



# Fintech: A Conduit for sustainability and renewable energy? Evidence from $R^2$ connectedness analysis

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## ABSTRACT

This study explores the evolving relationship between financial technologies (Fintech), sustainability initiatives, and the renewable energy sector. We utilize a novel  $R^2$  decomposed connectedness methodology, a significant leap from traditional analyses that mainly focus on the immediate effects, thereby missing out on the nuanced, delayed interactions that develop over time. This approach enables us to encompass both contemporaneous and lagged spillover effects, making it especially apt to examine this intricate system's dynamic interconnections. Covering the period from November 30, 2016, to November 14, 2023—marked by rapid technological advancements and an increasing global focus on sustainability—we uncover the Renewable Energy Efficiency Index's critical influence in driving fluctuations within this network. This finding is crucial amidst the current global shift towards sustainable energy practices and the vital role of technology in this transition. We note significant changes in how Fintech, sustainability, and renewable energy sectors interact over time, often in response to major global events. This observation indicates a particular vulnerability to external disturbances while presenting opportunities for strategic adaptability and creativity when confronted with these obstacles. Our research provides critical insights for readers interested in these interactions' economic and policy ramifications. For instance, the central importance of the Renewable Energy Efficiency Index emerges as a practical indicator for stakeholders aiming to steer their strategies towards more sustainable outcomes. Additionally, the variations in sector connectivity underscore the necessity for adaptable strategies amidst global uncertainties and pave the way for future investigations into the causes behind these shifts. By offering concrete recommendations, this study equips policymakers, investors, and industry leaders with the knowledge to harness the synergies between Fintech, sustainability, and renewable energy.

## 1. Introduction

In the contemporary discourse on sustainable development, the symbiosis between technological innovation within the financial domain—colloquially termed 'Fintech'—and the imperatives of environmental sustainability has garnered unprecedented attention. This scholarly manuscript ventures into the intricate web of connections that bind Fintech, sustainability metrics, and the burgeoning sphere of renewable energy markets against the canvas of a global crusade towards harmonizing economic progress with ecological prudence. As the

international community grapples with the dual challenges of fostering economic dynamism and upholding environmental integrity, the transformative potential of Fintech in propelling green finance and invigorating investments in renewable energy sources stands at the vanguard of academic and policy deliberations.

The interplay between financial technologies (FinTech), sustainability, and the renewable energy sector offers a rich tapestry for analysis, grounded in the confluence of the Theory of Financial Technology Adoption and the Diffusion of Innovations Theory. The former, through frameworks such as the Theory of Planned Behavior and the Unified

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Theory of Acceptance and Use of Technology, provides a nuanced understanding of the factors that propel the embracement of FinTech services. Key to this theory is the role of subjective norms, attitudes, and perceived behavioral control in shaping the adoption of FinTech innovations (Irimia-Diéguez et al., 2023; Xie et al., 2021). This approach is expanded by incorporating perceived value and risk constructs, which further elucidate individual and organizational inclinations toward FinTech (Alkhwaldi et al., 2022). Concurrently, the Diffusion of Innovations Theory elucidates how new ideas and technologies permeate various societal segments, underscored by the critical function of social networks in enabling this diffusion. The theory's breadth, incorporating insights from multiple disciplines, offers a comprehensive lens to view the spread of innovative practices, including those within the renewable energy domain (Gondal, 2023; Lopez-Merino and Rouchier, 2022). The theoretical framework intersects notably in renewable energy, where financial incentives are spotlighted as a pivotal adoption driver (Simpson and Clifton, 2017). This intersection suggests a synergistic potential between FinTech mechanisms and sustainability efforts within the renewable energy sphere, where financial innovations could underpin the broader uptake of sustainable solutions.

The academic underpinnings of this manuscript are thoroughly delineated within the Literature Review section, highlighting the complex lattice of connections among financial technologies (Fintech), the dynamics of energy markets, and the overarching goals of environmental sustainability as a central theme of prolific investigation. This corpus of scholarly inquiry, focusing on financial and technological novelties such as cryptocurrencies, has witnessed a marked surge in research efforts dedicated to deciphering the interrelations between environmental sustainability, the flux of energy markets, and the financial industry's evolving landscape. A significant strand of research within this field includes utilizing the connectedness method, initially proposed by Diebold and Yilmaz (2009, 2012, 2014). It has garnered substantial recognition for its comprehensive analytical framework mapping the interrelated dynamics among these sectors. The literature reveals a growing scholarly endeavor to unravel these domains' time-varying and multifaceted connectedness, utilizing advanced econometric models such as the time-varying parameter vector autoregressive (TVP-VAR) connectedness approach. This methodological pivot aims to capture the evolving nature of interactions and spillovers among variables, offering a nuanced understanding of the systemic linkages.

Moreover, the exploration extends beyond conventional models, incorporating innovative methodologies like the R-squared decomposed connectedness approach and the time-varying optimal copula model to dissect the relationships within energy markets and their connection to green finance. Collectively, the literature underscores a paradigm shift toward integrating sophisticated econometric techniques to probe the complex interrelations among Fintech, sustainability, and renewable energy markets. This scholarly endeavor enhances theoretical dialogue and furnishes empirical evidence that could guide the development of policies and strategic investment choices in green finance and sustainable energy initiatives.

Despite extensive exploration of the connections between financial technologies (Fintech), energy markets, and environmental sustainability, a discernible research gap still needs to be addressed. While the existing literature has effectively mapped out how Fintech intersects with green finance and renewable energy, the nuanced dynamics of these relationships, especially their temporal aspects, still need to be thoroughly understood. Notably, the temporal dimension—how these interconnections evolve over time and in response to external shocks—presents fertile ground for further investigation. Additionally, the existing body of research has not fully explored the integration of recent advancements in econometric methods for dissecting these intricate relationships. The untapped potential of modern analytical approaches, such as machine learning and network analysis, holds promise for unveiling the layered and non-linear dynamics between Fintech, sustainability metrics, and renewable energy sectors. This

shortfall highlights the imperative for empirical investigations leveraging state-of-the-art methodologies to unravel the evolving intricacies of these connections, especially against the backdrop of pressing global issues like climate change and technological advancements. To bridge this gap, this study is poised to harness sophisticated econometric techniques to meticulously examine both the simultaneous and sequential links within these critical areas. In undertaking this endeavor, the research aspires to deepen the understanding of how innovations in Fintech can catalyze a shift towards a more sustainable and energy-efficient global economic framework.

