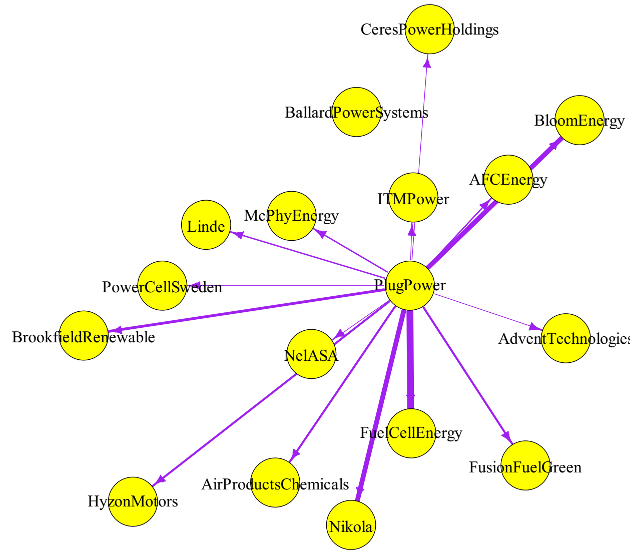

Fig. 2 Return NPC for lead transmitter (plug power)

and receives about 5.21% of information from the GHMN system returns. This makes Fuel Cell Energy a leading net return information receiver in the GHMN system.

Given that the leading net return information transmitter in the GHMN system is Plug Power, Fig. 2 shows the information spillover from Plug Power to the rest of the markets in the GHMN. The thicker the edge line, the more the information flows from Plug Power to the rest of the markets in the GHMN system. This goes to say that there is no net information spillover from Plug Power to Ballard Power System. This intuitively means that Plug Power spills less information to Ballard Power Systems than it receives from it. Similarly, Plug Power spills more information to Bloom Energy relative to Air Products Chemicals. This makes more sense since Air Products Chemicals ranks higher than Plug Power while Plug Power ranks higher than Bloom Energy in Dilallo's report.[2] Therefore, the information represented in Fig. 2 is the Net Pairwise Connectedness (NPC) from Plug Power to the rest of the markets in the GHMN system.

Similarly, static analyses on the full sample unconditional volatilities are conducted and presented in Table 4. The first 17×17 matrix in Table 4 is the directional volatility information variance contributions from the column, market $-j$ to the row, market $-i$. That is to say that the Advent Technologies market receives about 0.04 and 8.62 information spilt over from AFC Energy (AF) and Brookfield Renewable (BR) respectively. However, this does not appear very intuitive. A better way of interpreting this same result is that both AFC Energy and Brookfield Renewable, respectively, account for about 0.12% and 26.54% of

[2] See https://www.fool.com/investing/stock-market/market-sectors/energy/hydrogen-stocks/.

Table 4 Full sample volatility network

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Inflow
1. AT	67.52	0.04	0.18	2.55	0.55	8.62	0.03	0.08	4.38	3.04	1.94	1.01	0.48	5.92	0.26	2.59	0.80	32.48
2. AFCE	0.03	90.79	0.22	0.58	0.04	0.04	6.02	0.04	0.01	0.02	0.14	0.63	0.12	0.01	0.04	1.00	0.27	9.21
3. APC	0.38	0.08	45.92	0.90	16.23	0.18	0.04	0.04	0.13	0.13	0.51	31.01	0.65	0.20	0.16	2.57	0.87	54.08
4. BPS	1.38	0.06	5.47	54.76	4.65	3.30	0.25	0.28	0.44	1.41	3.12	3.25	2.86	2.78	0.35	13.03	2.61	45.24
5. BE	0.31	0.04	10.50	1.66	63.04	1.28	0.06	0.49	0.64	0.20	0.48	14.81	0.82	0.56	0.24	3.95	0.93	36.96
6. BR	3.58	0.02	0.59	4.87	2.11	70.01	0.01	0.03	0.71	1.72	2.61	1.11	0.58	5.78	0.09	5.77	0.41	29.99
7. CPH	0.01	6.67	0.15	0.38	0.09	0.02	91.75	0.01	0.01	0.00	0.22	0.36	0.03	0.02	0.01	0.16	0.11	8.25
8. FCE	0.19	0.02	0.28	0.38	0.35	0.06	0.00	95.30	0.03	0.03	0.30	0.05	0.09	0.08	0.08	0.78	2.00	4.70
9. FFG	1.40	0.01	0.13	0.72	0.60	1.40	0.01	0.01	88.01	1.82	0.58	0.34	0.12	3.63	0.20	0.71	0.31	11.99
10. HM	2.96	0.03	0.08	3.36	0.48	5.50	0.01	0.04	1.07	77.12	1.95	0.43	0.31	1.68	0.13	4.40	0.46	22.88
11. ITMP	2.62	0.31	3.51	3.55	4.11	3.91	0.14	2.06	0.97	1.88	56.60	3.66	1.14	2.53	4.03	3.17	5.81	43.40
12. LN	0.31	0.12	32.59	0.95	12.85	0.34	0.06	0.11	0.06	0.10	0.99	45.89	0.78	0.22	0.18	3.09	1.35	54.11
13. MPE	0.55	0.25	0.96	0.89	2.43	4.13	0.04	0.12	0.26	0.41	2.19	0.50	81.14	0.51	1.04	2.54	2.05	18.86
14. NASA	1.71	0.03	0.80	3.58	0.90	6.25	0.03	0.06	4.76	2.46	3.80	0.86	0.24	69.97	0.22	3.28	1.07	30.03
15. NK	1.14	0.21	0.63	1.12	1.39	0.17	0.02	0.06	0.39	0.22	1.73	0.28	15.33	0.41	75.77	0.59	0.55	24.23
16. PP	0.99	0.41	7.75	12.28	5.12	4.51	0.06	0.12	0.77	1.95	2.42	3.68	0.59	3.20	0.34	53.56	2.23	46.44
17. PCS	1.11	0.22	6.93	3.54	4.37	0.95	0.05	0.15	0.38	0.28	6.15	3.43	1.38	1.16	0.52	5.86	63.52	36.48
Outflow	18.68	8.52	70.76	41.30	56.28	40.65	6.82	3.68	15.03	15.67	29.12	65.41	25.52	28.68	7.89	53.50	21.83	**509.34**
NC	− 13.79	− 0.70	16.69	− 3.95	*19.32*	10.66	− 1.44	− 1.03	3.04	− 7.21	− 14.28	11.31	6.66	− 1.35	***− 16.34***	7.06	− 14.66	**29.96**

The 17 × 17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17 × 17 matrix, inflow, outflow, and the NC values are in percentages

