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*Research article*

# Carbon and safe-haven flows

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**Abstract:** This paper explores the role of European Union Allowances (EUAs) as a safe haven for a range of assets and analyses the effect of safe-haven flows on the European carbon futures market. In particular, we demonstrate that EUAs can be considered a refuge against fluctuations in corporate bonds, gold and volatility-related assets in periods of market turmoil. Furthermore, we have shown that extremely bearish and bullish movements in those assets for which the EUA acts as a safe haven induce excess volatility in carbon markets, higher carbon trading volume and larger than normal EUA bid-ask spreads. These findings support the idea that some traders, by considering carbon futures as a refuge asset, induce safe-haven flows into the carbon market. The presence of these flows provides additional insights into the financialisation of the European carbon futures market.

**Keywords:** carbon futures; EUAs; quantile regression; safe-haven asset; safe-haven flows; volatility

**JEL Codes:** G11, G15

**Abbreviations:** CBOE: Chicago Board of Option Exchange; ESMA: European Securities and Markets Authority; EUA: European Union Allowances; EU ETS: European Union Emissions Trading Scheme; IBOXX EU: IBOXX EURO Corporates AAA index; IBOXX NA: IBOXX USD Corporates AAA Index; ICE: Intercontinental Exchange; MSCI EU: MSCI Europe Index; MSCI NA: MSCI North America Index; NYMEX: New York Mercantile Exchange; OLS: Ordinary least squares; QR:

Quantile regression; VIX: S&P 500 Volatility index; VSTOXX: Euro STOXX 50 Volatility index; WTI: West Texas Intermediate

## 1. Introduction

The creation in 2005 of the European Union (EU) Emissions Trading System (EU ETS) began to bring carbon assets to the attention of academics, practitioners and the media. The EU ETS was launched as the EU's main mechanism for achieving greenhouse gas reductions; however, the absence of reliable emissions data caused the total quantity of allowances issued to exceed emissions and drove down the price of European Union Allowances (EUAs) to €0 in 2007. Low carbon prices, the oversupply of allowances due to the eruption of the global financial meltdown in 2008, the exploitation of weak carbon market regulations in order to commit financial crimes such as tax fraud and the theft of carbon credits through phishing scams, led to a loss of confidence in the European carbon market. Nevertheless, reforms to the ETS framework that took place from 2013 onwards, such as the European Commission's decision to delay the auctioning of 900 million allowances from 2014–2016 to 2019–2020 and, subsequently, the implementation of the Market Stability Reserve in 2019 in order to avoid a possible surplus of EUAs in the long-term, pushed up the price of EUAs from €5.69 per tonne of $CO_2$ equivalent (€/$TCO_2$) in December 2013 to around €65/$TCO_2$ by October 2021. In fact, the price of carbon reached all-time highs 40 times during 2021. This bullish rally in EUA prices has put carbon markets back in the spotlight, especially for traditional investors who see the EUA as an asset with safe-haven potential.

A number of financial studies have investigated whether specific assets can act as a refuge during a severe financial crisis. In addition to seeking a non-positive correlation with the market of choice in difficult times, following Baur and Lucey (2010), a potential refuge asset must fulfil other characteristics, such as being considered a medium of exchange or serving as a hedge against inflation. Kaul and Sapp (2006), Dutta et al. (2020), Conlon and McGee (2020) and Baur et al. (2021) have provided comprehensive reviews of studies on safe-haven assets, focusing on the US dollar, gold, cryptocurrencies and bonds, respectively. In general, the US dollar, gold and bonds are perceived as safe assets for periods of uncertainty; however, this is not the case for Bitcoin, for which recent empirical evidence is abundant but controversial (Wen et al., 2022).

As for carbon assets, several papers have studied the role of EUAs as a diversifier or as a hedge in a portfolio context. Chevallier (2009a), Gronwald et al. (2011), Mansanet-Bataller and Pardo (2011), Reboredo (2013), Uddin et al. (2018) and Demiralay et al. (2022), among others, have found that EUA returns are positively, though not perfectly, correlated with the returns of stock indices or energy commodities, making EUAs a potentially good diversifier of risk in portfolios that invest in equities, coal or crude oil. Chevallier (2009b) and Ahmad et al. (2018) observed a negative dependence between the junk bond yields and the carbon price, while Palao and Pardo (2021) have found that EUAs are negatively correlated with respect to European and US corporate AAA-rated bond indices and uncorrelated with reference to sovereign yields. These results suggest that EUAs can act as a hedge for fixed income portfolios. Furthermore, Pardo (2021) investigated whether EUAs can serve as an investment asset to hedge against inflation risk for two economic areas and six countries. He found a strong positive correlation between the nominal returns of EUAs and unexpected shifts in purchasing power, suggesting that EUAs can be an effective way to protect portfolios from the negative effects of unexpected inflation in all areas and countries except the USA.[1]