This research explores the  $R^2$  decomposed connectedness framework proposed by Balli et al. (2023), a pioneering methodological approach designed to dissect both contemporaneous and lagged spillover effects across the Fintech, sustainability metrics, and renewable energy sectors. By integrating this novel framework, the study aims to transcend the limitations of previous research that predominantly concentrated on immediate spillover effects, thereby neglecting the potential for lagged interactions that may emerge over time. This methodological innovation is crucial for capturing these sectors' intricate dynamics and interconnectedness, offering a more comprehensive analysis that accounts for both simultaneous and sequential spillover effects, thus addressing the gaps in earlier investigations and enriching our understanding of the complex interrelations within these pivotal areas.

Existing research on the interconnectedness of FinTech, sustainability, and renewable energy has often focused on contemporaneous effects, neglecting the potential for lagged interactions. These delayed influences, such as market adjustments or policy implementation effects, can be crucial in shaping these relationships over time. To overcome this limitation, this study employs the  $R^2$  decomposed connectedness methodology. This approach allows us to decompose the total connectedness into its permanent and transitory components, providing a clearer picture of the dynamic relationships between these sectors. By capturing both immediate and lagged spillovers, the  $R^2$  decomposed connectedness methodology offers a more comprehensive analysis of the complex interplay within this system.

This study makes a significant contribution by thoroughly examining the complex interactions between financial technology innovations, sustainable development, and renewable energy growth. It transcends traditional analyses by incorporating immediate and delayed interactions within these sectors. By meticulously examining these linkages, the research sheds light on how digital financial platforms and mechanisms can fundamentally alter capital flow landscapes, channeling resources toward sustainable ventures. This investigation not only contributes to the expansion of existing academic literature but also underscores the critical role of Fintech in fostering an economic environment where growth is inextricably linked with environmental preservation. By offering a nuanced understanding of these complex interplays, the study provides valuable insights for policymakers, investors, and industry leaders, guiding them toward making informed decisions that prioritize sustainability and energy efficiency, thereby potentially reshaping economic paradigms to align with ecological stewardship.

The study's organization is as follows: Section 2 reviews the relevant literature. Section 3 details the data and outlines the methodology applied. Section 4 discloses the empirical results. Section 5 concludes by discussing the findings and exploring their broader implications.

## 2. Literature Review

An extensive body of prior research has investigated the interrelationships between Fintech, energy markets, and the environment, particularly concerning financial and technological products like cryptocurrencies. The proliferation of recent studies exploring the connections between environmental issues, energy markets, and financial markets warrants attention. Notably, within this realm of research, the connectedness approach formulated by Diebold and Yilmaz (2009,

2012, 2014) (DY henceforth) has gained substantial traction. For example, Suleman et al. (2023) employed the spillover indexes developed by Baruník and Křehlík (2018) (BK henceforth) and Diebold and Yilmaz (2012) to examine time-frequency spillovers and the connectedness network between the European emissions trading system and sustainability indices. Likewise, DY's (2012) spillover index was utilized by Attarzadeh and Balcilar (2022) to explore the connectedness among technology markets, oil, common stock, and renewable energy. Moreover, the spillover index advanced by DY (2014) found application in a study by Caporale et al. (2023) to analyze the interconnectedness between renewable energy and fossil stock indices and climate policies.

It should be noted that recent studies have implemented the TVP-VAR connectedness methodology to estimate time-varying connectedness among variables. In this vein, Lucey and Ren (2023) leveraged a TVP-VAR model to scrutinize tail risk spillovers among sustainability-related products, energy equities, and futures. In a similar vein, Dogan et al. (2022) employed the TVP-VAR connectedness approach to compute volatility spillovers between green finance and various renewable energy sources, including biofuels, geothermal, solar, and wind. Expanding the scope, Ha and Huyen (2022) utilized the TVP-VAR and DY (2012) connectedness approaches to examine the interconnections among renewable and nonrenewable energy consumption, economic growth, and carbon dioxide emissions in Vietnam. Likewise, Doğan et al. (2023) employed a TVP-VAR connectedness model to unravel the dynamic interlinkages among the BIST sustainability index, BIST 100 index, S&P Global Clean Energy index, and the S&P GSCI carbon emission allowances.

Furthermore, there is a growing trend in the pertinent research domain toward an escalation in studies employing methodologies beyond the TVP-VAR connectedness approach. Among them, Balli et al. (2023) employed a novel R-Squared ( $R^2$ ) decomposed connectedness approach to analyze the relationships between energy future markets; (Naem et al., 2021) used a time-varying optimal copula (TVOC) model to analyze the linkages between green bonds and five energy markets; (Lorente et al., 2023) applied the Quantile Vector Autoregressive (QVAR) and wavelet coherence (WC) analysis to investigate the connectedness among the climate change and geopolitical risk index and renewable energy markets and green financial assets; (Hanif et al., 2021) utilized both time-varying spillover index and different copula functions to reveal the connectedness and frequency volatility spillovers between the renewable energy indices and the European emission allowance (EUA) prices; (Yuan et al., 2023) applied a quantile connectedness approach to study both the dynamic and static spillover relationship among carbon emissions prices, ESG stock index, clean energy, oil index and green bonds. Likewise, (Chatziantoniou et al., 2022) employed a novel quantile frequency connectedness approach to reveal the dynamic integration and return transmission among four environmental financial indices. Lastly, (Zhang et al., 2022) studied the dynamic connectedness between carbon emission futures, the ESG stock index, the green bond stock index, the renewable energy stock index, and the sustainability stock index through the DCC-GARCH model.

Notably, in line with the research topic of this study, there are a number of connectedness studies directly related to the nexus of Fintech, energy markets, and environmental issues. Noteworthy among them is the work of Le et al. (2021), who delved into frequency and time domain connectedness and spillover among Fintech, cryptocurrencies, and green bonds, employing both DY and BK spillover indices. Their findings indicated a pronounced connectedness between new technology assets and traditional common stocks. Another Fintech-centric study by Urom (2023) explored the dynamic dependence and connectedness between Fintech and green assets using a wavelet coherency analysis and a quantile-based connectedness approach. Results suggested positive and robust long-term co-movement between Fintech, clean energy stocks, and green bonds, albeit with weaker short-term correlations. However, Fintech did not emerge as a robust hedging opportunity for green financial indices. Tiwari et al. (2023) employed nonparametric