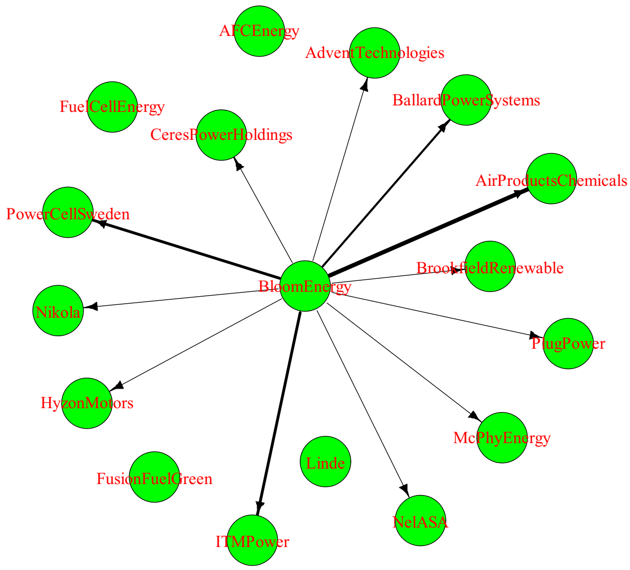

Fig. 3 Volatility NPC for lead tranmitter (bloom energy)

the total information received by Advent Technologies from the GHMN system. That is to say that Brookfield Renewable is the major or key volatility information giver to Advent Technologies. Conversely, Advent Technologies controls about 67.52% of their volatility information while the rest 32.48% comes from the rest of the markets in the GHMN. Similarly, information spillover from Advent Technologies to the other markets in the GHMN can be analysed. About 0.16% and 19.16% of the total volatility information spilt over from Advent Technologies goes to AFC Energy and Brookfield Renewable markets respectively. Ironically, while Advent Technologies spills over about 18.68% of volatility information to the other markets in the GHMN, it receives about 32.48% of information from the other markets in the GHMN. This typically makes Advent technologies a net volatility information receiver in the GHMN system. The overall information shared among these markets in the GHMN is about 509.34 and 29.96 on average. This goes to say that Advent Technologies contributes about 3.67% while receiving about 6.38% from the overall GHMN. Thereby, making Advent Technologies an overall net volatility information receiver in the GHMN system. On average, markets contributing at least 29.96 to the overall GHMN are key volatility contributors. Therefore, the key volatility contributors in the GHMN include Air Products Chemicals (APC), Ballard Power Systems (BPS), Bloom Energy (BE), Brookfield Renewable (BR), Linde (LN), and Plug Power (PP). Among these key volatility contributors, the leading GHMN volatility contributor is Bloom Energy, accounting for about 11.05% of the overall GHMN volatility system information and receiving about 7.85% from the GHMN. This makes Bloom Energy the leading net transmitter of information in the GHMN. On the other hand, Nikola (NK) contributes about 1.55% and receives about 4.76% of information from the GHMN system volatilities. This makes Nikola a leading net information receiver in the GHMN system.

Given that the leading net volatility information transmitter in the GHMN system is Bloom Energy, Fig. 3 shows the information spillover from Bloom Energy to the rest of the markets in the GHMN system. The thicker the edge line, the more the information flows from Bloom Energy to the rest of the markets in the GHMN system. This goes to say that there is no net information spillover from Bloom Energy to Linde and AFC Energy. This intuitively means that Bloom Energy spills less information to Linde and AFC Energy than it receives from them. Similarly, Bloom Energy spills more information to Air Products Chemicals relative to Plug Power. This makes more sense since Air Products Chemicals ranks higher than Plug Power in Dilallo's report. Therefore, the information represented in Fig. 3 is the Net Pairwise Connectedness (NPC) from Bloom Energy to the rest of the markets in the GHMN system. Generally, the overall NPC information spillovers from each of the 17 markets to the rest of the GHMN system, for full sample returns and volatilities are shown in Fig. 4. The edge lines are presented directionally, to show the directional flow or spillover of information from one market to another. The edge lines do not exist whenever there is no net information spillover from one market to the other. Also, thicker edge lines denote the flow of more information flow relative to thinner edge lines.

In providing support for the validity of the findings in this study, it will be interesting to compare the findings to Dilallo's list. According to the analysis report, entitled, *5 Hydrogen Stocks to Watch* on The Motley Fool platform written by Matthew Dilallo on March 8th, 2022. The leading green hydrogen market stocks are Air Products Chemicals, Plug Power, Bloom Energy, Ballard Power Systems, and Fuel Cell Energy. Interestingly, our findings confirm that these markets play leading roles in the GHMN. While Plug Power leads to information transmission, Fuel Cell Energy leads the information spillover receiving. Also, the rest; Air Products Chemicals and Ballard Power Systems co-lead the information transmitting and Bloom Energy co-leads the information receiving. A closer look at the full sample volatility network analysis results shows the top two leading information transmitters in the GHMN make Diillallo's list. From Matthew Dilallo's report on the top 5 hydrogen stocks to watch in 2022; Plug Power and Ballard Power Systems (ranking 2nd and 4th in Dilallo's list) and Air Product Chemicals and Bloom Energy (ranking 1st and 3rd in Dilallo's list) are the leading information transmitters of the GHMN for return and volatility respectively, from our analysis results.

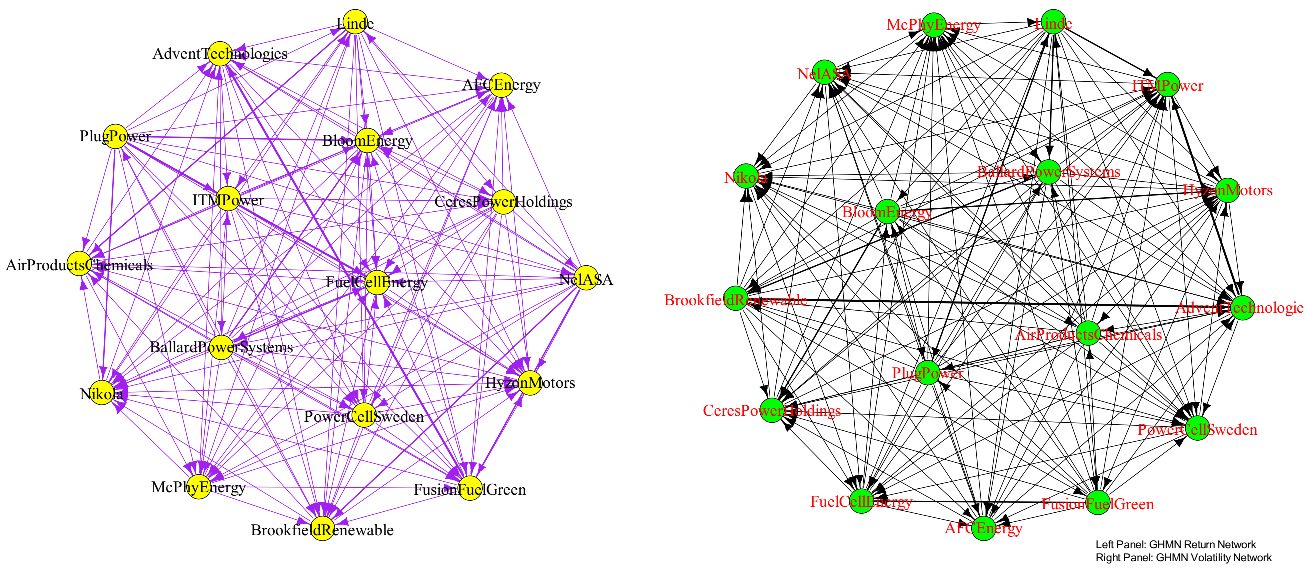

Fig. 4 Overall return and volatility net pairwise connectedness

Did the COVID-19 pandemic alter the network structure?