Despite the large number of papers that have investigated the possible advantages of investing in carbon assets, the role of the EUA as a safe-haven asset is poorly understood. Only Yang and Hamori (2021) have analysed the relationship between the carbon market and the cryptocurrency market, concluding that European carbon assets offer shelter from the crypto market, while the Chinese carbon market does not. The originality of our paper is twofold. First, we investigate the role that European carbon permits play as a safe haven for a range of assets such as crude oil, equities, corporate bonds, sovereign bonds, gold and volatility indices. Second, we analyse the effect that safe-haven flows have on liquidity and volatility in the European carbon market. As far as we know, no attempt has been made to study the effect of safe-haven flows on the carbon market.

To investigate whether the EUA has safe-haven properties, we will apply the model by Baur et al. (2021). They suggest a new approach based on the quantile regression (QR) methodology to identify safe-haven assets that aims to analyse the performance of the potential refuge asset and characterise its relationship with the target market. Specifically, following Baur et al. (2021), we have modelled conditional return quantiles for 12 benchmarks chosen from six target markets in order to focus only on the extreme market quantiles of such references and not on extreme EUA returns conditions. Unlike papers that apply the QR methodology to analyse conditional return quantiles of potential safe-haven assets with the returns of each target market, we model conditional return quantiles of each benchmark with the potential safe-haven asset returns. In addition, after identifying the benchmarks that can use the EUA as a safe haven, we assess the impact of safe-haven flows on some carbon market variables. Following the idea suggested by Kaul and Sapp (2006), if the EUA is viewed as a safe-haven asset by traders, funds should flow into the European carbon futures market on days of stress in the target markets from which safe-haven flows originate, causing abnormal behaviour in carbon liquidity and volatility.

Our key findings indicate that the EUA can act as safe haven for corporate bonds, gold and volatility-related assets. In addition, carbon trading volume rises during times of market stress in certain benchmark markets, and, in some cases, this occurs alongside increases in carbon market volatility and volume and wider bid-ask spreads. These results indicate the existence of safe-haven flows and provide additional insights into the financialisation of the European carbon futures market. The remainder of this work is structured as follows. Details about the data are provided in the following section, followed by a description of the methodology in Section 3. The empirical results on QRs are presented in the fourth section, which also investigates how carbon volatility and liquidity behave during times of stress in the target markets. Section 5 concludes the paper.

## 2. Data

The empirical analysis is focused on EUA futures prices and 12 daily benchmarks from six markets: carbon, oil, stocks, bonds, precious metals and cryptocurrencies.

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[1] Demiralay et al. (2022) reviewed the literature related to carbon as an investment vehicle. One line of study analyses how carbon interacts with energy markets, while another examines the univariate dynamics of carbon asset pricing. Finally, a third strand of the literature investigates the relationship between the carbon and the financial markets, including the potential benefits of using carbon assets as a hedge or to diversify portfolios.