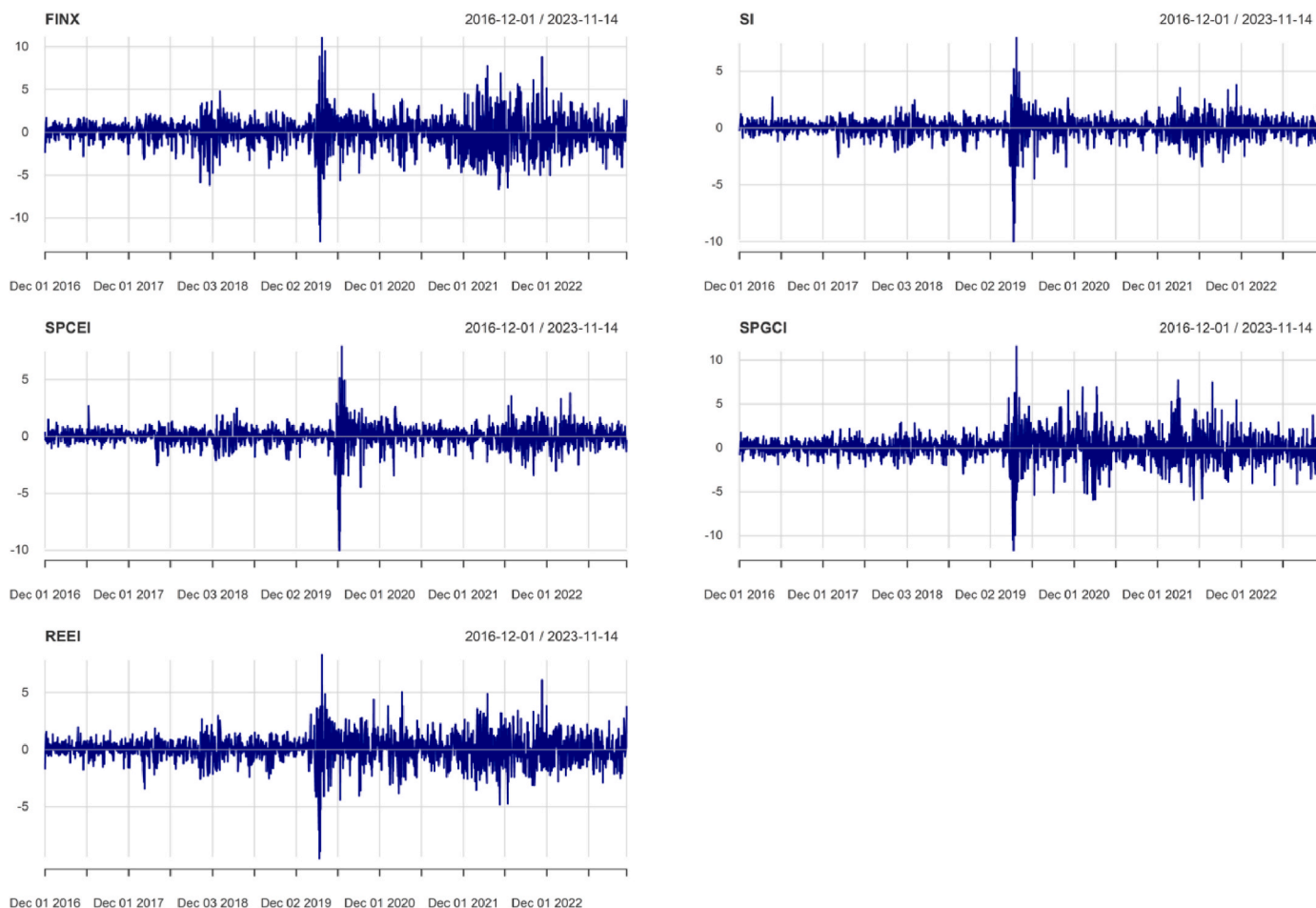
causality-in-quantile and cross-quantilogram approaches to examine linkages among Fintech, green financial assets, and energy markets. Their short-run results pointed to strong positive predictability of Fintech in all markets, except for green bonds markets in the lower quantiles. Fintech market fluctuations heightened the sensitivity of energy stock prices, sustainable development, and green equities and bonds. Analyzing the connectedness and spillover dynamics of Fintech, ESG stock index, gold, renewable energy, and MSCI indices, El Khoury et al. (2023) investigated the impact of the Russia-Ukraine Conflict (RUC) on financial markets in developed and emerging countries. Employing a TVP-VAR model and DCC-GARCH t-Copula approach, they found that Fintech, MSCI, and ESG acted as net transmitters of shocks in developed countries. At the same time, gold and renewable energy were net receivers before and during the conflict. In developing countries, ESG and MSCI indices emerged as net transmitters, with Fintech, renewable energy, and gold acting as net receivers in both periods. Similarly, Ha (2023), employing a TVP-VAR model and an extended joint connectedness technique, explored linkages between two Fintech indices and energy volatility indices (green bonds index, clean energy index, wind energy index, solar energy index, natural gas index, and crude oil index) during the COVID-19 outbreak and the RUC. The results highlighted Fintech as a significant net shock transmitter in the system.

Moreover, studies within this domain have employed diverse econometric methodologies beyond connectedness analysis to explore direct and specific relationships among Fintech, energy, and the environment. For example, Dong et al. (2024) scrutinized the symmetric and asymmetric effects of climate policy, clean energy consumption, and Fintech on environmental sustainability in the top five Asian economies. Employing the CS-ARDL model and NARDL approach, their findings revealed that Fintech, climate policy, and clean energy consumption positively enhance environmental sustainability. Similarly, Zhang et al. (2024) utilized the NARDL and CS-ARDL models to examine symmetric and asymmetric relationships among Fintech, renewable energy consumption, natural resource rents, and environmental policy in BRICS countries. Their results indicated that while Fintech contributes to economic welfare, it may adversely affect environmental quality. Additionally, Metawa et al. (2022) utilized the time-varying Granger causality test proposed by Shi et al. (2018) to unveil causal relationships between Fintech, green economy indices, and clean technology. The results highlighted high volatility and causality from the green economy to clean technology and Fintech during the sample period, confirming that clean technologies and Fintech developments contribute to a low-carbon economy. Wang and Wang (2023) employed the time-varying Granger causality test to examine the effects of Fintech and green bonds on Chinese clean energy investment. Their findings affirmed Fintech's significant and positive effect on renewable energy projects. In a study focused on China, Yang et al. (2021) examined the impacts of green finance and Fintech on high-quality economic development, utilizing panel random and fixed effects models and the GMM approach. Their results supported the positive and significant influence of Fintech on sustainability. Employing data from 290 Chinese cities, Muganyi et al. (2021) found that Fintech sector developments reduce SO<sub>2</sub> emissions and enhance environmental welfare through a semi-parametric difference-in-differences approach. Liu et al. (2022) confirmed the positive and significant effect of Fintech and green finance on the energy efficiency level of Emerging Seven (E7) economies, employing data envelopment analysis (DEA). Using a global country panel, Tao et al. (2022) examined the effects of Fintech on GHG emissions using OLS, 2SLS, and GMM approaches, substantiating the emissions-reducing role of Fintech. Examining linkages between Fintech, environmental performance during the COVID-19 outbreak, and green finance, Guang-Wen and Siddik (2023) utilized a structural equation model with data from 302 Bangladesh banking staff. Their empirical results underscored the importance of Fintech, green innovation, and finance in elevating the environmental performance of financial institutions. Khalil et al. (2023) analyzed the effects of