Generally, the findings show that the COVID-19 pandemic altered the nature of connectedness in the renewable GHMN. Before the outbreak of the pandemic, Power Cell Sweden emerged as the leading net return information transmitter in the renewable GHMN. After the outbreak, Ballard Power System took over the leading return transmitter position from ITM Power. It is vital to state that this is a comparative change of leading positions among the key net return transmitters in the renewable GHMN due to the COVID-19 pandemic. However, the full sample analysis reviews Plug Power as the net return transmitting leader. This is because, the full sample return analysis already revealed that these markets; Plug Power, Power Cell Sweden, and Ballard Power System are key leading net transmitters of return information spillover in the renewable GHMN system. Considering the volatility analyses, Air Product Chemicals remains the leading net volatility information transmitter in the GHMN system before and after the outbreak of the pandemic. However, a full sample analysis showed that Bloom Energy is the leading net volatility information transmitter in the renewable GHMN system. Again, this is not surprising since Air Product Chemicals is the first runner-up, to Bloom Energy, in the full sample analysis. Just like Bloom Energy was the first runner-up to Air Product Chemicals before the coronavirus outbreak. On the other hand, the leading net receiver position for return (volatility) changed from Bloom Energy (Ballard Power Systems) to Brookfield Renewable (Hyzon Motors) due to the COVID-19 pandemic in the Green Hydrogen markets. Again, these are still the leading markets in the GHMN markets. Furthermore, based on the TSC values, which show the strength of the system's connectedness, it is also found that the COVID-19 outbreak improved the strength or level of connection among the renewable GHMN system. This implies the survival of the Green Hydrogen markets after the coronavirus pandemic since markets' connectedness is shown to be vital for markets to survive the pandemic (Chit et al. 2022).

Statistically, based on the average Total System Connectedness (TSC), a difference-in-mean test can be conducted to ascertain the alteration effect of the COVID-19 pandemic on the GHMN system. It is important to mention that these averages equal the average of the GHMN system information inflow and outflow independently. Hence, the test results in Table 5 confirm that the pandemic altered the GHMN system connectedness. In an actual sense, the pandemic

Table 5 Alteration effect of the COVID-19 Pandemic on the GHMN system

	Ex-ante	Ex-post	Welch test	*p* Value
Return	14.98	55.19	7.49***	0.0000
Volatility	14.36	86.23	24.07***	0.0000

***p-value < 0.01; **p value < 0.05; *p value < 0.1

Table 6 GHMN before the COVID-19 outbreak

	1	2	3	4	5	7	8	11	12	13	15	16	17	Inflow
1. AT	95.68	0.10	0.52	1.23	0.12	0.08	0.00	0.01	0.25	0.39	0.67	0.11	0.83	4.32
2. AFCE	0.04	90.43	0.92	2.42	1.15	0.36	0.38	1.25	0.30	0.10	0.01	2.36	0.27	9.57
3. APC	0.33	0.37	61.55	0.63	0.61	0.16	0.03	1.81	29.53	0.61	0.17	2.48	1.72	38.45
4. BPS	0.68	2.08	0.82	77.18	0.29	0.18	1.46	2.12	2.18	0.44	0.13	11.28	1.17	22.82
5. BE	0.01	2.25	0.42	0.82	90.37	0.48	0.32	1.33	0.30	0.09	0.68	2.24	0.68	9.63
7. CPH	0.04	0.08	0.49	0.03	0.17	96.64	0.80	0.69	0.11	0.65	0.13	0.07	0.10	3.36
8. FCE	0.01	0.52	0.01	1.68	0.56	0.12	90.45	1.88	0.26	0.18	0.16	3.35	0.81	9.55
11. ITMP	0.06	0.39	1.70	2.06	1.24	0.23	1.11	85.99	1.19	1.62	0.02	1.08	3.31	14.01
12. LN	0.17	0.21	29.70	1.91	0.03	0.08	0.14	0.95	62.13	1.45	0.58	2.05	0.59	37.87
13. MPE	0.04	0.57	0.51	0.65	0.86	0.04	0.44	0.67	1.36	92.64	0.39	0.95	0.88	7.36
15. NK	0.47	0.02	0.41	0.20	0.63	0.05	0.13	0.12	1.21	0.40	95.65	0.05	0.65	4.35
16. PP	0.09	1.97	2.73	11.08	0.83	0.04	2.87	0.95	2.62	0.78	0.30	75.53	0.22	24.47
17. PCS	0.05	0.02	0.80	0.86	0.10	0.01	0.18	4.89	0.26	0.84	0.57	0.49	90.94	9.06
Outflow	2.00	8.59	39.02	23.57	6.60	1.84	7.85	16.65	39.59	7.54	3.81	26.50	11.24	**194.80**
NC Ret	− 2.31	− 0.98	0.57	0.75	*− 3.04*	− 1.53	− 1.69	***2.64***	1.72	0.19	− 0.54	2.04	2.19	**14.98**
NC Vol	1.28	− 0.62	***7.93***	*− 8.72*	5.14	− 5.35	− 3.69	1.14	− 0.17	− 1.94	4.93	1.66	− 1.60	**14.36**

The 17 × 17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17 × 17 matrix, inflow, outflow, and the NC values are in percentages. All information is from the return analysis except for NC Vol., which is from the volatility analysis. The following markets do not have ex-ante observations: 6. BR, 9. FFG, 10. HM, and 14. NASA. Therefore, are not included in the ex-ante network analysis

enhanced the level of connectedness in the GHMN system substantially. Nonetheless, the detailed findings for the ex-ante and ex-post analyses are presented in the subsequent subsections.

Ex-ante analysis

Table 6 presents the network analysis results using the ex-ante sample. The leading 13 × 13 arrays of information capture the return communications from one market to the other in the renewable GHMN. About four markets are excluded from the ex-ante analysis due to their insufficient level of observed data, necessary for analysis. These markets are Brookfield Renewable, Fusion Fuel Green, Hyzon Motors, and Nel ASA. However, the leading 13 × 13 results in Table 6 are interpreted as flows of return information from the column markets to the row markets, before the coronavirus outbreak. It follows the same explanation from the two preceding tables. The Net Connectedness values for both the ex-ante subsample return (NC Ret.) and volatility (NC Vol.) are reported in Table 6. Therefore, this allows us to concurrently draw some conclusions from both the return and volatility analysis. Before the coronavirus outbreak, the leading return information transmitters in the renewable GHMN system were Air Product Chemicals, Ballard Power System, ITM Power, Linde, and Plug Power. However, ITM Power emerged as the leading net return information transmitter given that it takes lesser return information from the renewable GHMN system relative to the level of return information spilt from the market. Likewise, Air Product Chemicals leads the net volatility information transmitters in the renewable GHMN while Bloom Energy and Ballard Power Systems are the leading net return and volatility receivers in the renewable GHMN system.

Ex-post analysis

The results presented in Table 7 directly follow that of Table 6. Their only difference is that while Table 6 results are from the ex-ante analysis, Table 7 presents the ex-post analysis results. Similarly, the leading 17 × 17 results in Table 7 are interpreted as flows of return information from the column markets to the row markets, during the COVID-19 periods. The Net Connectedness values for both the ex-post subsample return (NC Ret.) and volatility (NC Vol.) are reported in Table 7. Therefore, this allows us to simultaneously make inferences for both the return and volatility ex-post periods. During the coronavirus period, the leading return information transmitters in the renewable GHMN system are Ballard Power System, Ceres Power Holding, Fuel