### 2.1.1. *Carbon markets*

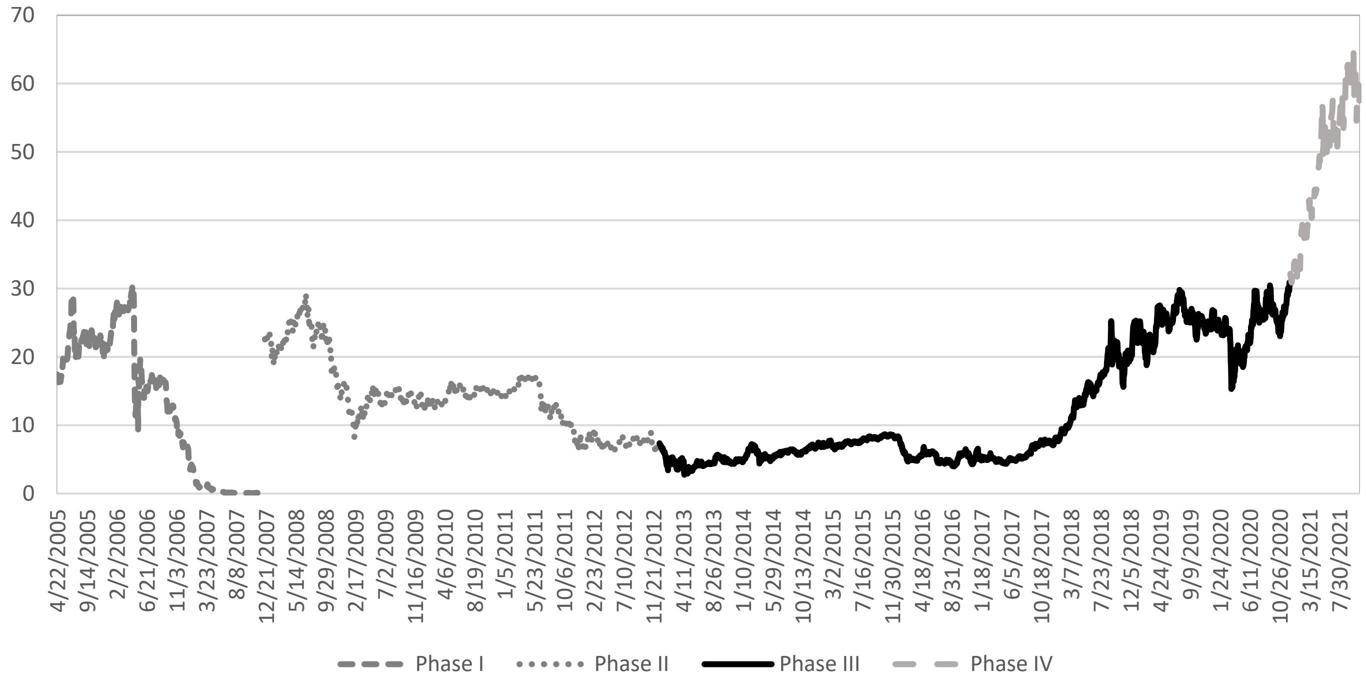


**Figure 1.** Evolution of the EUA price. The figure shows the evolution of the settlement price in €/$TCO_2$ for the EUA December futures front contract from April 17, 2015 to October 27, 2021. The graph plots the EUA front contract settlement price during the four phases of the program since it started: Phase I (2005–2007), Phase II (2008–2012), Phase III (2013–2020) and Phase IV (2021–2030).

Three European trading venues offer secondary markets for trading EUAs: EEX in Germany, ICE Endex in the Netherlands and Nasdaq Oslo in Norway. Spot, futures and options on futures contracts can be traded in these venues. They all have a standardised contract size of 1,000 allowances, where each allowance gives the holder the right to emit one tonne of $CO_2$ equivalent. Given that most of the carbon trading volume is concentrated in the ICE EUA December futures contracts listed on the ICE Endex futures market, we have chosen those futures contracts to carry out the study.[2] Specifically, the carbon dataset consists of the daily ICE EUA December futures settlement prices, the highest and the lowest traded EUA prices on each day expressed in €/$TCO_2$, the trading volume and the last bid and ask prices at the end of the trading session. The sample period consists of data from April 25, 2005 to October 27, 2021 for all series, except for the bid and ask series, where the period starts on April 17, 2015.[3] Figure 1 illustrates the price movements of EUA settlement futures during 2005–2021, based

[2] A recent comparison, based on open interest data, across the three markets by the European Securities and Markets Authority (ESMA) shows that the ICE Endex accounts for the largest share of outstanding contracts. Specifically, almost 45% of the open interest on the ICE Endex is concentrated in futures maturing in December 2021. See ESMA (2021).

[3] See https://www.theice.com/publicdocs/endex/ICE_Endex_Markets_B.V._Rules.pdf for further information on ICE Endex Futures contracts. (Last accessed in March 2022.)

on daily data. The figure shows that the EUA price ranges between €0/$TCO_2$ in October 2007 and €64/$TCO_2$ in October 2021. This radical pattern is closely related to the different regulations that have affected each of the four phases into which the EU ETS is divided. Phase I encompasses the pilot period from 2005 to 2007. Phase II runs from 2008 to 2012 and Phase III covers the period from 2013 to 2020. Finally, the current phase started in 2021 and will last until 2030.[4]

As mentioned above, EUA prices plummeted in 2007 due to an oversupply of EUAs, which brought down the price to nearly €0/$TCO_2$. Overall, the evolution of EUA prices since the beginning of the EU ETS is characterised by an initial price drop and a subsequent sustained price increase, ending with a sharp rise. In particular, in mid-2020, the EU increased the emission reduction target for the period of 2021–2030 from 40% to 55%, which caused the overall number of emission allowances to decline at an annual rate of 2.2% instead of the previous 1.74%. In this context, EUA prices increased from €30/$TCO_2$ on average in 2020 to more than €60/$TCO_2$ by the end of the period analysed.