**Table 1**  
Descriptive statistics.

|                 | FINX        | SI           | SPCEI        | SPGCI       | REEI        |
|-----------------|-------------|--------------|--------------|-------------|-------------|
| Mean            | 0.03452     | 0.03518      | 0.03339      | 0.04924     | 0.05367*    |
| Variance        | 3.2888      | 0.8593       | 0.8336       | 2.5062      | 1.5111      |
| Skewness        | -0.312***   | -0.954***    | -0.994***    | -0.167***   | -0.407***   |
| Excess Kurtosis | 5.449***    | 17.851***    | 19.079***    | 8.087***    | 6.622***    |
| JB              | 2273.684*** | 24359.705*** | 27812.490*** | 4951.865*** | 3364.347*** |
| ERS             | -5.805      | -14.686      | -13.274      | -12.269     | -5.672      |
| Q(20)           | 38.749***   | 124.908***   | 126.876***   | 71.958***   | 58.559***   |
| Q2(20)          | 1498.683*** | 1411.245***  | 1382.130***  | 1062.067*** | 920.887***  |

**Note:** \*\*\*, \*\*, and \* indicate statistical significance at the 1%, 5%, and 10% levels, respectively. “ERS” refers to the unit root test developed by [Stock et al. \(1996\)](#). “Q(20)” and “Q2(20)” denote the Ljung–Box test statistics for serial correlation in the raw series and squared residuals, respectively.



**Fig. 1.** Trends in returns.

innovation, green finance, Fintech, and the ESG stock index on sustainable development in Gulf Cooperation Council (GCC) countries. Employing moment’s quantile regression (MMQR) methods, their results revealed that green innovation, finance, and Fintech significantly contribute to the sustainable development of the GCC region.

Lastly, a distinct group of studies has focused on the interconnections among cryptocurrencies, a pivotal Fintech product, energy markets, and environmental considerations ([Abakah et al., 2023](#); [Anwer et al., 2023](#); [Hong and Zhang, 2023](#); [Kumari et al., 2024](#); [Le, 2023](#); [Le et al., 2021](#); [Qin et al., 2023](#); [Marco et al., 2023](#); [Othman and Ben Bob, 2022](#); [Pham et al., 2023](#)). This strand of research delves into examining short- and long-term volatility spillovers between cryptocurrency prices, energy market indices, and environmental-based indices. It scrutinizes whether cryptocurrencies act as net receivers or transmitters of shocks within the system and explores the role of cryptocurrencies in portfolio

diversification to hedge investment risks. Furthermore, these studies investigate how major geopolitical events, such as the RUC and the COVID-19 outbreak, have influenced the interconnectedness among cryptocurrencies, energy markets, and the environment.

### 3. Data

In this study, we employ a daily dataset covering the Global X Fin-Tech ETF (FINX), the S&P Global Clean Energy Index (SPGCI), the MSCI Renewables and Energy Efficiency Index (REEI), the S&P Carbon Efficient Index (SPCEI), the Dow Jones Sustainability World Index (SI). FINX, SPGCI, SPCEI, and the SI data were gathered from the S&P Global, while the MSCI was collected from the MSCI. The sample period ranges from November 30, 2016, to November 14, 2023. To address non-stationarity, we employed percentage changes for log returns based on

the unit root test proposed by Stock et al. (1996). Table 1 and Fig. 1 present descriptive statistics and their plots, respectively.

The results depicted in Table 1 elucidate that REEI attains the most substantial return (0.05367), closely trailed by SPGCI (0.04924). Conversely, FINX demonstrates the lowest variance (3.288), followed by SPGCI (2.5062). Notably, the distributions of all indices are right-tailed and manifest leptokurtic behaviour, as evidenced by their excessive JB values, indicative of an abnormal distribution. Moreover, all returns exhibit stationarity, notable autocorrelation, and errors consistent with ARCH/GARCH models.

Throughout the observed period, returns exhibit significant spikes that align with major financial and geopolitical disruptions, such as the onset of the COVID-19 pandemic's first wave in March and April 2020, as well as the RUC in early 2022.

#### 4. Methodology

In this study, we employ a novel  $R^2$  decomposed connectedness developed by Balli et al. (2023), which allows us to disentangle lagged and contemporaneous spillover effects. This approach addresses a constraint in previous studies that predominantly concentrated on contemporaneous spillovers.

Define a VAR( $p$ ) model with contemporaneous effects:

$$x_t = \sum_{i=0}^p A_i x_{t-i} + v_t, v_t \sim N(0, \pi) \tag{1}$$

where  $x_t$ ,  $x_{t-1}$ , and  $v_t$  are  $N \times 1$  dimensional demeaned vectors in time  $t$ ,  $A_i$  and  $\pi$  are  $N \times N$  dimensional matrices with  $diag(A_0) = 0$  - hence the left-hand side (LHS) variable is omitted from the right-hand side (RHS) variables.

Here, the sum of  $R^2$  contributions, determined through bivariate linear regression (BLRs), corresponds to the  $R^2$  goodness-of-fit metric in the case of multivariate linear regression (MLR) only when there is no correlation among the RHS variables. Therefore, it is imperative to discern a transformation that converts the correlated series  $x_{n,t}^1$  into an orthogonal series. This conversion can be achieved by employing PCA, where the count of latent factors aligns with the number of RHS variables. Thus, the decomposition of  $R^2$  for an MLR can be calculated as follows:

$$R_{yy} = V\Lambda V' = CC' \tag{2}$$

$$C = V\Lambda^{1/2}V' = CC' \tag{3}$$

$$R^{2d} = C^2(C^{-1}R_{xy})^2 \tag{4}$$

Where  $V$ ,  $\Lambda = diag(\lambda_1, \lambda_2, \dots, \lambda_{N(p+1)-1})$ , and  $R_{yy}$  represents  $[N(p+1) - 1] \times [N(p+1) - 1]$  eigenvector, eigenvalue, and Pearson correlation coefficients (PCC),  $R_{xy}$  and  $R^{2d}$  represent  $[N(p+1) - 1]$  PCC and  $R^2$  contribution vectors.  $R_{yy}$  and  $R_{xy}$  denote PCC across RHS variables and the LHS and RHS variables, respectively. The first  $N - 1$  components of  $R^{2d}$  denote the contemporaneous  $R^2$  contributions, and the remaining represent the lagged  $R^2$  contributions. Hence, the vector sum of  $R^{2d}$  equals the MLR  $R^2$  goodness-of-fit measure. Stacking the  $R^{2d}$  contribution of all  $N$  MLRs to derive the  $N \times N(p+1)$  dimensional  $R^{2d}$  decomposition matrix,  $[R_0^{2d}; \dots; R_1^{2d}; \dots; R_q^{2d}]$ .

