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# Analysis of the spillover effects between green economy, clean and dirty cryptocurrencies

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ABSTRACT

Cryptocurrencies have been widely used as financial instruments over the past decade. Given the development of the cryptocurrency market and the increasing awareness of greener and more energy-efficient tokens, their connection to the green economy has become a popular topic for understanding economic and policy issues. However, the literature still lacks clear evidence on how cryptocurrencies interact with green economy indicators. Therefore, this study examines the correlations and spillover relationships between green economy indices, five black cryptocurrencies, and five clean cryptocurrencies for the U.S., Euro, and Asian markets. To this end, it applies the novel quantile spillover index approach of Ando et al. (2018) to daily data from November 9, 2017, to April 4, 2022. The empirical results show that the overall linkage is stronger for green economy indices and clean cryptocurrencies than for dirty cryptocurrencies. Moreover, green economy indices show net receiving behavior, while cryptocurrencies' results differ across variables, quantiles, and time. In addition, a notable point for clean cryptocurrencies is 2020, which was the start of the COVID-19 pandemic. The overall spillover effect is very high for all quantiles for the three markets, especially for Asia. This outcome signifies the safe harbor property for diversification purposes of the green economy. The results presented in this study are important for investors, regulators and, policymakers, cryptocurrency founders as they seek to be financially integrated and develop a more sustainable business.

## 1. Introduction

Environmental risks have significantly increased in recent years (Zhang and Da, 2015; Ustaoglu et al., 2021; Gul et al., 2015; Liu et al., 2021; Zhang et al., 2021a, 2021b; Balsalobre-Lorente et al., 2021). Without significant carbon emissions reductions, the 21st century will experience a temperature rise of almost 2 °C. According to the Intergovernmental Panel on Climate Change (IPCC), which released its sixth report in August 2021, the presence of CO2 has never been more critical for at least two million years. It is claimed that the massive consumption of fossil fuels is responsible for the increase in global CO2 emissions (Dong et al., 2018; Jardón et al., 2017; Vlachou et al., 1996; Dogan and Seker, 2016; Wen et al., 2023), resulting in rising temperatures and environmental degradation. We must replace fossil fuels with new energy sources called “clean” or “green”. This new green economy thus represents a form of sustainable development (Wang et al., 2021). This data is taken into account by investors, policymakers, state actors, international organizations, and researchers (Barbier, 2010; Lee and Lee, 2022). In recent years, the need to transition to a greener, more sustainable economy has increased due to environmental concerns, and the Covid-19 pandemic has precipitated it. Several organizations and countries have initiated a global reset that could offer an opportunity to transform them in terms of sustainability radically. This was reflected in the search for environmental sustainability in investment strategies/instruments (Chaudhry et al., 2020; Pham, 2021b).

. The United Nations has therefore introduced the Sustainable Development Goals (SDGs) to address this global concern. By 2030, 17 programs must be implemented, focusing primarily on increasing the

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share of renewable energy. Forward-thinking countries are implementing supportive policies that encourage innovation. For example, the United States invested $1.3 trillion annually in the green economy, creating 9.5 million full-time jobs (Georgeson and Maslin, 2019). Europe and Asia were not left behind (Pham, 2021a). The EU set a goal of becoming carbon neutral by 2050 through its "Green Deal" (European Commission, 2022). As major emitters of greenhouse gases (GHGs) globally, Asian countries are under pressure to move towards a greener economy (Fekete et al., 2021). However, many reports state that, despite the last decade's progress, renewable energy deployment is too insufficient to achieve the SDGs and the goals of the Paris Agreement and, thus, a significant decarbonization of the energy sector. The pandemic and the Russian-Ukrainian war have led several economies to move towards investments less concerned with climate change and sustainable development. Companies are considering green investments not only with social and environmental goals (Mahmood et al., 2020) but also to achieve better financial returns (Tuhkanen and Vulturius, 2020; Khalil and Nimmanunta, 2022; Sharma et al., 2022). This green finance must focus on slowing down climate change through the search for sustainability.

However, while identifying corporate finance instruments that can achieve the SDGs goals has been completed (Umar et al., 2022), there is very little research on the performance of green assets. Concerning the risks posed by cryptocurrency markets, even as sustainable or green cryptocurrencies evolve (Lee et al., 2022a; Pham et al., 2022). These tend to replace conventional or dirty cryptocurrencies, which, like Bitcoin, consume a lot of energy in the extraction process (Haq et al., 2022). Their energy-intensive use of Proof of Work (PoW) results in high carbon footprints (Ghosh and Bouri, 2022; Wang et al., 2022). It is, therefore, a question for investors and policymakers to favor its replacement by a consensus without PoW, which is much more energy-efficient (Ren and Lucey, 2022a). Given the monetary impact on their portfolios (Krueger et al., 2020; Mohsin et al., 2020; Zhang et al., 2019), investors also need to be aware of their ethical and environmental responsibilities (Cambridge Centre for Alternative Finance, 2021). So, Tesla Motors CEO Elon Reeve Musk's decision to reject bitcoin as a payment method is serious. This could help achieve the United Nations Sustainable Development Goals (Chen et al., 2021). ESG, or "environmental, social, and governance," must play an even greater role in financial markets. Nevertheless, many investors use cryptography to create exchange-traded funds. They increasingly include cryptocurrency in portfolios as a hedge against inflation alongside gold. On May 8, the cryptocurrency had a total market capitalization worth $1.8 trillion (CoinMarketCap, 2022). Most of them are based on blockchain technology, and more than 2500 cryptocurrencies are circulating worldwide (Goodkind et al., 2020).

Attention has shifted to cryptocurrencies' energy and environmental footprint, even as Bitcoin's price has skyrocketed since 2017 (Dittmar and Praktiknjo, 2019; Masanet et al., 2019; Baur and Oll, 2021. Badea and Mungiu-Pupăzan, 2021). Having piqued the curiosity of researchers, investors, speculators, and regulators (Glaser et al., 2014), these cryptocurrencies are now arousing public concern (Corbet et al., 2020). The impact of Bitcoin mining on the ecosystem has led to heated debates (Khalfaoui et al., 2022). Many researchers argue that large-scale Bitcoin mining will contribute to the inevitable climate crisis due to the carbon dioxide emissions it generates. Mora et al. (2018) predict that this carbon dioxide production will raise the temperature by 2 °C in 30 years. The cryptocurrency Bitcoin secures its network thanks to an energy-intensive proof of work (PoW) scheme. The Cambridge Center for Alternative Finance (CCAF) reports that Bitcoin's energy consumption is currently around 110 TWh per year. This represents 0.55% of the world's electricity production, the production of small states like Malaysia and Sweden). Electricity consumption from of operation and generation process would be close to that of a medium-sized country (O'Dwyer and Malone, 2014), such as Ireland (3.1 GW per year). They could reach that of Austria (8.2 GW per year) soon (IEA, 2017). Crypto-extraction[1] is estimated to consume more energy than mining to produce equivalent market value.

This consensus algorithm is at the origin of a highly competitive mining company. Miners compete in ingenuity to solve complex mathematical problems and thus win the 12.5 BTC[2] rewards for each newly created block (Antonopoulos, 2014, 2017. This requires huge sums of money to purchase increasingly sophisticated equipment, which increases energy consumption because of the powerful cooling systems (Vranken, 2017; de Vries, 2019; Gehlot and Dhall, 2022). miners, the consideration of this consumption is decisive in the same way as the profit or loss prospects (Cocco and Marchesi, 2016; Brousmiche et al., 2018). Recent changes in the cryptocurrency market, particularly the introduction of more sustainable and energy-efficient tokens, point to the potential of cryptocurrencies to reduce carbon emissions. Thus, the transition to renewable energy adoption, optimistically portrayed as increasingly affordable, is likely underway.

As a result, researchers stressed the urgency of reducing cryptocurrency extraction activities and non-PoW (Hays and Valek, 2018; Schinckus, 2021). Corbet et al. (2021) and Gallersdörfer et al. (2020) highlighted the choice that future practitioners make between cryptocurrencies using energy-intensive or, conversely, energy-efficient algorithms. This can be seen with the launch of Ethereum 2.0 and the transition from a proof-of-work (PoW) consensus to a proof-of-stake (PoS) model.[3] Since the PoS hardware requirements are significantly lower than the PoW hardware requirements, the energy required to facilitate secure transactions will only decrease by 99.95%. Ethereum is not alone in this consensus revolution. New generation ascending blockchains such as Cardano, Polkadot, EOS, and Cosmos implement their version of PoS. Out of all these concerns came the Crypto Climate Accord, a private-sector initiative to decarbonize the cryptocurrency industry. Finally, in recent years, more and more environmentally friendly cryptocurrencies have been launched on the market, labeled as "clean" (as opposed to conventional currencies with the addition of "dirty"), a response to the trend towards a greener industry.

We feel that most empirical studies have so far abandoned the analysis of the impact of shocks on green markets and cryptocurrencies. We believe that a good knowledge of these relationships is essential for policymakers and environmental investors to adjust investment portfolios and develop good hedging strategies. The COVID -19 pandemic demonstrated the need to understand the interactions between different financial markets better to manage market turbulence. In this sense, cryptocurrencies played a hedging role. This is why this study examines the bi-directional connectivity between OMX and cryptocurrencies. Based on these observations and arguments, this study aims to analyze the spillover effects between the green economy and clean and dirty cryptocurrencies for the US, Europe and Asia economies by applying the novel quantile spillover index approach developed by Ando et al. (2018) on the daily data from November 9, 2017, to April 4, 2022. Spillover is defined here in the impact of OMX volatility on cryptos and vice versa. The channels through which the green economy influences cryptocurrencies arise from the association of volatility through the integration of cryptocurrencies into portfolios with OMX and vice versa. Since climate performance indicators help evaluate companies in terms of sustainability, our empirical results should inform portfolio

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[1] The extraction process refers to creating a consensus on a shared computer ledger to create a digital asset.

[2] This amount is halved every four years or every 10,000 BTC.