Table 7 GHMN in the COVID-19 period

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Inflow
1. AT	89.58	0.36	0.08	0.62	0.80	0.43	0.60	1.04	0.40	0.86	0.37	0.12	0.27	2.78	0.38	0.63	0.68	10.42
2. AFCE	0.22	47.51	1.09	3.98	1.81	0.89	8.84	3.10	0.81	0.35	9.89	2.08	4.93	4.73	0.06	2.34	7.39	52.49
3. APC	0.23	0.98	47.43	4.41	2.04	0.46	2.24	2.75	0.05	0.09	2.47	28.81	2.19	0.12	0.42	2.93	2.37	52.57
4. BPS	0.52	2.40	2.15	25.19	7.93	2.14	5.02	11.13	2.69	1.73	6.17	3.36	3.55	4.24	1.57	12.99	7.21	74.81
5. BE	0.45	3.36	1.58	11.57	36.73	1.55	4.41	8.12	1.83	0.99	3.07	3.07	3.20	3.11	1.70	11.04	4.21	63.27
6. BR	0.87	1.62	0.43	4.85	2.43	53.64	4.55	2.85	3.35	1.98	2.64	1.50	2.47	6.72	0.66	5.69	3.75	46.36
7. CPH	0.24	5.95	1.60	5.56	2.79	2.43	31.25	2.75	1.51	0.87	12.99	3.38	5.62	7.37	0.49	4.31	10.90	68.75
8. FCE	0.57	2.12	1.71	14.29	7.02	1.28	3.13	31.79	2.96	1.74	4.05	1.90	2.83	3.35	1.76	14.49	5.01	68.21
9. FFG	1.06	1.31	0.10	4.99	2.12	2.78	2.01	4.78	55.48	5.30	1.47	0.30	1.52	7.93	1.35	5.73	1.78	44.52
10. HM	0.73	0.57	0.08	4.34	1.70	2.33	1.79	3.42	6.15	62.63	1.04	0.82	0.95	5.55	1.70	3.64	2.55	37.37
11. ITMP	0.24	6.93	1.57	7.25	2.48	1.40	12.62	3.83	1.07	0.50	30.79	2.43	5.29	5.37	0.29	4.37	13.58	69.21
12. LN	0.08	1.98	24.53	5.52	3.30	1.14	4.29	2.38	0.24	0.42	3.33	40.81	3.37	0.75	0.33	3.81	3.71	59.19
13. MPE	0.05	4.36	2.06	5.23	2.87	1.82	7.53	3.40	1.32	0.61	7.62	3.61	42.38	4.28	1.04	3.52	8.30	57.62
14. NASA	1.37	3.86	0.06	5.09	2.08	4.03	8.66	3.44	5.03	3.19	6.50	0.68	3.76	38.14	1.04	5.21	7.88	61.86
15. NK	0.39	0.57	0.09	4.36	3.22	0.82	1.08	3.87	1.77	1.98	0.45	0.03	1.69	2.13	70.50	6.62	0.41	29.50
16. PP	0.41	1.56	1.49	14.38	8.39	2.80	4.14	12.63	3.20	1.61	4.03	2.57	2.73	4.38	2.61	27.82	5.24	72.18
17. PCS	0.34	4.97	1.74	8.00	2.74	1.76	10.48	4.01	1.15	0.95	13.56	2.97	5.89	6.24	0.18	4.95	30.08	69.92
Outflow	7.77	42.91	40.37	104.44	53.73	28.07	81.38	73.50	33.53	23.17	79.64	57.62	50.25	69.03	15.60	92.27	84.98	**938.25**
NC Ret	−2.65	−9.58	−12.20	***29.64***	−9.54	*−18.29*	12.63	5.29	−10.99	−14.20	10.43	−1.57	−7.37	7.17	−13.90	20.08	15.05	**55.19**
NC Vol	10.61	−3.81	***64.71***	−3.69	7.48	−10.50	−25.94	−1.82	49.59	*−43.27*	−10.43	−5.33	−14.18	11.65	−13.12	25.52	−37.46	**86.23**

The 17×17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17×17 matrix, inflow, outflow, and the NC values are in percentages. All information is from the return analysis except for NC Vol., which is from the volatility analysis

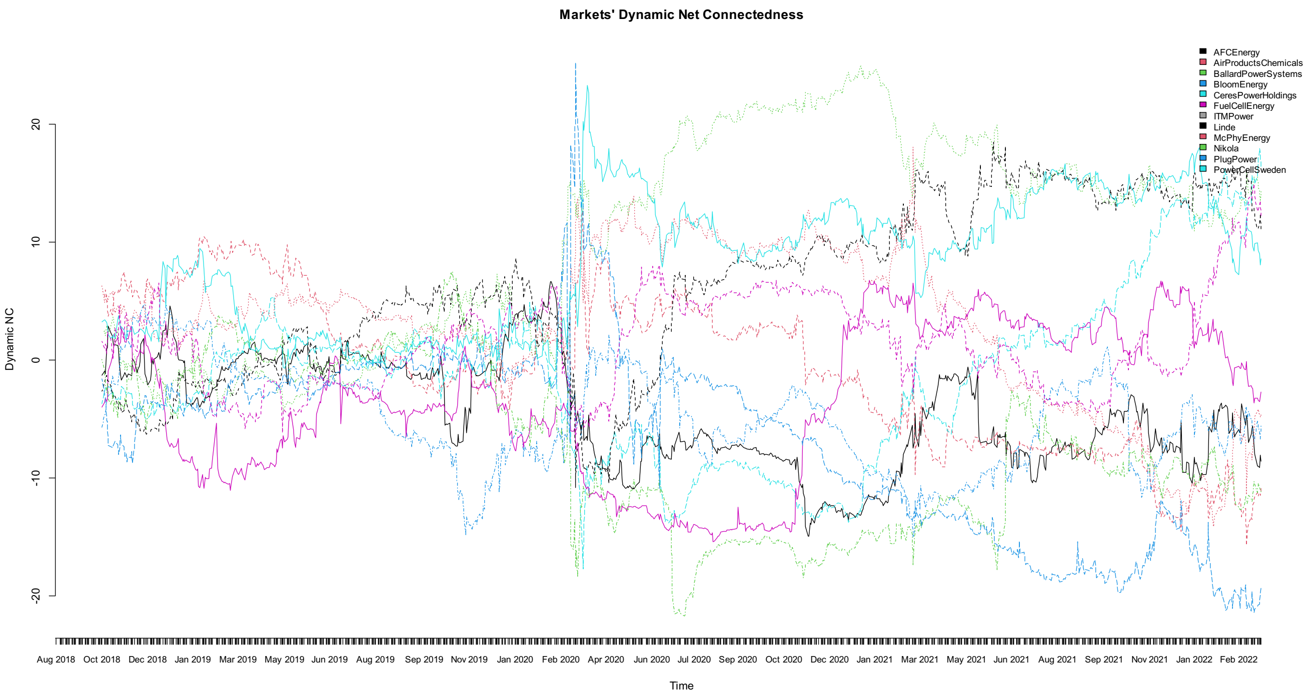

Fig. 5 GHMN dynamic behaviours

Cell Energy, ITM Power, Linde, Nel ASA, Power Cell Sweden, and Plug Power. However, Ballard Power Systems (Brookfield Renewable) emerged as the leading net return information transmitter (receiver) given that it takes lesser (more) return information from the renewable GHMN system relative to the level of return information spilt from the market. Likewise, Air Product Chemicals (Hyzon Motors) leads the net volatility information transmitters (receivers) in the renewable GHMN system.

Dynamic analysis of returns and volatility

It is interesting to also show the development of the net transmitter and receiver positions in the renewable GHMN system. This informs the need for a dynamic analysis over a static analysis. A 250-rolling window is used to compute the NC positions of the markets in the network. Advent Technologies, Brookfield Renewable, Fusion Fuel Green, Hyzon Motors, and Nel ASA were also removed from this dynamic analysis due to their missing observations, necessary for parameter estimations. As a result, the dynamic NC plotted in Fig. 5 is that of the remaining markets in the renewable GHMN system. Firstly, it can be observed that the renewable green hydrogen markets' variability is low as these markets are closely associated. That is to say that their net connectedness positions were closely behaved and related. But after the outbreak of the coronavirus, their variability increased and they varied relatively farther from each other. However, the net return information transmitters in Table 3 remain the renewable GHMN's dynamic return information transmitters. This is also the case as the static net return information receivers remain the dynamic net return information receivers. The story of the dynamic net volatility spillover is not different from that of the static behaviour.