Herein,  $R_0^{2d}$ ,  $R_L^{2d} = (R_1^{2d} + \dots + R_i^{2d} + \dots + R_q^{2d})$  represent the contemporaneous spillovers ( $R_C^{2d}$ ), and the lagged spillovers, respectively.

Relying on the methodology of Diebold and Yilmaz (2012, 2014),  $R_C^{2d}$  and  $R_L^{2d}$  replace the scaled GFEVD matrix.

The total connectedness index (TCI):

**Table 2**

Average connectedness.

|       | FINX                      | SI                         | SPCEI                      | SPGCI                      | REEI                      | FROM                             |
|-------|---------------------------|----------------------------|----------------------------|----------------------------|---------------------------|----------------------------------|
| FINX  | 0.53<br>(0.00,<br>0.53)   | 24.37<br>(23.66,<br>0.71)  | 0.61<br>(0.28,<br>0.33)    | 14.73<br>(14.3,<br>0.43)   | 29.23<br>(28.83,<br>0.39) | 68.94<br>(67.08,<br>1.86)        |
| SI    | 24.64<br>(23.57,<br>1.08) | 0.75<br>(0.00,<br>0.75)    | 0.71<br>(0.43,<br>0.28)    | 15.41<br>(14.73,<br>0.68)  | 28.8<br>(28.06,<br>0.74)  | 69.57<br>(66.79,<br>2.78)        |
| SPCEI | 1.24<br>(0.53,<br>0.71)   | 1.41<br>(0.76,<br>0.65)    | 2.61<br>(0.00,<br>2.61)    | 1.40<br>(0.77,<br>0.63)    | 1.23<br>(0.62,<br>0.61)   | 5.27<br>(2.68,<br>2.59)          |
| SPGCI | 15.27<br>(14.85,<br>0.42) | 15.86<br>(15.35,<br>0.51)  | 0.78<br>(0.57,<br>0.21)    | 0.83<br>(0.00,<br>0.83)    | 32.93<br>(32.51,<br>0.42) | 64.84<br>(63.28,<br>1.56)        |
| REEI  | 27.37<br>(26.82,<br>0.56) | 26.99<br>(26.49,<br>0.51)  | 0.51<br>(0.29,<br>0.22)    | 29.44<br>(28.99,<br>-3.85) | 0.37<br>(0.00,<br>0.37)   | 84.32<br>(82.58,<br>1.75)        |
| TO    | 68.53<br>(65.76,<br>2.77) | 68.63<br>(66.26,<br>2.37)  | 2.61<br>(1.57,<br>1.04)    | 60.98<br>(58.79,<br>2.19)  | 92.19<br>(90.03,<br>2.16) | 292.93<br>(282.41,<br>10.52)     |
| NET   | -0.41<br>(-1.32,<br>0.91) | -0.93<br>(-0.53,<br>-0.41) | -2.66<br>(-1.11,<br>-1.55) | -3.85<br>(-4.49,<br>0.63)  | 7.86<br>(7.45,<br>0.41)   | TCI =<br>58.5<br>(56.4,<br>2.10) |

**Notes:** The decomposition of  $R^2$  measures is computed based on a 200-day rolling-window VAR model incorporating a lag length of order one determined using the Bayesian Information Criterion (BIC).

$$TCI = \frac{1}{N} \sum_{n=1}^N R_n^2 \tag{5}$$

$$TCI = \left( \frac{1}{N} \sum_{n=1}^N \sum_{i=1}^N R_{C,n,i}^{2,d} \right) + \left( \frac{1}{N} \sum_{n=1}^N \sum_{i=1}^N R_{L,n,i}^{2,d} \right) \tag{6}$$

$$TCI = TCI^C + TCI^L \tag{7}$$

Where  $TCI^C$  and  $TCI^L$  stand for the contemporaneous and lagged spillovers, respectively.

TO, FROM, and NET spillovers:

$$TO_i = \left( \frac{1}{N} \sum_{i=1}^N R_{C,n,i}^{2,d} \right) + \left( \frac{1}{N} \sum_{i=1}^N R_{L,n,i}^{2,d} \right) \tag{8}$$

$$TO_i = TO_i^C + TO_i^L \tag{9}$$

$$FROM_i = \left( \frac{1}{N} \sum_{i=1}^N R_{C,i,n}^{2,d} \right) + \left( \frac{1}{N} \sum_{i=1}^N R_{L,i,n}^{2,d} \right) \tag{10}$$

$$FROM_i = FROM_i^C + FROM_i^L \tag{11}$$

$$NET_i^C = TO_i^C - FROM_i^C \tag{12}$$

$$NET_i^L = TO_i^L - FROM_i^L \tag{13}$$

$$NET_i = TO_i - FROM_i \tag{14}$$

#### 5. Empirical results

##### 5.1. Connectedness results

First, we compute the average connectedness for the returns and display them in Table 2. The provided figures exhibit the overall  $R^2$  decomposed measures, while the values encompassed in parenthesis represent contemporaneous and lagged  $R^2$  decomposed measures.