[3] The Proof of Work (PoW) system uses a competitive validation method to confirm transactions and add new blocks to the blockchain (the fastest miner to confirm the transaction wins the reward). The Proof of Stake (PoS) system uses randomly selected minors to validate transactions.

diversification strategies and set policy frameworks for achieving the SDGs.

In recent times, Europe's and US's green equity prices have an upward trend, unlike Asia. During the COVID-19 crisis, index prices fell considerably to recover in 2021 thanks to vaccinations against the pandemic, but dropped again during the 2022 Russia-Ukraine war. In addition, US has a higher mean return on green equity stocks and a higher standard deviation than Asia. Such initiative is supported by a strong political will as well as the required infrastructure for the green shift projects. Many Asian governments, China in particular, are making efforts to achieve the UN green goals. The similarities between the green economies of the US and EU are twofold. First, the two regions have two integrated economic blocs and the same green vision and goals. This is not the case for Asia which includes countries with developing economies. Second, Europe's efforts towards a sustainable economy are supported by the European Green Deal, which helps transforming climate and environmental challenges into opportunities across all policy areas and allows this shift to be fair and inclusive for all countries. Indeed, this Green Deal makes it possible to use resources efficiently thanks to the shift to a cleaner and more circular economy. In this way, climate change can be stopped, pollution can be curbed and biodiversity loss can be avoided. Moreover, the Green Deal presents all the necessary investments and the financing tools available. It also explains how a fair and inclusive transition can be ensured. However, based on the 2017 ADB report, the article presents not only Asia's interest in innovation but also its comparative advantage in the technologies of mitigating climate change. The article focuses on the importance of using efficient lighting, photovoltaic energy, as well as energy storage technologies including nuclear and smart grids. It is worth noting that there are regional disparities in Asia, since some countries (e.g., the PRC, Japan and the Republic of Korea) are performing better than others. Indeed, Shao et al. (2022) underline these disparities. The authors show that the farther Asian countries move away from green economy, the more lagged they are and the poorer their green development performance is. Overall, the countries with a high green development level are the leaders. Those which are moving towards green economy are medium countries, but the countries with bad green performance are still lagging behind. There is a negative skewness among regional green equity return series.In general, regional green markets showed increased volatility especially during the COVID-19 pandemic in the first quarter of 2020 and also during Russia-Ukraine war of 2022.

In this regard, the contribution of the present work to the literature is threefold. First, our study provides sound evidence of the relationship between cryptocurrencies and the green economy in regional markets, under different market conditions, and with different investment horizons. Green economy market indices are designed to capture the performance of companies committed to a sustainable business model. They are also helpful in analyzing green stock market performance in the regions mentioned above. They, therefore, allow us to examine the short, medium, and long-term impact of cryptocurrencies on the green stock markets of a given country. **Second**, our study extends related research by measuring the herd behavior of “black/dirty” versus “green/clean” cryptocurrencies, as suggested by recent studies by Ren and Lucey (2022a,b). It is thus the first study to empirically examine the hedge and safe haven properties and then the spillover properties of a broad range of green energy indices. It also looks at two types of cryptocurrencies in times of extreme instability and market turmoil. Thus, it is possible to educate investors when it is shown that a certain type of green energy stock can act as a safe haven or hedge against one cryptocurrency or another, or vice versa. It is possible to manage declines in cryptocurrencies with the help of green energy stocks or vice versa. Everything indeed depends on the currency. Therefore, any economic investment program for green energy will conflict with the environmental argument if only “dirty” currencies are used as a hedge or safe haven against green energy. **Third,** our study is the first to rely on the new quantile spillover index approach. This approach was developed by Ando et al. (2018) to analyze the risk of spillover effects in the relationship between regional renewable energy markets and cryptocurrencies. It covers a wide range of market conditions, such as exposure to extreme risks in extreme events with different frequencies (i.e., short-, medium-, and long-term). Previous work primarily relied on the traditional tests of Diebold and Yilmaz (2009, 2012, 2014). Ando's approach is essential in our context because this new technique of econometric analysis of financial networks allows the network's topology to vary with the size of the shocks that affect the system. It also isolates the distinctive component of the error process from the systematic component. This was necessary as we analyzed indices that only face systematic risk and cryptocurrencies whose idiosyncratic risk is greater than most other financial assets. Finally, our findings highlight the dependency structure between cryptocurrencies and regional sustainable energy markets in periods of financial market uncertainty and under volatility conditions for different investment portfolios.

The remainder of this paper is organized as follows. Section 2 conducts the literature review, and Section 3 describes the methodologies and data. Section 4 presents the empirical results and discussion. Finally, Section 5 provides conclusions and policy implications.

## 2. Literature review

Numerous studies have first examined these crypto assets from various perspectives: their role as hedges, and safe havens (Bouri et al., 2018), especially during the COVID-19 crisis (Bariviera and Merediz-Sola, 2021; Goodell and Goutte, 2021; Smales, 2019) and diversification from traditional assets (Shahzad et al., 2019; Kliber et al., 2019; Urquhart and Zhang, 2019); price formation of cryptocurrencies ( Ciaian et al., 2016); market efficiency and long-term memory (Urquhart, 2016; Bariviera, 2017; Tiwari et al., 2018); return behavior (Aalborg et al., 2019; Papadamou et al., 2021; Caferra and Vidal-Tomás, 2021); the comovement of crypto price volatility with market efficiency (Tu and Xue, 2018; Zhang et al., 2018), the strong growth of cybercrime (Corbet et al., 2019), the use of cryptocurrency for illicit purposes (Foley et al., 2019), and liquidity schemes (Scharnowski, 2021; Manahov, 2021; Zhang and Gregoriou, 2020).

However, despite a significant increase in the green energy market in recent years, little work has focused on the link between cryptocurrency and green energy markets. Although the literature continues to explore the links between cryptocurrency prices and mining costs in different regions and thus their profitability (Delgado-Mohatar et al., 2019; Das and Dutta, 2019; Kistoufek, 2020), their environmental impact has yet to be thoroughly analyzed (Truby, 2018; Easley et al., 2019; Greenberg and Bugden, 2019; Li et al., 2019 Nevertheless, a recent stream of literature has focused on the relationship between cryptocurrencies and green assets (Le et al., 2021a; Karim et al., 2022b); the relationship between cryptocurrencies and carbon prices (Yang and Hamori, 2021); and the relationship between electricity prices and bitcoin energy consumption in the context of bitcoin and sustainability dynamics (Kistoufek, 2020; Baur and Oll, 2019; Krause and Tolaymat, 2018). Symitsi and Chalvatzis (2018) relied on an asymmetric multivariate VAR-GARCH model to examine spillovers between bitcoin and stock indices of clean energy, fossil fuel, and technology companies. The researchers found one-way return spillovers and volatility spillovers. Indeed, there is a long-term spillover between bitcoin and energy markets and a short-term spillover between technology markets and bitcoin.

The link between cryptocurrency market volatility and green financial assets is being increasingly studied (Kamal and Hassan, 2022). The Index of Cryptocurrency Environmental Attention (ICEA) also gives rise to research (Karim et al., 2022a). For example, Haq (2022) used the TVP-VAR model to investigate the impact of the environmental uncertainty of cryptocurrencies on green financial assets. This research is consistent with studies on the spillover effects of bitcoin mining (Naeem and Karim, 2021) and specific uncertainty measures for green financial assets (Wang et al., 2022). Note also that the COVID -19 crisis has increased the prospects of volatility transmission ( Naeem and Karim, 2021), reducing hedging opportunities in financial markets.

Several recent studies have also suggested that perceived sustainable energy is a potential direct hedging tool or safe haven for cryptocurrencies. Thus, Le et al. (2021a) consider the temporal and frequency linkage between cryptocurrencies, green assets, and various other assets. Nevertheless, fintech and clean energy are constraints for them. Following Baur and Oll (2019), Corbet et al. (2021) show an insignificant link between bitcoin price volatility and larger green ETF markets, as cryptocurrency market investments are not sustainable. On the other hand, Karim et al. (2022a) relied on the TVOC (time-varying optimal copula) approach. They showed that bitcoin and sustainable financial assets have a dependent structure. It is not extreme in the case of clean energy, but the researchers indicate that the hedging ratio and efficiency of bitcoin are more important concerning green energy. This is a sign of Bitcoin's diversification potential.

This is in contrast to the findings of Pham et al. (2021), who suggest that green investments, such as clean energy, are a diversification or hedging tool for cryptocurrency investors. In contrast, Ren and Lucey (2022a) examined the hedging and safe haven property of a wide range of clean energy indices based on two types of cryptocurrencies, "clean" and "dirty" (i.e., according to their energy consumption level) and using the dynamic conditional correlation Generalized Autoregressive Conditional Heteroskedasticity (DCC-GARCH) model. They also showed that the time-varying dynamic conditional correlations between clean energy indices and cryptocurrencies are generally positive, regardless of the type of cryptocurrency. In other words: Sustainable energy indices are not necessarily a direct hedge for "dirty" and "clean" cryptocurrencies. Ren and Lucey (2022b) studied the herding behavior in cryptocurrency markets of two types of cryptocurrencies ("black/dirty" versus "green/clean") based on their energy consumption values. Their results showed black cryptocurrencies exhibit herding behavior, especially in bearish markets.

Using the wavelet coherence method, Haq et al. (2022) analyzed the co-movement between two indices (S&P Green Bonds and Dow Jones Sustainability World) and several sustainable cryptocurrencies (Cardano, Solar Coin, Ripple, Stellar and BitGreen). They showed that they positively impact global sustainability. Hence their possible use in portfolios alongside green bonds this register, Pham et al. (2022) investigated the tail dependence between carbon prices, green cryptocurrencies, and non-green cryptocurrencies in a quantum connectivity framework. As a result, green cryptocurrencies are only weakly linked to conventional or dirty cryptocurrencies. Thus, investors can diversify their portfolios and benefit from hedging advantages using climate risk carbon certificates. A recent strand of literature linking cryptocurrencies and other assets focuses on ancient energy assets, as they consume a lot of energy in mining and trading cryptocurrencies (Jareño et al., 2021; Jiang et al., 2022; Zeng et al., 2020; Rehman and Kang, 2021; Okorie and Lin, 2020; Umar et al., 2021; Le et al., 2021b; Maghyereh and Abdoh, 2020; Bouri et al., 2018; Uzonwanne, 2021; Wang et al., 2021).