How sensitive are these results?

Based on the model definition of the GHMN information variance contribution of market $-j$ to market $-i$ in equation (5). The market information spillover depends on the n-steps ahead horizon, H. The choice of H in network modelling is arbitrary. As such, any steps-ahead horizon can be selected. However, the network connectedness results are supposed to be insensitive and not respond substantially to the choice of n-steps ahead horizon. For all the analysis, the n-steps ahead horizon selected is 10. However, n-steps horizons one (1) to hundred (100) are used to compute a hundred Net Connected (NC) for all the seventeen (17) renewable green hydrogen markets in the network system. This is done using the returns full sample. From these NC values, the density plots are presented in Fig. 6. It is expected that the net positions of the markets are not sensitive to any choice of n-steps ahead horizon (Okorie and Lin 2022). Therefore, the NC results in Table 3 are compared to the values with the highest density in Fig. 6, for each of the 17 markets. The results confirm that our main analysis results are not sensible, in any way, to the arbitrary choice

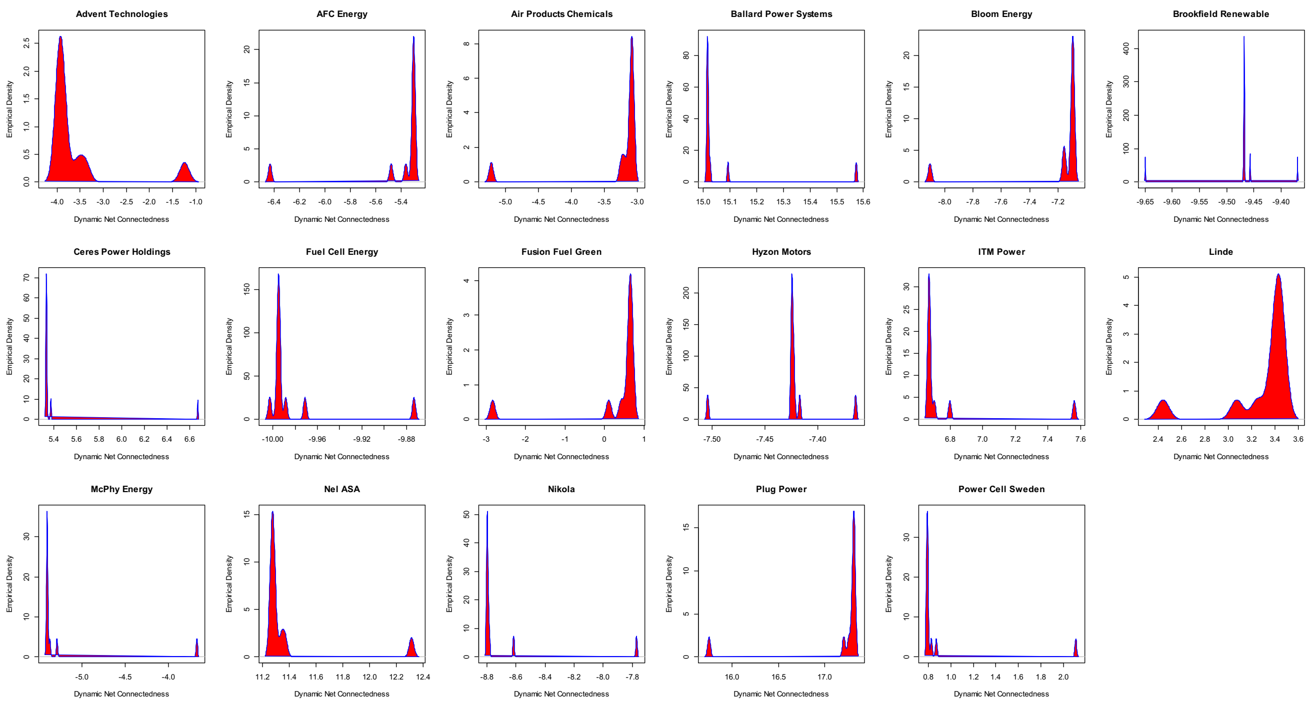

Fig. 6 Markets net position sensitivity tests

of the n-steps ahead horizon. That is to say that no matter the choice of the n-steps ahead horizon, the net return information transmitters or receivers in the GHMN system, as shown in Table 3, remain the same. This is also the case using the full volatility sample.

Can we rely on these findings?

In this subsection, efforts are made to validate our findings and results. As a result, we employed the alternative normalization scheme for network modelling techniques, proposed by Caloia et al. (2019). it postulates that it performs better than the original row or column normalization adopted in the original network modelling techniques proposed by Diebold and Yilmaz (2012). Instead, the maximum scalar normalization scheme is proposed to better show the values and positions of the markets that are net transmitters or receivers of information in the renewable GHMN system. As such, the true leading markets can be identified (Okorie and Lin 2022). Hence, the results and findings are validated using this alternative network modelling normalization scheme. In other words, this subsection provides robust results to validate the reliability of the findings in this study.

To this end, the full sample (return and volatility) and subsample (ex-ante and ex-post) analyses are performed for the second time using the scaler normalization scheme (Okorie and Lin 2022; Caloia et al. 2019). The robustness of full sample return and volatility results are presented in Table 8 and Table 9 respectively. Based on the results in Table 8 and Table 9, the conclusion that Plug Power is the leading net return information transmitter in the GHMN system remains robust and reliable since it is the same conclusion using the alternative maximum scaler normalization scheme technique. Conversely, both schemes equally confirm that both Brookfield Renewable and Fuel Cell Energy are the leading net return information receivers in the renewable GHMN system. Another super interesting fact is that all the identified net return information transmitters and receivers, according to the row/column normalization scheme (see Table 3), remain or occupy the same net return transmitter and receiver positions using the maximum scaler normalization scheme (see Table 8). Considering the full sample volatility analysis, the robustness results in Table 9 also confirm that Bloom Energy is the leading net volatility information transmitter in the renewable GHMN system using both normalization schemes. Similarly, Nikola is also identified by both normalization schemes as the leading net volatility receiver in the renewable GHMN system. Therefore, the findings of this study are reliable. Yes, we can rely on these findings and we should (Table 10).

Taking a step further to consider the robustness of the subsamples analysis (ex-ante and ex-post), similar comparisons are made between the results of the row/column normalization scheme and the maximum scaler normalization scheme. Both normalization schemes on the ex-ante coronavirus pandemic subsample confirm that Air Product Chemicals leads the net