The average connectedness findings suggest that the TCI is, on

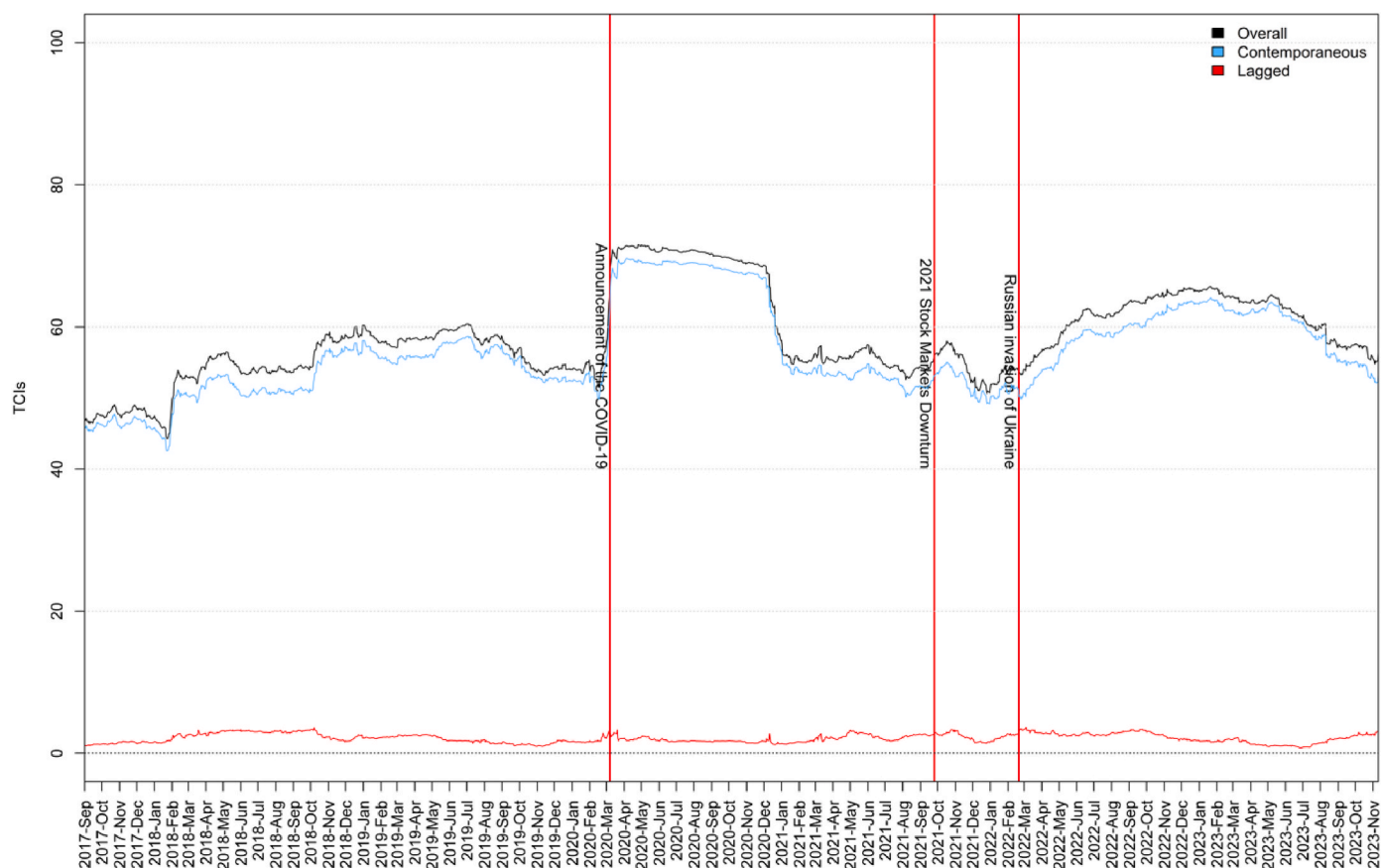


Fig. 2. Time-varying overall, contemporaneous, and lagged connectedness.

average, 58.5%, signifying that, on average, 58.5% of the variability in the LHS variables can be attributed to the RHS variables. Upon breaking down this metric into its contemporaneous and lagged components, our analysis reveals that 56.4% can be ascribed to contemporaneous dynamics, while approximately 2.10% is associated with lagged connectedness.

Upon closer examination, we observed that all contemporaneous "FROM" connectedness measures exhibit significantly higher values compared to their corresponding lagged measures, aligning with the findings of Balli et al. (2023) and Naeem et al. (2024). This observation aligns with the rapid responsiveness of markets to emerging information. Notably, events like the WHO's declaration of COVID-19 (April 2020) or the Russian invasion of Ukraine (March 2022) are anticipated to promptly trigger reactions across all indexes (FINX, SI, SPCEI, SPGCI, REEI). Moreover, the diminishing strength of lagged effects could be attributed to markets' gradual adjustment and adaptation to evolving information.

The primary transmitter/recipient of shocks is REEI, accounting for 92.19% and 84.32%, followed by SI (68.63% and 69.57%) and FINX (68.53% and 68.94%). This finding implies that improving efficiency could enhance the cost competitiveness of renewable energy, potentially influencing conventional energy markets (SPCEI) and stimulating investments in FinTech solutions for renewable energy (FINX) (Miron et al., 2023; Zhang et al., 2023). Besides, rising REEI might signal government support for renewables, which could influence investor sentiment towards sustainable investments (SI) and potentially lead to policy changes impacting other sectors (SPGCI) (Wang and Fan, 2023; Wang and Wang, 2023). Additionally, on average, except for REEI, all indexes are net recipients of shocks.

Next, we compute dynamic connectedness (overall, contemporaneous, and lagged) among the returns and plot them with prominent

incidents in Fig. 2.

Examining the dynamics of TCIs, we observe that overall and contemporaneous interdependencies display similar patterns, consistent with the findings of Balli et al. (2023). Moreover, contemporaneous connectedness is tighter than its lagged counterparts. Overall and contemporaneous TCIs reached their peaks in April 2020 (29th and April 4, 2020), coinciding with the WHO's announcement of COVID-19, while the lagged TCI peaked on March 9, 2022, shortly after the start of the Russian invasion of Ukraine on February 24, 2022. Furthermore, TCIs experienced a precipitous surge on September 29, 2021, aligning with the moment when initial public offerings by U.S. tech companies hit their lowest levels since the global financial crisis of 2008,<sup>1</sup> and the Dow dropped by 500 points.<sup>2</sup>

Next, we estimate the total connectedness of the dynamic net and plot them in Fig. 3.

The net spillover results illustrated in Fig. 3 reveal that the REEI primarily acts as a persistent transmitter of shocks. In contrast, the SPCEI and the SPGCI predominantly serve as recipients of shocks throughout the episode. Furthermore, exhibiting a shared trend, contemporaneous spillovers are significantly higher than their lagged counterparts for the REEI and SPGCI. Notably, it is essential to highlight that the spillovers transmitted or received from the REEI and SPGCI experienced a substantial surge between late 2020 and mid-2021, as well as in early 2022 and late 2022.

It is crucial to acknowledge that on November 25, 2021, the Dow

<sup>1</sup> <https://www.reuters.com/technology/tech-ipo-market-faces-worst-year-since-global-financial-crisis-2022-09-29/>.