## 3. Methodology and data

This research examines the connectedness and spillover relationship between three green economy indices (US, EURO and ASIA) and five black cryptocurrencies: Bitcoin (BTC), Ethereum (ETH), Bitcoin Cash (BCH), Ethereum Classic (ETC), and Litcoin (LTC); on the one hand, and five clean cryptocurrencies: Cardano (ADA), Ripple (XRP), Iota (MIOTA), Stellar (XLM) and Nano (XNO). For us, dirty cryptocurrencies (Bitcoin (BTC); Ethereum (ETH); Bitcoin Cash (BCH), Ethereum Classic (ETC), and Litcoin (LTC) rely on PoW consensus algorithms that result in massive energy consumption in mining and transactions. Proof-of-Work is the predominant consensus model in this type of cryptocurrency, first used in Bitcoin, the largest cryptocurrency, and then in other cryptocurrencies, such as Ethereum; Bitcoin Cash; Ethereum Classic; Litcoins. Conversely, clean cryptocurrencies are built on various energy-saving consensus algorithms, including Proof-of-Stake (PoS), Ripple Protocol, and Stellar Protocol. They are, therefore, the least harmful to the environment. The main difference between these algorithms is their computational intensity. The choice of the consensus algorithm implies a balance between the computational intensity (and, therefore, energy costs) and the security benefits of the different consensus mechanisms.

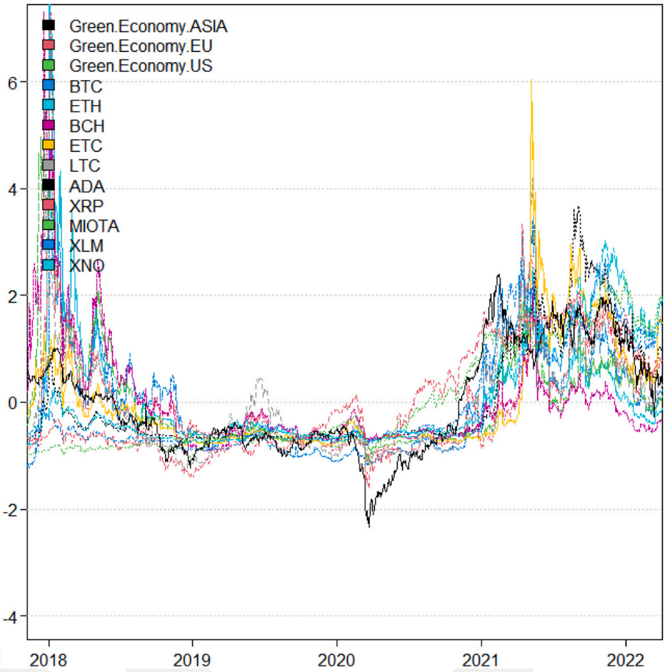

**Fig. 1.** Time series plot of the variables.

We use three green stock indices for the US, Europe and Asia: the NASDAQ OMX Green Economy U.S Index, the NASDAQ OMX Green Economy Europe Index, and the NASDAQ OMX Green Economy Asia Index, respectively. These indices consider the performance of companies in these regions compared to other companies associated with an economic model of sustainable development. Each index allows us to understand the stock markets in these countries better. We create six models. Model 1 includes Asia green economy index and the five major dirty cryptocurrencies. Model 2 includes Asia green economy index and the five major clean cryptocurrencies. Model 3 encompasses US green economy index and the five major dirty cryptocurrencies. Model 4 encompasses US green economy index and the five major clean cryptocurrencies. Model 5 contains the EU green economy index and the five major dirty cryptocurrencies. Model 6 includes the EU green economy index and major clean cryptocurrencies. The daily datasets span extends from November 9, 2017, to April 4, 2022. All the data are obtained from DataStream.[4] Figs. 1 and 2 illustrate the time series and returns plots. A summary statistic table of our variables and some pre-tests are reported in Table 1. Table 1 shows that all series are significantly non-normal, have a leptokurtic distribution, are particularly autocorrelated and present ARCH/GARCH errors.

Then, during the COVID-19 pandemic, dirty cryptocurrencies are extremely volatile (Naeem et al., 2021). In addition, clean cryptocurrencies have been associated with high-risk spillover effects during Brexit, the US interest rate hike, the cryptocurrency price bubble, and the COVID -19 crisis. This meant that clean cryptocurrencies were extremely volatile due to their exposure to external financial, economic, and global circumstances. ADA has the highest average return among clean cryptocurrencies, followed by XNO, XLM, XRP and MIOTA, which marks the lowest level. ETH has the highest average return among dirty

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[4] https://www.refinitiv.com/en/

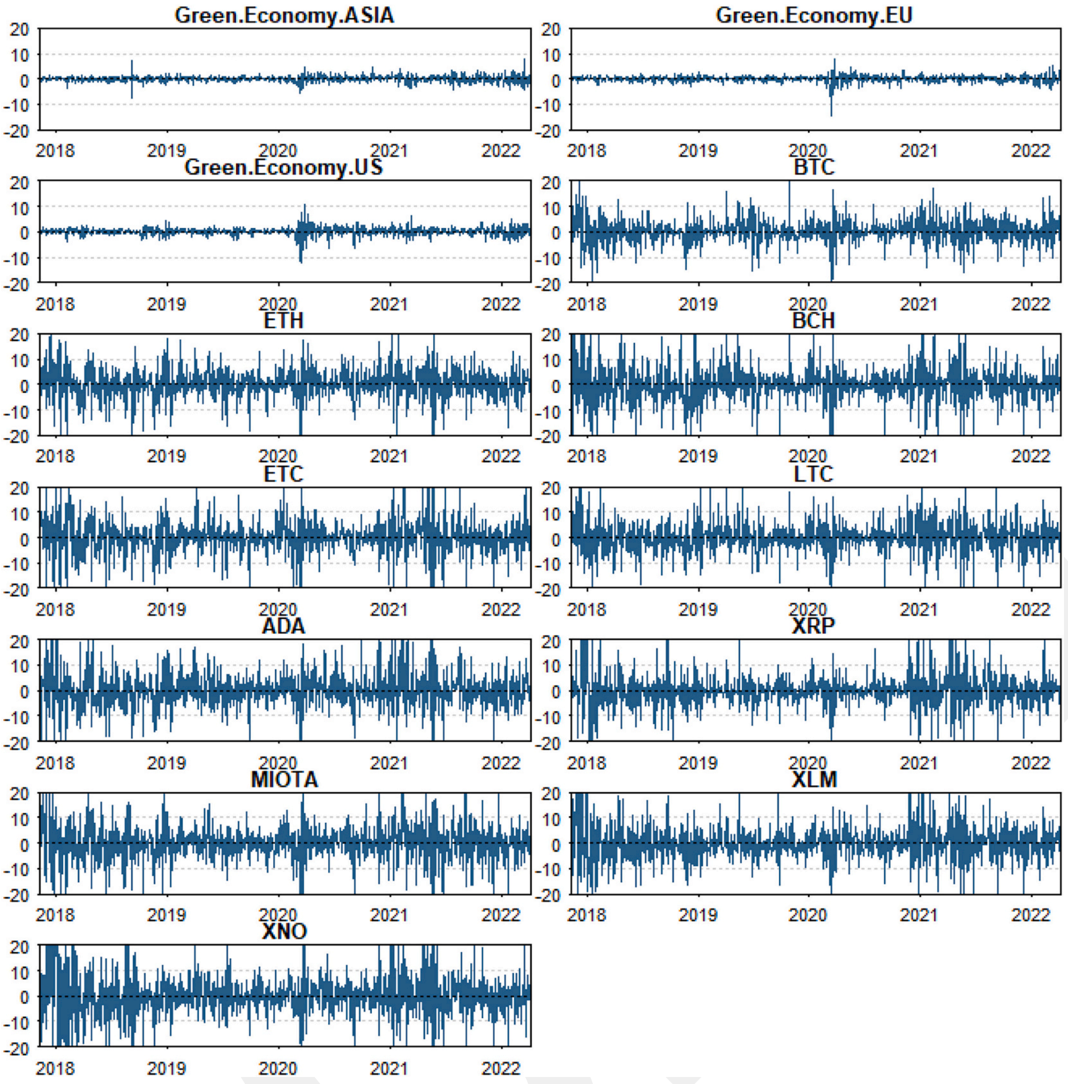

**Fig. 2.** Returns plot of the variables.

**Table 1**

Summary statistics and pretests.