Table 8 Robust full sample return network

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Inflow
1. AT	84.50	0.17	0.32	0.42	0.57	0.57	0.34	0.30	4.14	0.65	0.20	0.87	0.59	1.77	0.49	0.59	0.20	12.20
2. AFCE	0.15	62.33	0.96	3.18	1.69	0.65	4.21	0.80	0.66	0.44	4.51	1.35	2.12	2.63	0.04	1.98	2.87	28.25
3. APC	0.17	0.97	50.37	2.78	1.78	0.41	1.77	0.82	0.06	0.07	1.97	28.34	1.61	0.11	0.30	2.91	1.59	45.66
4. BPS	0.55	2.17	1.88	37.92	5.64	2.19	3.58	4.86	2.74	1.61	5.62	3.25	2.91	3.78	1.59	14.11	4.69	61.18
5. BE	0.57	2.95	1.38	7.79	52.12	1.59	3.61	3.24	1.88	0.93	2.98	2.22	2.39	2.76	1.73	9.22	2.66	47.88
6. BR	0.98	0.95	0.38	3.37	1.73	59.48	4.04	0.81	3.90	2.24	2.12	1.47	2.43	7.85	0.79	4.29	2.36	39.71
7. CPH	0.53	2.97	2.29	3.46	2.41	2.91	42.84	0.91	1.73	1.00	10.08	2.79	5.07	7.76	0.73	3.20	6.59	54.44
8. FCE	0.35	1.45	0.87	7.69	3.56	0.70	1.18	59.15	1.88	1.09	3.00	1.02	1.19	1.69	0.85	9.71	2.32	38.54
9. FFG	0.88	0.60	0.14	3.37	1.62	2.73	1.73	1.60	54.71	5.53	1.26	0.40	1.54	8.09	1.49	4.35	1.08	36.42
10. HM	0.81	0.29	0.05	2.80	1.27	2.63	1.48	1.21	6.34	66.19	0.80	0.52	1.14	5.47	2.00	2.52	1.31	30.63
11. ITMP	0.31	3.45	1.94	5.99	2.42	1.78	9.79	2.09	1.31	0.50	41.85	2.52	4.83	5.03	0.34	3.75	10.06	56.12
12. LN	0.08	1.20	26.24	3.93	1.96	1.07	2.53	0.89	0.30	0.34	2.44	45.73	2.53	0.56	0.26	3.33	1.99	49.66
13. MPE	0.12	2.31	2.61	3.83	2.24	1.85	6.18	1.13	1.54	0.67	6.66	3.52	51.44	4.33	1.05	3.34	5.58	46.96
14. NASA	1.56	1.80	0.05	3.31	1.57	4.66	7.43	1.09	6.07	3.51	4.94	0.52	3.50	42.66	1.12	4.02	4.56	49.72
15. NK	0.42	0.31	0.17	3.34	2.53	0.89	1.13	1.32	2.22	2.21	0.73	0.12	1.47	2.06	72.87	5.01	0.32	24.24
16. PP	0.46	1.37	1.72	13.88	6.66	2.83	2.92	6.28	3.39	1.46	3.22	2.62	2.50	3.96	2.64	38.03	2.86	58.78
17. PCS	0.38	2.18	1.73	4.98	1.74	1.80	7.00	1.20	1.09	0.76	10.97	2.08	4.92	4.92	0.23	3.42	45.70	49.41
Outflow	8.31	25.15	42.73	74.10	39.40	29.27	58.93	28.56	39.26	23.03	61.50	53.61	40.72	62.79	15.63	75.75	51.05	**729.78**
NC	−3.89	−3.10	−2.93	12.93	−8.48	*−10.43*	4.49	−9.99	2.84	−7.60	5.38	3.95	−6.23	13.06	−8.61	***16.97***	1.64	**42.93**

The 17×17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17×17 matrix, inflow, outflow, and the NC values are in percentages

Table 9 Robust full sample volatility network

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Inflow
1. AT	62.21	0.04	0.16	2.35	0.51	7.94	0.03	0.08	4.03	2.80	1.79	0.93	0.44	5.45	0.24	2.39	0.74	29.92
2. AFCE	0.03	74.90	0.18	0.48	0.03	0.03	4.97	0.03	0.01	0.02	0.11	0.52	0.10	0.01	0.04	0.83	0.22	7.60
3. APC	0.38	0.08	45.92	0.90	16.23	0.18	0.04	0.04	0.13	0.13	0.51	31.01	0.65	0.20	0.16	2.57	0.87	54.08
4. BPS	1.18	0.05	4.70	47.06	4.00	2.84	0.21	0.24	0.38	1.21	2.68	2.80	2.45	2.39	0.30	11.20	2.24	38.89
5. BE	0.17	0.02	5.89	0.93	35.38	0.72	0.03	0.27	0.36	0.11	0.27	8.31	0.46	0.32	0.13	2.22	0.52	20.75
6. BR	2.65	0.01	0.44	3.61	1.56	51.88	0.01	0.02	0.53	1.28	1.93	0.83	0.43	4.28	0.07	4.28	0.31	22.23
7. CPH	0.01	5.60	0.12	0.32	0.07	0.02	76.93	0.01	0.01	0.00	0.18	0.30	0.02	0.02	0.01	0.13	0.10	6.92
8. FCE	0.15	0.01	0.22	0.31	0.29	0.05	0.00	77.54	0.03	0.03	0.24	0.04	0.07	0.06	0.07	0.63	1.62	3.83
9. FFG	1.23	0.01	0.11	0.63	0.52	1.22	0.01	0.01	76.88	1.59	0.51	0.29	0.11	3.17	0.18	0.62	0.27	10.48
10. HM	2.50	0.03	0.06	2.84	0.40	4.65	0.01	0.03	0.91	65.24	1.65	0.36	0.26	1.42	0.11	3.72	0.39	19.36
11. ITMP	2.51	0.29	3.35	3.39	3.93	3.74	0.14	1.97	0.92	1.80	54.11	3.50	1.09	2.41	3.85	3.03	5.56	41.49
12. LN	0.25	0.10	26.03	0.76	10.27	0.27	0.05	0.09	0.05	0.08	0.79	36.66	0.63	0.17	0.15	2.47	1.08	43.22
13. MPE	0.41	0.19	0.72	0.67	1.83	3.11	0.03	0.09	0.20	0.31	1.65	0.37	61.12	0.39	0.78	1.91	1.55	14.21
14. NASA	1.31	0.02	0.61	2.73	0.69	4.78	0.02	0.04	3.64	1.88	2.91	0.66	0.18	53.48	0.17	2.51	0.82	22.95
15. NK	1.10	0.21	0.62	1.09	1.35	0.16	0.02	0.06	0.38	0.21	1.68	0.28	14.88	0.40	73.55	0.57	0.53	23.52
16. PP	0.76	0.31	5.94	9.41	3.93	3.46	0.05	0.09	0.59	1.49	1.86	2.82	0.46	2.45	0.26	41.05	1.71	35.58
17. PCS	1.04	0.20	6.47	3.31	4.08	0.88	0.05	0.14	0.36	0.26	5.74	3.20	1.28	1.09	0.48	5.47	59.29	34.06
Outflow	15.69	7.17	55.65	33.72	49.69	34.05	5.65	3.20	12.52	13.20	24.50	56.22	23.52	24.23	6.98	44.55	18.51	**429.06**
NC	− 14.23	− 0.43	1.57	− 5.17	***28.94***	11.82	− 1.28	− 0.63	2.05	− 6.16	*− 16.99*	13.01	9.32	1.27	− 16.53	8.97	− 15.54	**25.24**

The 17 × 17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17 × 17 matrix, inflow, outflow, and the NC values are in percentages