<sup>2</sup> <https://www.cnbc.com/2021/09/29/stock-market-futures-open-to-close-newshtml.html#:~:text=The%20S%26P%20500%20finished%20September,its%20worst%20month%20in%202021.>

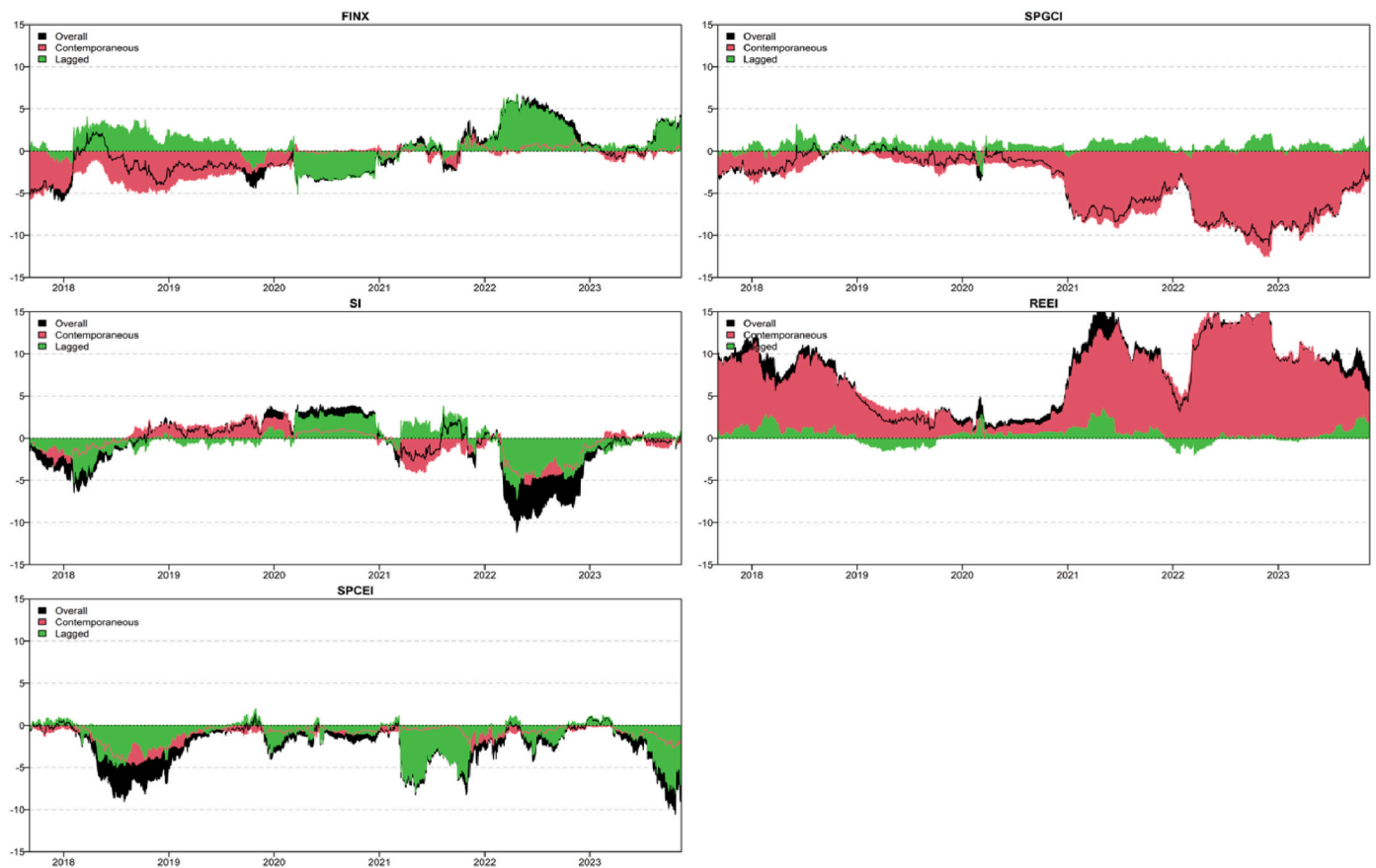


Fig. 3. Net total directional connectedness.



Fig. 4. Network Connectedness

Notes: The diagrams show contemporaneous connectedness on the left, lagged connectedness in the center, and overall connectedness on the right.

plummeted by 900 points, marking the worst performance of the year due to concerns about a new Covid variant.<sup>3</sup> This event may have triggered the first observed trend. Simultaneously, the RUC could be attributed to the latter surge in spillovers.

Additionally, it is noteworthy that FINX and SI consistently alternate between roles as net transmitters and net receivers, transmitting or receiving notable shocks around early 2022, likely influenced by the RUC.

5.2. Network analysis

In this subsection, we compute overall, contemporaneous, and lagged network connectedness and present them in Fig. 4.

Several notable observations merit attention when examining the

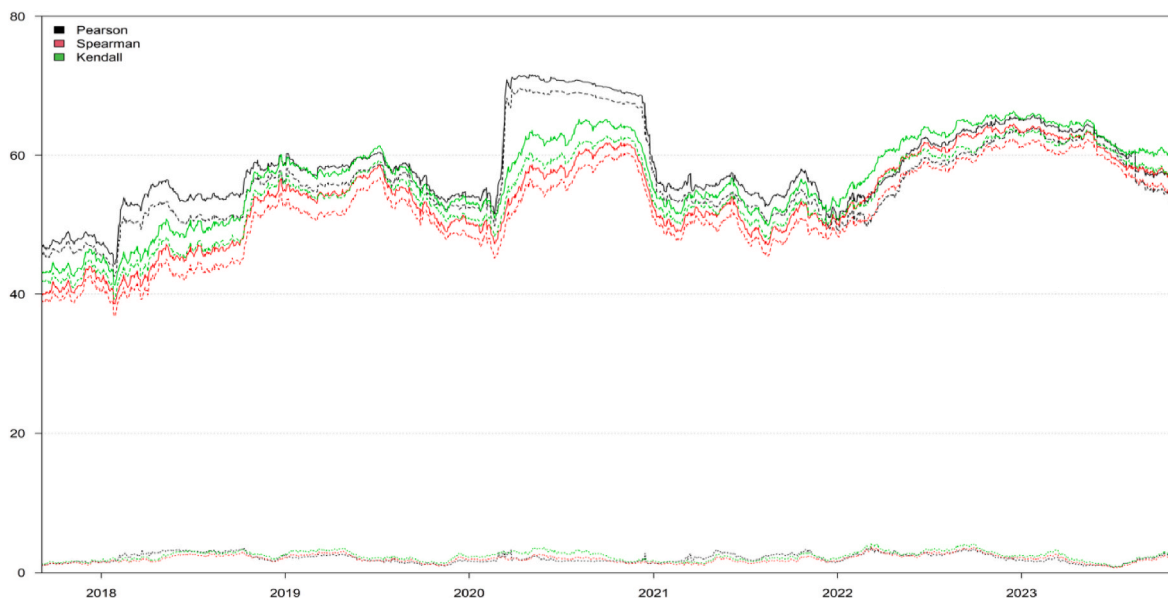
<sup>3</sup> <https://www.cnbc.com/2021/11/26/stock-futures-open-to-close-market-news.html>.

interconnectedness of networks. Firstly, significant spillover effects, both contemporaneous and lagged, are evident in the interconnections between REEI and SPGCI, SI, and FINX. Aligning with our earlier findings, REEI emerges as the most substantial node in both contemporaneous and lagged connectedness networks, while SPGCI plays a pivotal role in the overall connectedness network. Moreover, contemporaneous interdependencies among indexes take precedence over their lagged counterparts. In conclusion, within the overall network of connectedness, the SPCEI emerges as the predominant transmitter of shocks.