| | Green.Economy.ASIA | Green.Economy.EU | Green.Economy.US | BTC | ETH | BCH | ETC |
|---|---|---|---|---|---|---|---|
| Mean | 0.000 | 0.025 | 0.088 | 0.160 | 0.212 | −0.043 | 0.105 |
| Variance | 1.427 | 1.501 | 2.496 | 3.127 | 3.782 | 3.418 | 5.657 |
| Skewness | −1.019*** | −1.677*** | −0.739*** | −0.663*** | −0.831*** | 0.601*** | −0.127* |
| Kurtosis | 5.062*** | 21.467*** | 9.628*** | 9.108*** | 7.997*** | 13.370*** | 6.831*** |
| JB | 223.562*** | 2541.344*** | 530.651*** | 444.858*** | 385.248*** | 864.613*** | 2231.070*** |
| ERS | −7.226*** | −13.371*** | −14.337*** | −7.108*** | −8.515*** | −8.697*** | −13.420*** |
| Q(20) | 12.832 | 47.030*** | | 9.280 | 21.962*** | 11.535 | 20.699** |
| $Q^2(20)$ | 225.253*** | 234.940*** | 1186.002*** | 25.711*** | 27.681*** | 34.761*** | 192.532*** |
| | LTC | ADA | XRP | MIOTA | XLM | XNO | |
| Mean | 0.063 | 0.336 | 0.118 | 0.056 | 0.170 | 0.280 | |
| Variance | 4.048 | 2.234 | 2.274 | 3.731 | 5.729 | 4.360 | |
| Skewness | 0.113* | 2.140*** | 0.828*** | −0.353*** | 0.829*** | 1.002*** | |
| Kurtosis | 8.530*** | 20.596*** | 13.562*** | 6.783*** | 8.701*** | 8.275*** | |
| JB | 3473.999*** | 2129.252*** | 8913.121*** | 2220.475*** | 3745.855*** | 3461.677*** | |
| ERS | −9.892*** | −2.454** | −13.249*** | −4.423*** | −3.123*** | −2.006** | |
| Q(20) | 23.456*** | 65.128*** | 23.170*** | 21.353*** | 23.396*** | 54.172*** | |
| $Q^2(20)$ | 130.651*** | 223.923*** | 131.437*** | 153.458*** | 170.601*** | 262.111*** | |

Notes: ***, ** and * show significance at 1%, 5% and 10%, respectively; Skewness: D'Agostino (1970) test; Kurtosis: Anscombe and Glynn (1983) test; JB: Jarque and Bera (1980) normality test; ERS: Stock et al. (1996) unit-root test with constant; Q(20) and $Q^2(20)$: Fisher and Gallagher (2012) weighted portmanteau test. Moreover, Bitcoin (BTC), Ethereum (ETH), Bitcoin Cash (BCH), Ethereum Classic (ETC) and Litcoin (LTC) denote the five dirty cryptocurrencies while Cardano (ADA), Ripple (XRP), Iota (MIOTA), Stellar (XLM) and Nano (XNO) show the five clean cryptocurrencies.

cryptocurrencies, followed by BTC, ETC, LTC and BCH. Since clean cryptocurrencies have high standard deviation, they imply moderate risk. However, these currencies have high volatility and are therefore exposed to higher risk due to their standard deviation. Both clean and dirty cryptocurrencies have high volatility and are extremely risky. This can be explained by the fact that all green cryptocurrencies have a high standard deviation and are therefore exposed to higher risk. Nevertheless, ADA and XRP have a lower risk, given their standard deviation. After applying the Jarque-Bera normality test (Jarque and Bera, 1980), we can see that all markets have remarkably high values, which means that the series has an abnormal distribution.

Our methodology is built on the quantile connectedness framework. In particular, Chatziantoniou et al. (2021) based on Ando et al. (2022) proposed an alternative estimation quantile connectedness approach. The first estimated connectedness metrics of a quantile vector autoregression (QVAR) model can be calculated by the below function:

$$f_t = k_t(r) + \pi_1(r) f_{t-1} + \pi_2(r) f_{t-2} + \ldots + \pi_n(r) f_{t-n} + \omega_t(r) \tag{1}$$

in the expression (1), $f_t$ denotes a vector of the endogenous variables, $r$ takes values from zero to one $(0-1)$ and depicts the quantile. The letter $n$ shows the lag length of the QVAR framework, $\pi_n(r)$ describes a QVAR coefficient matrix, $k_t$ is a conditional mean vector and lastly, $\omega_t$ is the error vector.

Briefly, the total directional connectedness TO others, if there is a shock of one variable $i$ TO all other variables $j$, can be calculated by the below function:

$$TO_i(H) = \sum_{i=1, i \neq j}^{N} \widetilde{\lambda}_{ji}(H) \tag{2}$$

in equation (2), $\widetilde{\lambda}_{ji}(H)$ displays the influence of the *ith* variables to the variance of the forecast error of the *jth* variables at horizon $H$.

Likewise, the total directional connectedness FROM others, if there is a shock to one variable $i$ FROM all other variables $j$, can be calculated by the below function:

$$FROM_i(H) = \sum_{i=1, i \neq j}^{N} \widetilde{\lambda}_{ij}(H) \tag{3}$$

in equation (3), $\widetilde{\lambda}_{ij}(H)$ displays the impact of the *jth* variables from the variance of the forecast error on the *ith* variable at horizon $H$.

The net total directional connectedness documents the difference between the total directional connectedness TO others and the total directional connectedness FROM others:

$$NET_i(H) = TO_i(H) - FROM_i(H) \tag{4}$$

in equation (4), when the difference between TO and FROM is higher from zero the variable $i$ has more impact to other variables $j$. Therefore, it is called a net transmitter. Otherwise, if the difference between TO and FROM is less from zero the variable $i$ is influenced more from the other variables $j$. Then, it is called a net receiver. Finally, Eq. (5) estimates the total connectedness index (TCI) which is the degree of network interconnectedness. TCI calculates the mean influence of one variable on all others

$$TCI(H) = N^{-1} \sum_{i=1}^{N} TO_i(H) = N^{-1} \sum_{i=1}^{N} FROM_i(H) \tag{5}$$

## 4. Empirical findings

Fig. 3 depicts our models' total dynamic connectedness findings through a heatmap plot. In particular, the heatmap plots were calculated via a QVAR model involving a 200-days rolling window with the lag length of order 1 (BIC) and a forecast of 20 steps ahead. Furthermore, the chart's left vertical axis shows the quantile distribution level (q = 0.05, 0.06, 0.07, 0.08, …, 0.92, 0.93, 0.94, 0.95), the right vertical axis, the

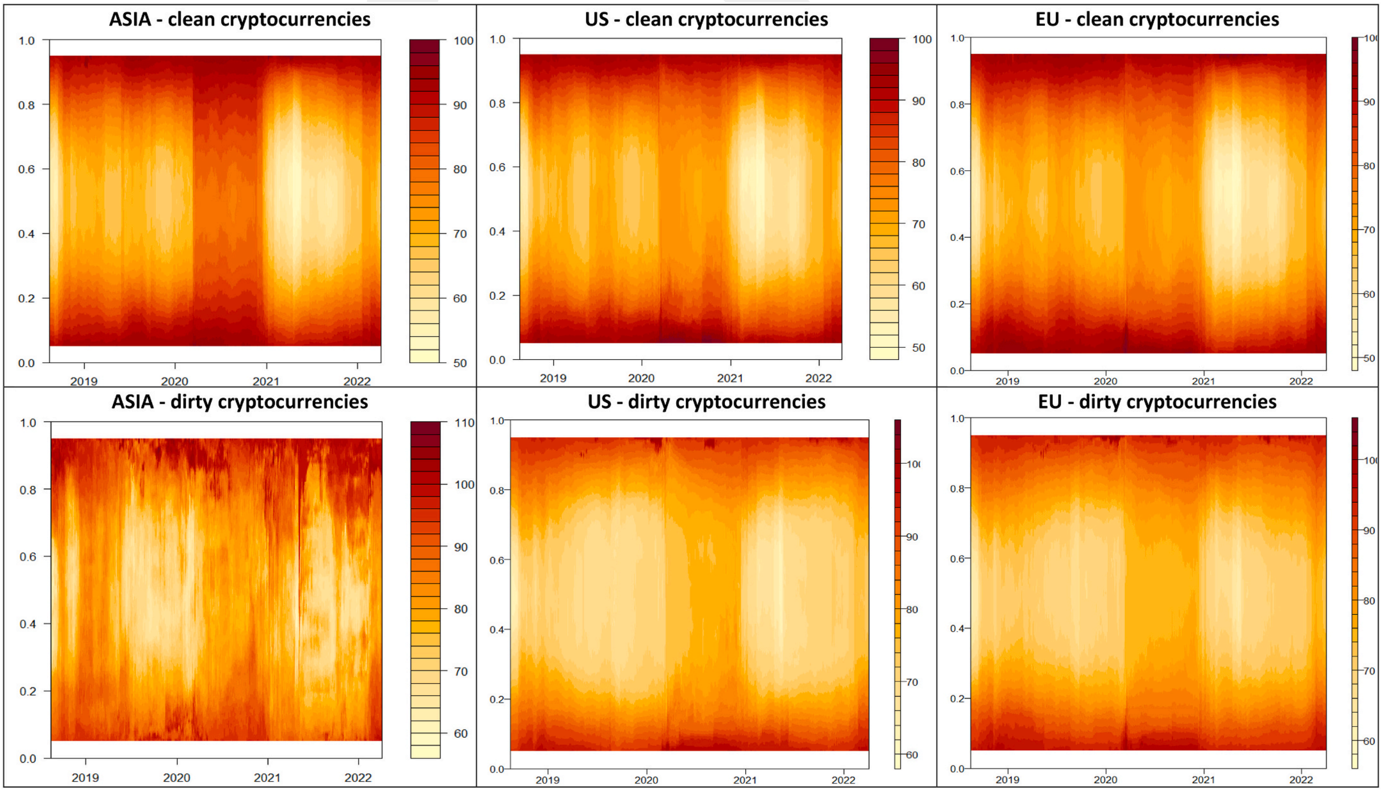

**Fig. 3.** Dynamic total connectedness.
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

color bar, displays the degree of total spillover connectedness. A higher degree (stronger connectedness) of total spillover connectedness among the covariates is illustrated by a warmer shade. Lastly, the horizontal axis describes the time. At a first glance, total connectedness seems to be stronger (warmer shades on the charts) among green economy indices and clean cryptocurrencies than dirty cryptocurrencies. To elaborate it, for clean cryptocurrencies the total spillover connectedness is very high at upper quantiles (at 0.80th – 0.95th), insinuating positive returns, and at lower quantiles (at 0.05th – 0.20th), implying negative returns. For the EU and the US, in particular, the findings are almost the same but not tantamount. However, the clean and dirty cryptocurrencies' green economy has an asymmetric connectedness and spillover relationship over time and across quantiles. This implies that the spillover effect pattern varies depending on the nature of the market (i.e., bust, normal, or boom).