Table 10 Robust GHMN before the COVID-19 outbreak

	1	2	3	4	5	7	8	11	12	13	15	16	17	Inflow
1. AT	95.06	0.10	0.52	1.22	0.12	0.08	0.00	0.01	0.25	0.39	0.67	0.11	0.82	4.29
2. AFCE	0.04	88.03	0.89	2.35	1.12	0.35	0.37	1.22	0.30	0.09	0.01	2.30	0.27	9.32
3. APC	0.33	0.37	61.29	0.62	0.61	0.16	0.03	1.80	29.40	0.61	0.17	2.47	1.71	38.28
4. BPS	0.66	2.02	0.79	75.01	0.28	0.17	1.42	2.06	2.12	0.42	0.12	10.97	1.14	22.18
5. BE	0.01	2.25	0.42	0.82	90.37	0.48	0.32	1.33	0.30	0.09	0.68	2.24	0.68	9.63
7. CPH	0.04	0.08	0.48	0.03	0.17	95.30	0.79	0.68	0.11	0.64	0.13	0.07	0.10	3.32
8. FCE	0.01	0.51	0.01	1.65	0.55	0.12	89.00	1.85	0.26	0.18	0.16	3.29	0.80	9.39
11. ITMP	0.06	0.37	1.60	1.94	1.16	0.21	1.04	80.82	1.12	1.52	0.02	1.01	3.11	13.17
12. LN	0.17	0.21	29.09	1.87	0.03	0.08	0.14	0.93	60.87	1.42	0.57	2.01	0.58	37.09
13. MPE	0.03	0.54	0.48	0.62	0.83	0.04	0.42	0.64	1.30	88.82	0.37	0.91	0.85	7.05
15. NK	0.46	0.02	0.40	0.20	0.62	0.05	0.13	0.11	1.18	0.39	93.15	0.05	0.63	4.23
16. PP	0.08	1.90	2.62	10.67	0.80	0.04	2.76	0.91	2.52	0.75	0.29	72.73	0.21	23.56
17. PCS	0.05	0.02	0.75	0.81	0.10	0.01	0.17	4.60	0.25	0.79	0.53	0.46	85.64	8.53
Outflow	1.95	8.39	38.07	22.81	6.38	1.80	7.58	16.14	39.12	7.30	3.72	25.88	10.90	**190.04**
NC Ret	− 2.33	− 0.92	− 0.21	0.64	*− 3.25*	− 1.52	− 1.81	***2.97***	2.02	0.24	− 0.51	2.32	2.38	**14.62**
NC Vol	1.16	0.10	***9.28***	*− 10.02*	4.44	− 5.29	− 3.46	1.40	− 1.68	− 1.69	5.34	1.99	− 1.57	**13.22**

The 17 × 17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17 × 17 matrix, inflow, outflow, and the NC values are in percentages. All information is from the return analysis except for NC Vol., which is from the volatility analysis. The following markets do not have ex-ante observations: 6. BR, 9. FFG, 10. HM, and 14. NASA. Therefore, are not included in the ex-ante network analysis

Table 11 Robust GHMN in the COVID-19 period

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Inflow
1. AT	80.31	0.32	0.07	0.55	0.72	0.38	0.54	0.93	0.36	0.77	0.33	0.10	0.24	2.49	0.34	0.56	0.61	9.34
2. AFCE	0.19	41.85	0.96	3.50	1.60	0.79	7.78	2.73	0.72	0.31	8.71	1.83	4.34	4.16	0.05	2.06	6.51	46.25
3. APC	0.22	0.94	45.70	4.25	1.97	0.44	2.16	2.65	0.05	0.09	2.38	27.75	2.11	0.11	0.40	2.83	2.28	50.65
4. BPS	0.50	2.31	2.07	24.30	7.65	2.06	4.84	10.74	2.59	1.67	5.95	3.24	3.42	4.09	1.52	12.53	6.96	72.15
5. BE	0.45	3.36	1.58	11.57	36.73	1.55	4.41	8.12	1.83	0.99	3.07	3.07	3.20	3.11	1.70	11.04	4.21	63.27
6. BR	0.86	1.61	0.43	4.81	2.41	53.21	4.52	2.83	3.32	1.96	2.61	1.49	2.45	6.66	0.66	5.64	3.72	45.98
7. CPH	0.23	5.48	1.47	5.13	2.57	2.25	28.83	2.53	1.39	0.80	11.98	3.12	5.18	6.80	0.45	3.97	10.06	63.42
8. FCE	0.54	2.03	1.64	13.66	6.71	1.22	2.99	30.40	2.83	1.66	3.88	1.82	2.71	3.20	1.68	13.86	4.79	65.22
9. FFG	0.96	1.19	0.09	4.55	1.93	2.53	1.83	4.35	50.56	4.83	1.34	0.27	1.38	7.22	1.23	5.22	1.62	40.57
10. HM	0.70	0.54	0.08	4.13	1.62	2.22	1.70	3.25	5.85	59.54	0.99	0.78	0.91	5.28	1.62	3.46	2.42	35.52
11. ITMP	0.23	6.52	1.48	6.81	2.33	1.31	11.86	3.60	1.00	0.47	28.95	2.29	4.97	5.05	0.27	4.10	12.77	65.06
12. LN	0.07	1.86	23.01	5.17	3.10	1.06	4.03	2.23	0.23	0.39	3.13	38.28	3.16	0.70	0.31	3.57	3.48	55.52
13. MPE	0.05	3.99	1.89	4.79	2.63	1.67	6.89	3.11	1.21	0.55	6.97	3.31	38.78	3.91	0.95	3.22	7.60	52.73
14. NASA	1.21	3.41	0.05	4.49	1.83	3.56	7.65	3.04	4.44	2.82	5.75	0.60	3.32	33.71	0.92	4.60	6.97	54.66
15. NK	0.37	0.54	0.08	4.07	3.00	0.77	1.01	3.61	1.65	1.85	0.42	0.03	1.57	1.99	65.71	6.17	0.39	27.49
16. PP	0.39	1.49	1.43	13.78	8.03	2.69	3.96	12.09	3.07	1.54	3.86	2.47	2.62	4.19	2.50	26.64	5.02	69.15
17. PCS	0.31	4.56	1.59	7.33	2.51	1.62	9.61	3.68	1.06	0.87	12.43	2.72	5.40	5.72	0.17	4.54	27.57	64.11
Outflow	7.28	40.16	37.93	98.61	50.62	26.12	75.78	69.50	31.59	21.58	73.79	54.88	46.99	64.70	14.78	87.39	79.39	881.10
NC Ret	−2.06	−6.08	−12.72	***26.46***	−12.65	*−19.86*	12.36	4.28	−8.98	−13.94	8.73	−0.64	−5.75	10.04	−12.71	18.24	15.29	**51.83**
NC Vol	19.16	3.02	3.38	9.10	−7.24	−8.52	−8.97	16.13	43.47	−15.85	8.02	*−64.87*	13.77	26.04	−3.56	***30.02***	−63.11	**30.45**

The 17 × 17 matrix represents the flow of information or information spillovers from one of the renewable green hydrogen markets to the other in the Network. The last column and row represent the Information Inflow (II) and Information Outflow (IO) in the Green Hydrogen Markets Networks (GHMN). The Net Connectedness (NC) row shows the overall position of each market in the GHMN as to whether or not it is a net transmitter or receiver in the Network. Finally, the overall average (sum) Total System Connectedness (TSC) of information in the GHMN is the last element on the NC-row (Outflow-row) and column-inflow. They are also in bold. The diagonal elements of the 17 × 17 matrix, inflow, outflow, and the NC values are in percentages. All information is from the return analysis except for NC Vol., which is from the volatility analysis volatility information transmitter in the renewable GHMN system while the leading net volatility information remains Ballard Power Systems. For the ex-ante return subsample analysis, Bloom Energy maintains the leading net return information receiving market in the renewable GHMN system while ITM Power is the ex-ante leading net return information transmitter in the renewable GHMN system. These also confirm that the findings are very robust and thus, reliable and dependable. Examing the ex-post subsample analysis using the maximum scaler normalization scheme also confirms that Ballard Power System and Brookfield Renewable are the leading COVID-19 period return information transmitters and receivers in the renewable GHMN system respectively. This is the same result found using the original maximum row/column normalization scheme. However, both normalization schemes identify different net-leading volatility information transmitters and receivers in the renewable GHMN system. This could also be attributed to the altercations of the GHMN connectedness nature by the coronavirus pandemic. However, the leading net information transmitters are jointly identified by both normalization schemes (Table 11).