5.3. Robustness analysis

We conduct a diagnostic check on our dynamic connectedness results by substituting the Pearson correlation coefficients with the Spearman and Kendall rank correlation coefficients. The outcomes of this diagnostic check are depicted in Fig. 5, providing a comprehensive overview of our analysis.

The overall, contemporaneous, and lagged dynamic total



**Fig. 5.** Robustness analysis

**Notes:** The black/red/green solid, dashed, and dotted lines indicate the overall, contemporaneous, and lagged dynamic total connectedness when using the Pearson, Spearman, and Kendall rank correlation coefficients in the model, respectively.

connectedness indices, estimated using Pearson and Spearman rank correlation coefficients, exhibit similar patterns. This consistency underscores the robustness of our empirical findings.

## 6. Conclusion

This study synthesizes the findings and implications of the interconnected dynamics between financial technologies, sustainability initiatives, and the renewable energy sector. It utilizes a ground-breaking  $R^2$  decomposed connectedness methodology to analyze both immediate and lagged spillover effects, thereby addressing a significant gap in the existing literature mainly focused on contemporaneous spillovers. This approach enhances our understanding of these critical areas' intricate relationships and dependencies, offering insights into their collective impact on sustainable development and environmental stewardship. The study revealed a significant level of interconnectivity, as evidenced by the TCI averaging 58.5%, signifying considerable variability in the analyzed variables due to spillover effects. This underlines the entwined nature of Fintech, sustainability indices, and renewable energy markets, suggesting that innovations in Fintech could be instrumental in accelerating the adoption of sustainable practices and renewable energy solutions (Udeagha and Ngepah, 2023). Notably, contemporaneous connectedness constituted most of this interconnectivity, indicating that immediate spillover effects predominate over their lagged counterparts. This situation highlights the reactive nature of these sectors to current events and market conditions, underscoring the importance of real-time data and analytics in understanding and leveraging these dynamics (Liu et al., 2024). The Renewable Energy Efficiency Index (REEI) was identified as a primary transmitter of shocks within the network, emphasizing the pivotal role of renewable energy indices in the dynamics of connectedness. This finding aligns with the global momentum towards sustainable energy solutions and underscores the potential of integrating Fintech to enhance green finance and investment in renewable energy. The prominence of REEI as a central transmitter also suggests areas for strategic investment and policy focus to bolster the resilience and growth of the renewable energy sector (Sadiq et al., 2024).

The study's observation of dynamic variations in connectedness over time, particularly during major global events such as the COVID-19 pandemic and geopolitical tensions, provides crucial insights into

these sectors' adaptive and responsive nature. This temporal analysis is vital for understanding how external shocks and global crises shape the interconnected landscape of Fintech, sustainability, and renewable energy sectors, offering a lens through which to view the potential impacts of future global challenges (Ali et al., 2024). The empirical findings' robustness, validated through diagnostic checks using various correlation coefficients, strengthens the study's contributions and implications for stakeholders. For investors, the pivotal role of the Renewable Energy Efficiency Index (REEI) as a significant influencer within the financial-technological nexus emerges as a beacon, guiding investment decisions towards high-impact sustainable avenues. This observation holds significant importance within the current investment environment, with an increasing focus on sustainability and ethical investment strategies. These discoveries allow investors to harmonize their investment portfolios with financial gains and broader environmental and societal objectives. The nuanced understanding of how these sectors respond to external shocks and their interconnected dynamics is invaluable for policymakers. It provides a robust empirical foundation to develop resilient policies that foster innovation in Fintech and promote investments in renewable energy, thereby advancing the agenda of sustainable development. Industry professionals, specifically in the fields of Fintech and sustainable energy, have the potential to benefit from the practical implications of this study. The research emphasizes the transformative capacity of Fintech in promoting the use of renewable energy, proposing a mutually beneficial relationship where financial and technological advancements can significantly expedite the transition towards sustainable energy solutions. It underscores a chance for organizations to incorporate sustainable behaviours into their activities, not simply as a regulatory requirement but as a tactical decision that can unlock new markets, improve brand reputation, and contribute to a more sustainable global economy.

Furthermore, the empirical evidence presented in this study offers a solid ground for NGOs and sustainability advocates to bolster their initiatives to promote sustainable economic practices. The interconnectivity between Fintech and renewable energy provides a compelling narrative to advocate for technology-driven solutions in achieving sustainability objectives, enhancing the efficacy of advocacy campaigns. Finally, the broader societal ramifications of our discoveries must be considered. Through illuminating the impact of Fintech on enabling sustainable investment and the significance of metrics related to

renewable energy within the financial sector, this research holds the capacity to impact consumer conduct. It encourages a more conscious approach to financial decisions, supporting businesses and products that align with sustainability principles, thereby contributing to a collective movement towards a more sustainable economic model.

This research fills a critical void in the literature and sets the stage for future inquiries to explore the evolving interplay among Fintech, sustainability, and renewable energy. The findings call for a multi-disciplinary approach, combining insights from finance, technology, and environmental studies, to further unravel the complex dynamics at play. The study focuses on return connectedness, providing valuable insights into the interconnectedness between FinTech, sustainability efforts, and the renewable energy sector. However, volatility connectedness is another crucial aspect of market dynamics. Future investigations could explore volatility connectedness between these sectors to provide a more comprehensive picture of the complex relationships at play. Analysing volatility spillovers could offer valuable insights into how fluctuations in one sector propagate and impact the volatility of others. It would further enhance our understanding of this interconnected system's risk transmission and potential vulnerabilities.

In sum, this study broadens the academic discourse by offering a more intricate understanding of the interconnected dynamics among Fintech, sustainability indices, and renewable energy markets. It presents actionable insights for policymakers, investors, and industry stakeholders. It highlights the transformative potential of Fintech innovations in steering the global economy towards greater sustainability and energy efficiency, advocating for an ecosystem where technology and green initiatives synergistically drive sustainable growth.

#### CRedit authorship contribution statement

**Onur Polat:** Software, Methodology, Formal analysis, Data curation.  
**Burcu Ozcan:** Writing – review & editing, Writing – original draft, Conceptualization.  
**Hasan Murat Ertugrul:** Writing – review & editing, Supervision.  
**Emre Atılgan:** Writing – review & editing.  
**Alper Özün:** Data curation.

#### 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.

#### Data availability

Data will be made available on request.

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