In addition, a notable point in Fig. 3 for clean cryptocurrencies is the year 2020 (nearly the beginning of the year), which was the beginning of the COVID-19 pandemic, the total spillover connectedness influence is very high at all quantiles (warmer shades), specifically for Asia, marked by the big red band. In other words, during the COVID-19 crisis and concurrent with the Russian-Ukrainian war, the transmission of risk appeared to be very high, regardless of whether the market events were in a collapse, normal, or expansion phase. Thus, the COVID-19 pandemic and the Russian-Ukrainian war intensified the spillover effect. More information about the connectedness behavior can be drawn at the tails. Indeed, the market interconnectedness seems to be higher at the extremes, i.e., for the lowest and highest quantiles, along the horizontal axis. The findings of Chatziantoniou et al. (2021) support our observation. The quantiles' higher uncertainty periods are represented by the shades along the vertical axis. In general, these are economic and financial crisis periods. Likewise, the outcomes of dirty cryptocurrencies but this time total connectedness is not very high as for clean cryptocurrencies. Again, US and EU appear to have very similar behavior, but Asia's spillover connectedness differs across quantiles and during the period with warmer shades at upper quantiles.

Fig. 3 illustrating the dynamic total connectedness shows that connectivity is very strong during large variations in yields, both upward and downward. This translates into more red parts up to the 20th quantile for downward movements, and beyond the 80th quantile for upward movements. We note that the COVID-19 period starting in March 2020 is characterized by stronger connectivity for all quantiles, resulting in a redder vertical band. These results are consistent with those of Khalfaoui et al. (2022). The same is true as of the end of Q1 2022, which corresponds to the outbreak of the war in Ukraine. These periods are characterized by larger fluctuations in financial markets. It is interesting to note that investors seem to have a preference for clean cryptos. In fact, the red parts are more marked than the dirty ones, which is consistent for investors who “trade” OMX.” Economically, this can be explained by the fact that the very large variations generally result from shocks strong enough to affect all the assets studied. In such situations, investors look for alternative assets to avoid absorbing the full magnitude of the shock, which is a basic portfolio management strategy.

As a further step and to provide a comprehensive picture of each variable, Figs. 4-10 show each index and cryptocurrency's net results. Warmer shades (red color) in each heatmap diagram reveal a net contributing variable (green economic index or cryptocurrency), while colder shades (blue color) reveal a net receiving variable. This means that investors' sensitivity to green commodities, green economic indices, and dirty, as well as the spillover shock from clean cryptocurrencies, may change depending on the market scenario (i.e., bearish, stable, or bullish markets). Accordingly, it is worth examining the net spillover of markets in a time-quantile space. In summary, green economy indices exhibit net spillover behavior, while cryptocurrency results vary across variables, quantiles, and time.

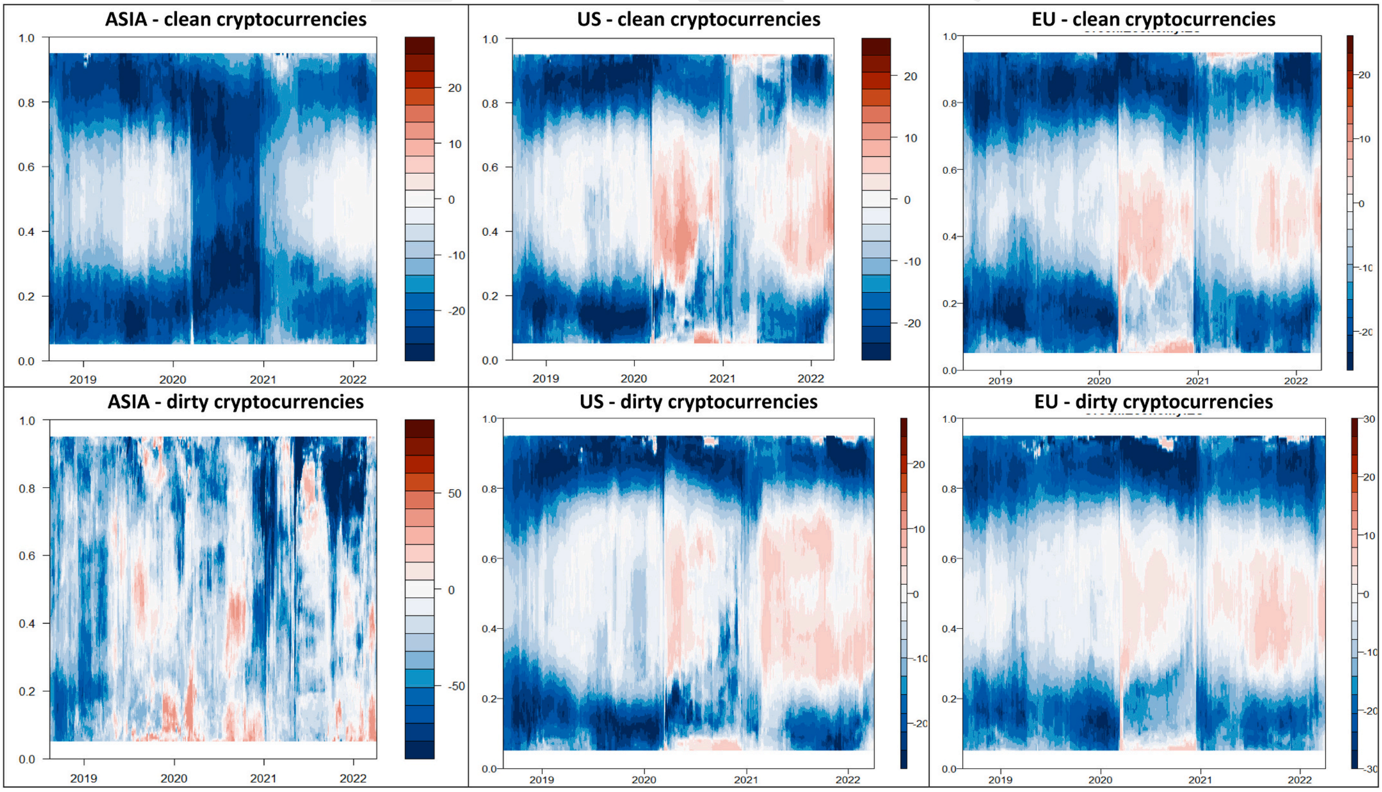

**Fig. 4.** Net total directional connectedness for green economy indices.
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

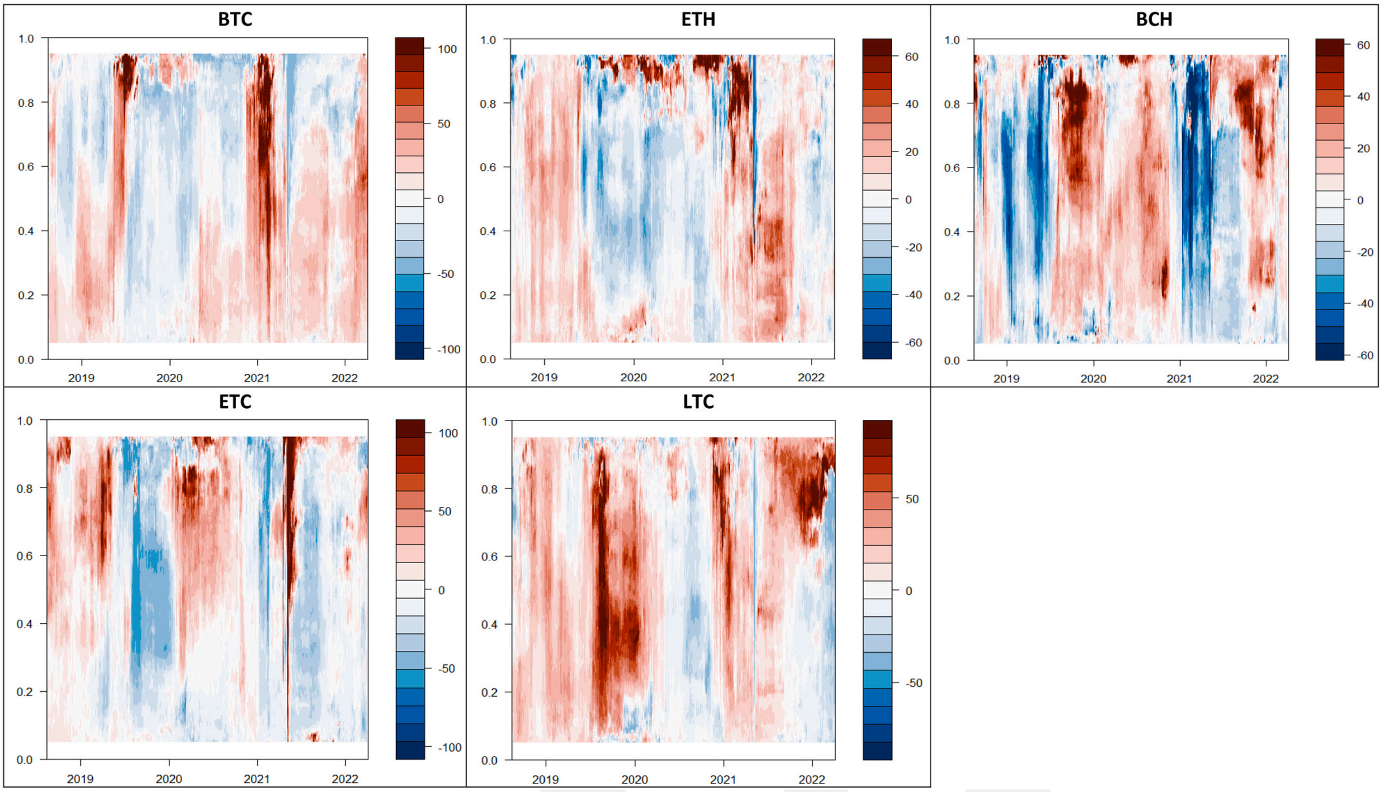

**Fig. 5.** Net total directional connectedness for dirty cryptocurrencies (ASIA).
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