Concerning existing studies, it is important to highlight that this study is the first of its kind in the green hydrogen industry. This is the basic difference between this study and other related existing studies. Hence, this study identifies the level of connectedness and information spillover existing in the green hydrogen industry, identifies the key or driving markets in the industry and presents evidence of alterations in the industry due to the coronavirus outbreak. Conversely, similarities exist between this study and existing related studies from other markets and/or industries. This study shows that the COVID-19 pandemic altered the level of connectedness, inherent in the green hydrogen industry just like other markets like the stock market (Rehman et al. 2022; Okorie and Lin 2021), cryptocurrency markets (Okorie and Lin 2023), carbon emissions and the environment (Yuwen et al. 2022; Ray et al. 2022), etc. Secondly, like other related studies (Okorie and Lin 2022; Mensi et al. 2022; Qian et al. 2022; Okorie 2021; Diebold and Yilmaz 2012; Kang and Lee 2019), the leading net information transmitters and receivers are identified for the green hydrogen industry. Also, following Diebold and Yilmaz (2012) a sensitivity analysis on the choice of n-steps ahead horizons for the analysis is conducted and presented in "How Sensitive are these Results?"Section while following Caloia et al. (2019) and Okorie and Lin (2022), "Can we rely on these findings?"Section presents the robustness and reliability analysis using an alternative normalization scheme.

Conclusions and implications

This study embarks on studying the nature of connectedness in the renewable GreenHydrogen Market Network (GHMN) system given the rising global attention towardss the market. As such, the network modelling techniques proposed by Diebold and Yilmaz (2012) and the alternative normalization scheme proposed by Caloia et al. (2019) are applied. The five (5) network connectedness measures applied are the Information Inflow (II), Information Outflow (IO), Net Connectedness (NC), Net Pairwise Connectedness (NPC) and Total System Connectedness (TSC). Seventeen (17) renewable green hydrogen markets are sampled for the full sample and subsample analyses due to the outbreak of the coronavirus pandemic. These analyses are on the markets' returns and unconditional volatilities. The models identified the net information transmitters and receivers of return and volatility in the renewable GHMN system. Also, according to the STC measures, there is a moderate degree of connection in the GHMN system, which improved after the outbreak of the coronavirus. Other shreds of evidence confirm that the COVID-19 pandemic altered the nature of connectedness in the GHMN system. Based on these findings, the following recommendations are made:

1. After the coronavirus outbreak, investments in the renewable green hydrogen markets like Plug Power, Bloom Energy, etc., are highly recommendable given their improved levels of system connectedness during the COVID-19 period. This intuitively implies more development, variability, and flow of information among the markets in this green hydrogen system. More connectedness implies that neither of the markets is operating in isolation but is collectively driven by the same market information for profit maximization and risk minimization.
2. The identified leading information transmitters in the renewable green hydrogen markets are the key indicators or benchmark markets to watch out for. These leading companies include Plug Power, Bloom Energy, etc. This is because they play vital roles in the directional movement of the overall network market system. They are the leaders of the flow of information in the GHMN system. As such, when there is any good news or bad news emanating from within this system, it is expected to be depicted by these leading markets before the rest of the markets in the system.
3. For minimizing green hydrogen portfolio investment risk purposes, the identified leading volatility markets in the renewable green hydrogen markets systems, such as Bloom Energy, are key and vital. This is because they are found to dictate and inform the risk movement of the whole market system. In other words, while the leading return drivers are vital for return maximization, the lead-

ing volatility drivers are key for risk minimization. The importance of these leading drivers in the investment portfolio cannot be undermined. Also, to highlight this importance, Okorie and Lin (2022) used ‘Givers never lack’ while Diebold and Yilmaz (2012) used ‘It’s better to give than to receive in the titles of their studies.

4. Aside from forming green hydrogen investment portfolios using a substantial amount of these leading markets’ stocks. It is also important to pay attention to the news (good and bad) about these leading markets, such as Plug Power and Bloom Energy, to take quick actions that are well-informed and formulated. Such actions may be for portfolio adjustments, reformation, and formation.
5. Given good or bad news scenarios, spontaneous actions should be taken on the investment portfolios formed using the leading net information receivers such as Fuel Cell Energy, Brookfield Renewable, etc. This is because they are relatively prone to the overall market's performance since they accept more information from the system relative to what they give back to the system.
6. The overall system total connectedness measure also suggests that investors, both private and institutional investors, should consider the green hydrogen stocks given their developments and promises of improved performances in the forms of their connectivity over time. Plug Power, Bloom Energy, etc. stocks are vital in optimizing an investment portfolio in this industry. Generally, an in-depth understanding of these markets’ connectivity measures is essential for investment portfolio formation, risk management, and optimization.
7. The green hydrogen industry is not immune to external shocks just like several other industries. This study has presented evidence of an alteration in the leading net information transmitter and receiver of the industry due to the outbreak of the coronavirus pandemic. As such, both the markets and investors need to be proactive to make adjustments and policies to mitigate losses and risks given external shocks or information.
8. Based on the results, it is clear that no single market is powerful enough to maintain a leading net transmitter position for both return and volatility, before and after the outbreak of the coronavirus pandemic. This suggests that there are opportunities and room for every market in the green hydrogen industry to strengthen, grow and develop through the implementation of strategic and market-specific policies that are targeted to better position the market in the industry, gain more market share, and increase its profitability as risks are minimized.

At this stage, a few study limitations are highlighted. The main limitation of this study is the availability of data for most of the green hydrogen energy markets. There are over two hundred existing hydrogen energy markets but the data on these markets are rarely available within the selected periods. This played a major role and limited the sample size and market choice of this study. Secondly, the scope of this study is limited to the green hydrogen markets. As suggestions for future research directions, other kinds of hydrogen markets could be investigated and explored. This will be a worthy study and will further broaden the understanding of the entire hydrogen industry. However, in a broader study of the entire hydrogen industry, including both green and other hydrogen markets, there is likely to be little or no potential impact on the results of this study. This is mainly because, of all the kinds of hydrogen markets, green hydrogen dominates the industry and has enjoyed relatively more attention and investments than the other hydrogen markets. As such, it is expected that green hydrogen remains dominant in the hydrogen industry and this will have little or nontrivial impacts on the results of this study. Secondly, it will be interesting to investigate the outbreak of the Russia-Ukraine war on both the green hydrogen and other hydrogen industries. Similarly, this may have potential impacts on the leading net information transmitter and receiver in the green hydrogen market given the evidence that exogenous shocks, like the coronavirus pandemic, altered the nature and connectedness of the green hydrogen markets. Finally, longer sample periods for the ex-ante and ex-post event study on exogenous impacts on the GHMN system can be investigated since more data is observed after the completion of this study. It is expected to have nontrivial potential impacts on the results of this study. This is based on the reliability, sensitivity and robustness of the study’s results.

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Declarations

Conflict of 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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Authors and Affiliations

David Iheke Okorie[1,2,3,4]

✉ David Iheke Okorie
okorie.davidiheke@gmail.com

1 Hangzhou City University (HZCU), Hangzhou, China

2 Waikato Management School, School of Accounting, Finance and Economics, University of Waikato, Hamilton, New Zealand

3 Centre for the Study of the Economies of Africa (CSEA), Abuja, Nigeria

4 SD Consulting Agency (SCA), Lagos, Nigeria