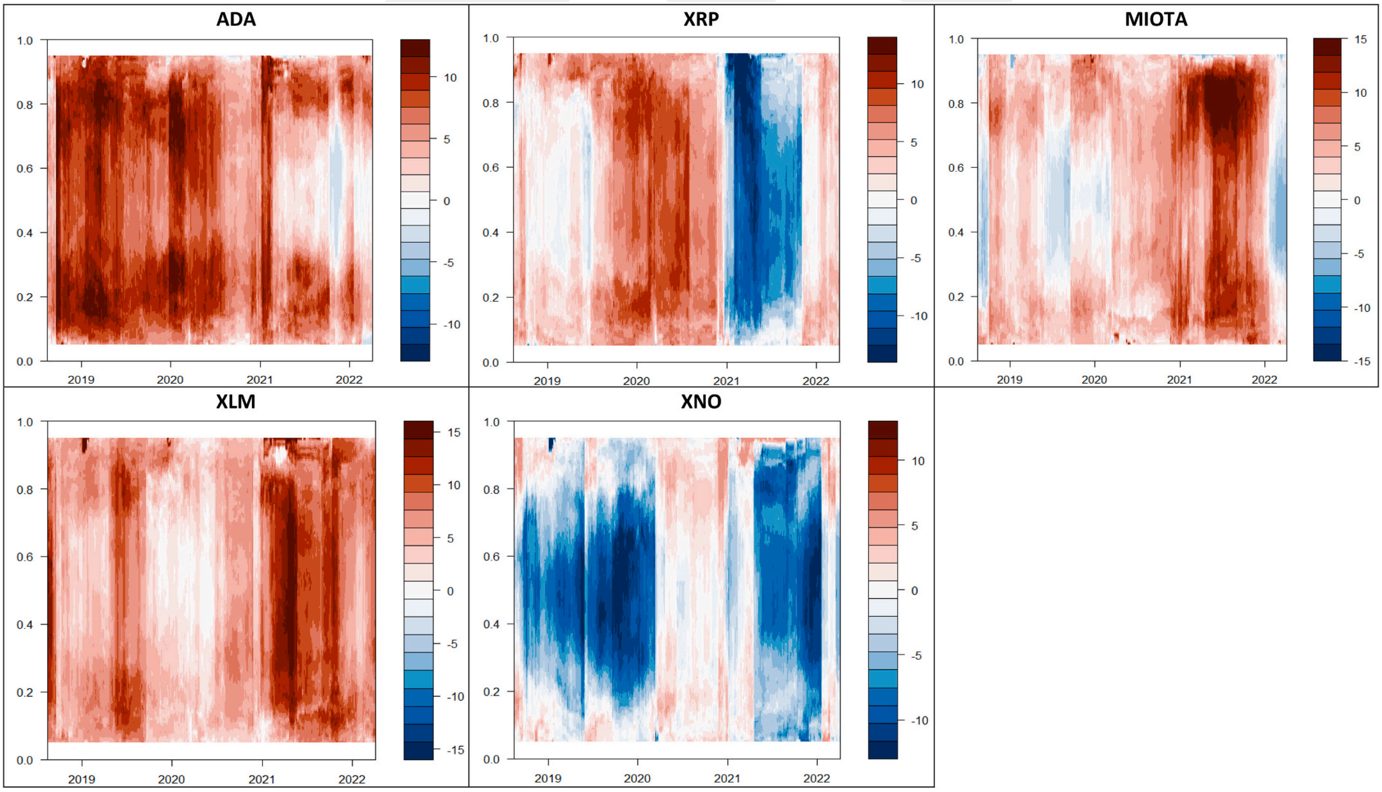

**Fig. 6.** Net total directional connectedness for clean cryptocurrencies (ASIA).
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

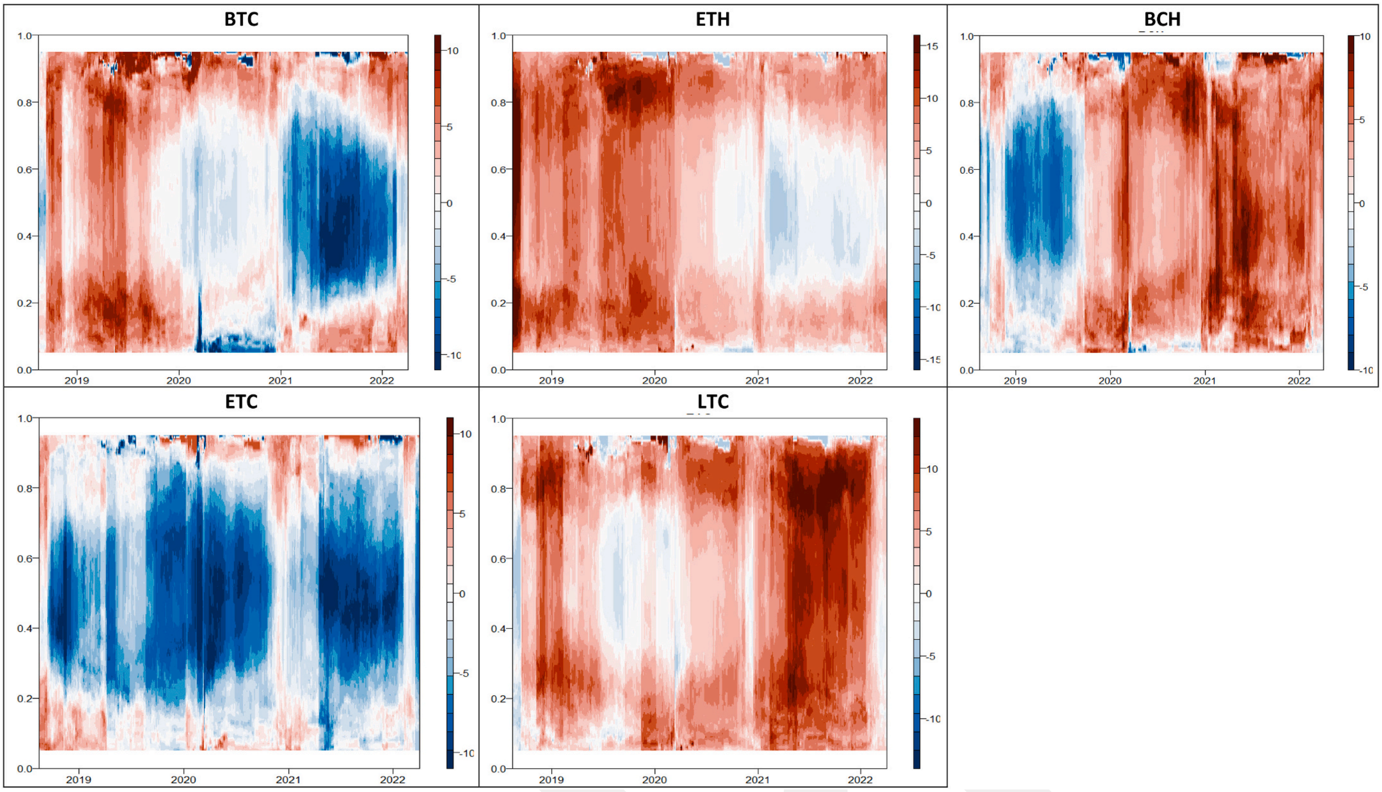

**Fig. 7.** Net total directional connectedness for dirty cryptocurrencies (EU).
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

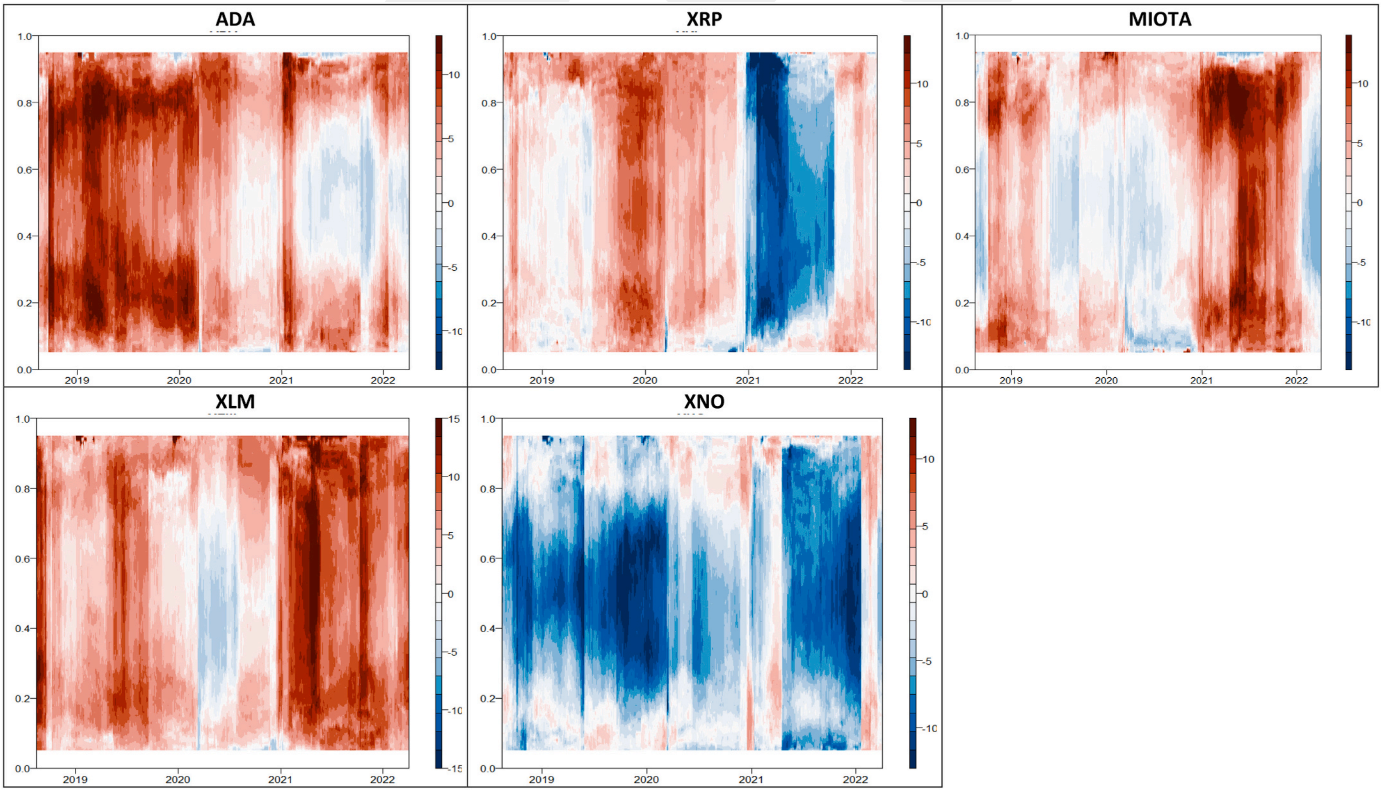

**Fig. 8.** Net total directional connectedness for clean cryptocurrencies (EU).
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

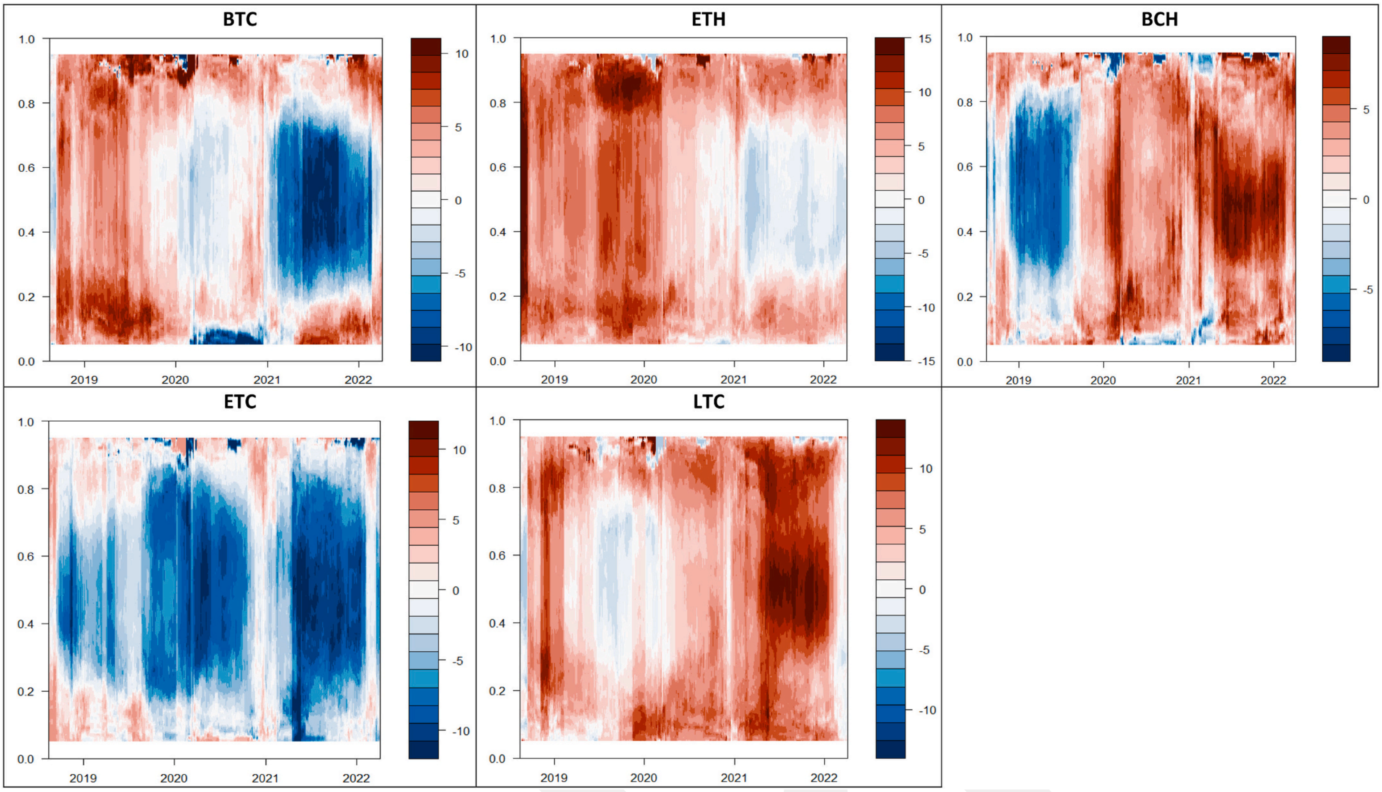

**Fig. 9.** Net total directional connectedness for dirty cryptocurrencies (US).
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.

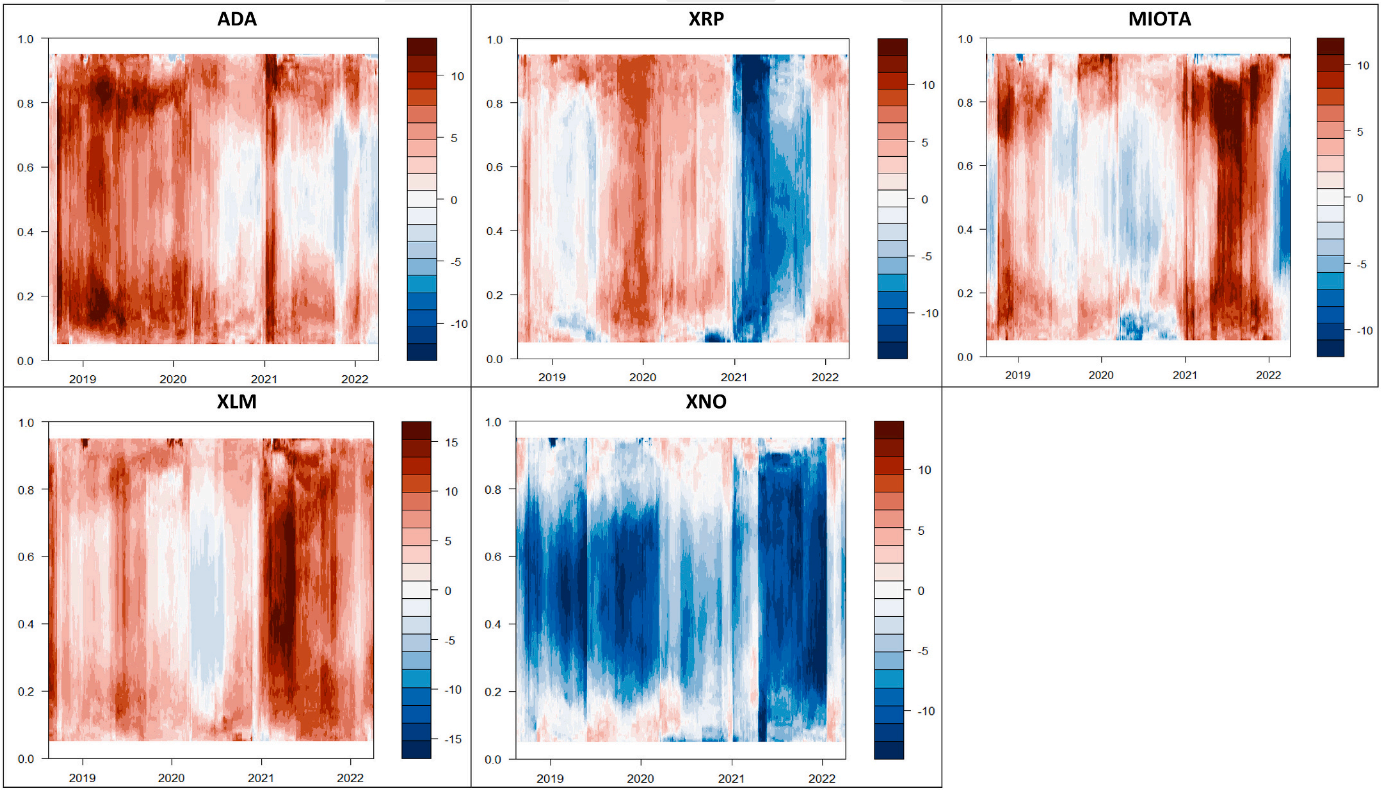

**Fig. 10.** Net total directional connectedness for clean cryptocurrencies (US).
Notes: Findings are based on a 200-days rolling-window QVAR model with lag length of order 1 (BIC) and a 20-step-ahead forecast.s

Based on Fig. 4, which shows the effect of green economy indices, three green economy indices show a net-receiving action in the system with clean cryptocurrencies at the upper quantiles (at 0.80th – 0.95th) and at the lower quantiles (at 0.05th – 0.20th). The year 2020 is interesting to observe is the year 2020 (as shown in the graph of total spillover connectedness in Fig. 3). On the one hand, the Asia index appears more as a net-receiving for the middle quantiles (at 0.40th – 0.60th), for the upper middle quantiles (at 0.65th – 0.85th), and the lower middle quantiles (at 0.15th – 0.40th).

On the other hand, the U.S. and EU indices show a slight warming effect (net contribution) in the middle quantiles (we can see this tendency also towards the end of 2021 and the beginning of 2022) but a net receiver role in the lower and upper quantiles (which is stronger). As for the role of indices in the dirty cryptocurrency system, the US and the EU play almost the same role, but Asia shows an idiosyncratic tendency. In particular, it seems to be more of a net receiver at the upper quantiles, especially during the Covid period.

Fig. 4 confirms that spillovers have become bi-directional, with cryptos sometimes becoming net emitters by 2020. Before COVID-19, most graphs were predominantly blue, while blue and red were present starting in 2020, especially when volatility was not at its extreme levels. On the other hand, the role of clean and dirty cryptocurrencies is pictured in Figs. 5-10.

If the spillovers between the stock market indices and the cryptos were initially relatively low- which justified the integration of the cryptos for portfolio diversification purposes-they have strengthened substantially since 2019, especially in 2020, with the increasing adoption of cryptos by investors, both private and institutional. These investors use cryptos to rebalance their portfolios when the stock market faces shocks and vice versa since spillovers can be bi-directional, as our results show (Fig. 4-10). If cryptos can be net transmitters, investors have massively adopted them. In September 2021, BTC and ETH alone were among the top 20 traded assets (Iyer, 2022). Cryptos are therefore held for the return they can bring and for carrying out portfolio management strategies. If cryptos can be net transmitters, they have been massively adopted by investors.

Starting from the dirty cryptocurrencies, BTC provides a net contribution for the US and EU indices until 2019, at the end of the same year, and towards the end of 2020, this behavior seems to be at the upper quantiles. During the COVID -19 pandemic, BTC is a net receiver at the middle quantiles, the upper middle quantiles, and the lower middle quantiles but a net contributor at the lower and upper quantiles. The role of BTC in the Asian system seems to shift between a net receiver and a net payer during the period and quantiles. Nonetheless, BTC is a strong net contributor in the period of COVID -19 (early 2021), especially in the middle and upper quantiles, but shows a weak net receiver function in the upper quantile and a weak net contributor function in the lower and middle quantiles at the end. ETH cryptocurrency shows a net contributing role in all quantiles for the U.S. and EU. However, at the beginning of the period of COVID -19, BTC has a weak net-contributing effect only at the lower and upper quantiles. ETH and the other dirty cryptocurrencies for the Asian system seem very sensitive to all quantiles and the period. As for the rest of the dirty cryptocurrencies for the US and EU, BCH is a net receiver at the beginning in the middle and upper/lower middle quantiles, but after that, it is a strong net contributor. ETC (for the US and EU) is a strong net receiver, while LTC is a net contributor for the rest of the markets.

As for the net directional results of clean cryptocurrencies, ADA, MIOTA, and XLM show strong net contribution performance, but for ADA, this was more evident before the COVID -19 pandemic and for MIOTA and XLM during the COVID -19 pandemic, starting in early 2021. For the clean cryptocurrencies XRP and XNO, XRP appears to be a strong net receiving at all quantiles in 2021 but shows a net contributing effect for the rest of the period. Finally, XNO clearly shows a net receiving action at intermediate quantiles and all quantiles in 2021. We find that green markets are characterized by variable bidirectional net spillover effects over time to multiple market events.

To sum up, from an economic point of view, the connectivity between OMXs and cryptos has not always been so strong (Lee et al., 2022b; Iyer, 2022). In their early years, cryptocurrencies were not integrated into other asset portfolios, and spillovers were lower. Iyer (2022) shows that spillovers have increased since 2020, as seen in our graphs (Fig. 3-4). Prominent investors are increasingly integrating crypto-assets into their portfolios, and 2020 was characterized by very high volatility due to the COVID-19 pandemic. After a lull in 2021, we also note a stronger link to all quantiles from March 2022, the start of the war in Ukraine. When a shock occurs in the financial markets, OMX is directly affected, impacting cryptocurrencies hedged in OMX portfolios. In this case, the OMX is net-contributing, and the cryptos are net-receiving. The reverse was also observed when significant shocks occurred on cryptos, and OMXs integrated as hedges were impacted, becoming net-receiving (Fig. 4-10).

Overall, important implications can be drawn from our sensitivity analysis for environmental and financial investors and policymakers. Indeed, this work can help policymakers, and central banks in charge of financial stability better understand the effects of contagion between markets to intervene effectively in episodes of boom and sharp fall in financial markets. Understanding the structure of networks, transmission channels, and spillover effects can help intervene with appropriate regulatory measures tailored to the risk posed by crypto assets. Moreover, the net spillover mechanism between markets greatly interests investors. The latter can implement hedging strategies under low, normal, or rising markets thanks to optimal portfolios. Policymakers can consider the spillover effect between markets to make the right decisions in case of a stock market crash or boom.

## 5. Conclusion, discussions and policy suggestions

With sustainable energy and green cryptocurrencies, there are growing worries about their security and environmental footprint. This has created new opportunities to improve the mining carbon footprint and provide greener alternatives. The profitability of renewable energy companies is a prerequisite for the sustained allocation of private investment to clean energy. Green energy stocks now represent a new category of assets. Indeed, they will likely survive and compete against similar assets in different markets and regions, including cryptocurrencies.

For this reason, we examine the correlation and spillover relationship between the green economy indices and “dirty” and “clean” cryptocurrencies from November 2017 to April 2022 in the time and time-frequency domains. Accordingly, we use the quantile vector autoregressive (Q- VAR) correlation approach developed by Ando et al. (2022) to analyze the relationship between green stock markets in a given region and the market for cryptocurrencies. First, the empirical results of dynamic aggregate interdependence show that aggregate interdependence is stronger for green economy indices and clean cryptocurrencies than for dirty cryptocurrencies. For clean cryptocurrencies, the results show that the impact of total spillover connectedness is very high for all quantiles (warmer shades), especially for Asia. The same results hold for dirty cryptocurrencies, but this time the overall connectedness is not as high as that of clean cryptocurrencies. Again, the U.S. and EU appear to behave very similarly, but the connectedness of Asian spillovers differs between quantiles and across time, with warmer shades at higher quantiles.

In particular, the results are almost identical but not equivalent for the EU and the US. Second, the overall directional net connectedness results suggest that green economy indices exhibit net spillovers, while the results for cryptocurrencies vary by variable, quantile, and time. Moreover, three green economy indices show a net receiving action in the system with clean cryptocurrencies in the upper quantiles (at 0.80–0.95) and in the lower quantiles (at 0.05–0.20). The year 2020 is interesting to observe: on the one hand, the Asia index shows up more with a net receiving action in the middle quantiles (at 0.40–0.60), in the upper middle quantiles (at 0.65–0.85) and in lower middle quantiles (at 0.15–0.40).

On the other hand, the U.S. and EU indices show a slight warming effect (net contribution) on the middle quantiles (this strand is also observed towards the end of 2021 and early 2022). Still, a net receiver role on the lower and upper quantiles (which is stronger). As for indices in the dirty cryptocurrency system, the U.S. and EU play almost the same role, but Asia exhibits an idiosyncratic orientation. In particular, it seems to be more of a net beneficiary at the upper quantiles during the period COVID -19.

Starting from the dirty cryptocurrencies, BTC provides a net contribution for the US and EU indices until 2019, at the end of the same year, and towards the end of 2020, this behavior seems to be at the upper quantiles. During the COVID -19 pandemic, BTC is a net receiver for the middle quantiles, upper middle quantiles, and lower middle quantiles but a net contributor for the lower and upper quantiles. The role of BTC in the Asian system seems to fluctuate between a net receiver and a net payer over time and in quantum. Nonetheless, BTC has been a strong net contributor during the period of COVID -19 (early 2021), especially in the middle and upper quantiles. Still, in the end, it shows weak net receiving action at the upper quantile and weak net contributor action at the lower and middle quantiles. ETH cryptocurrency shows a net contributing role in all quantiles for the U.S. and EU.

However, at the beginning of the period, COVID -19 BTC is a weak net contributor only at the lower and upper quantiles. ETH and the other dirty cryptocurrencies for the Asian system seem very sensitive to all quantiles and the period. As for the rest of the dirty cryptocurrencies for the US and EU, BCH is a net receiver at the middle and upper/lower middle quantiles at the beginning but becomes a strong net contributor after that. ETC (for the US and EU) has a strong net receiving function, while LTC has a net contributing function for the other markets. In terms of net insights on the direction of clean cryptocurrencies, ADA, MIOTA, and XLM show a strong net contribution function; however, for ADA, this is more evident before the COVID -19 pandemic, and for MIOTA and XLM during the COVID -19 pandemic, more specifically from the beginning of 2021. For the clean cryptocurrencies XRP and XNO, XRP appears to be a strong net receiver at all quantiles in 2021, while the rest of the period is a net payer. Finally, XNO clearly shows net receiver action at the intermediate quantiles and all quantiles in 2021.

At the end of this study, we believe that market participants and policymakers may find food for thought. So, this primarily affects retail investors or institutional managers who want to use green economy bonds to hedge cryptocurrencies and build their portfolios. Therefore, investors should consider the dynamics of directional net spillovers between the markets under study, provided that they distinguish between risk spillovers, net payers, and net takers. The findings can also serve as a guide for optimizing stock trading, especially when the market is concerned about climate change risks. Policymakers should pay more attention to the network structure and dynamic changes in the spillover effects of shocks across relevant markets. Therefore, it is necessary to consider the path of net risk spillovers, especially under extreme market conditions. Hence, the need for new regulatory policies to be implemented after extreme negative or positive events occur. It is true that the current weak regulatory framework for cryptocurrencies, as well as their high carbon footprint, has deterred environmentally conscious investors. However, environmental awareness among their creators could lead to a technological shift that encourages using more sustainable, less carbon-intensive algorithms. In addition, introducing a carbon tax could help market players internalize the negative environmental costs of cryptocurrencies, especially in countries with high carbon emissions. Their energy consumption could be reduced if PoW-based consensus gives way to green alternatives. However, this must be part of increased government policies to support green businesses and improve the financial system. All of these projections, of course, require further research. First, on the impact of climate change on investors' positions on the performance of various environmentally friendly investments. Regarding the latter, various uncertainty factors should be considered, including those related to economic policy, the social safety net, and climate change. Finally, using fractional integration or Markov switching copula approaches, it is possible to account for the presence of cyclical patterns and the persistence of volatility in green assets.

## Credit author statement

**Eyup Dogan**: Supervision, data curation, writing-review&editing; **Panayiotis Tzeremes**:, Software, Methodology, writing-original draft

**Arshian Sharif:** Writing-original draft, writing-review&editing, methodology; **Mariem Brahim**: wiriting-original draft, writing-review&editing.

## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2023.106594.

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