Following Davino et al. (2014, p. 68), while the QR analysis is robust to outliers in the dependent variables (selected benchmarks) to ensure that the estimates are minimally impacted by anomalous values, the same is not true for extreme values in the independent variable (EUA returns). The large number of outliers observed in EUA prices from 2005 to 2007, along with the low carbon market liquidity that characterised that period, make the analysis of the carbon market highly reliant on the chosen time frame. Consequently, we have decided not to consider Phase I data. Therefore, daily data covering the time period from December 18, 2007 to October 27, 2021 are used in this investigation.

### *2.1.2. Benchmarks and target markets*

Based on the previous empirical results regarding the diversification and hedging properties of EUAs commented on in Section 1, we have considered 12 benchmarks, which are briefly described next. For the crude oil references, we have selected the Brent monthly futures contract (BRENT) quoted on the ICE as the European crude oil benchmark and the West Texas Intermediate (WTI) traded on the NYMEX as the most liquid US crude oil benchmark. Both crude oil benchmarks have monthly maturity contracts and are quoted in dollars per barrel. The conversion into euros has used the USD/EUR exchange rate provided by Refinitiv (Reuters).

For equity market benchmarks, we have chosen the MSCI Europe Index (MSCI EU) and the MSCI North America Index (MSCI NA), both expressed in euros, which cover approximately 85% of the free float-adjusted market capitalisation in Europe and the USA and Canada, respectively.[5]

For bond markets, corporate as well as government references have been considered. First, we have included the IBOXX EURO Corporates AAA Index and the IBOXX USD Corporates AAA Index, both expressed in euros. IHS Markit computes these indices every day, and they reflect the AAA investment-grade bond markets for euro and US dollar denominated bonds, respectively.[6] Second, we

[4] See https://ec.europa.eu/clima/eu-action/eu-emissions-trading-system-eu-ets/development-eu-ets-2005-2020_en for further information on the key features and main changes of each phase. (Last accessed in December 2021.)

[5] More details on the MSCI indexes are available at https://www.msci.com/documents/10199/f6179af3-b1d1-4df0-8ac9-215451f3ac0a for MSCI Europe and https://www.msci.com/documents/10199/7ded14f4-a8c8-49f5-af2e-11b2fe1f3cfe for MSCI North America. (Last accessed in January 2022.)

[6] To learn more about these indices, see: https://ihsmarkit.com/products/iboxx.html (Last accessed in January 2022).

have used the yields of German (GER ZERO) and US (US ZERO) 10-year zero coupon sovereign bonds. Both represent two of the highest credit quality fixed-income investments available in the world.[7]

In addition, we have also considered Bitcoin quotes, gold futures prices and two volatility indices. In the case of Bitcoin, we have used the exchange rate Bitcoin/€ (BITCOIN) published by Refinitiv (Reuters). In this respect, our sample period is similar to that used by Yang and Hamori (2021), although our sample contains more observations (1,720 observations versus 1,408). In the case of gold, we have chosen the gold futures contract (GOLD) listed in COMEX and quoted in dollars per troy ounce.[8] Finally, we have also included two equity market volatility indices. Specifically, we have selected the Euro STOXX 50 volatility index (VSTOXX) as a proxy for European stock market volatility and the Chicago Board of Option Exchange (CBOE) volatility index (VIX) as the reference for the US market. VSTOXX and VIX are based on EURO STOXX 50 and S&P 500 Indices real-time options prices, respectively. The calculation of these volatility indices not only gives the implied volatility of two of the most widely followed equity indices in the world, but it also allows investors to directly trade volatility by taking positions through exchange-traded funds, exchange-traded notes, futures or options contracts that have VSTOXX or VIX as the underlying factors.[9]

In summary, for the empirical analysis, we have used historical daily time series. Data for EUA, Brent, WTI, GOLD and BITCOIN have been obtained from Refinitiv (Reuters); IBOXX indices and GER ZERO data have been sourced from Bloomberg; and, MSCI, US ZERO, VSTOXX and VIX series have been taken directly from their institutional webpages. Data for the sample period are from December 18, 2007 to October 27, 2021, except for BITCOIN, where the data are only available from December 8, 2014.

We follow Carchano et al. (2014) and employ the last-day criterion to create a front contract series for EUA and gold futures prices. In the case of the EUA, December futures contracts are switched upon expiration of the December contract closest to maturity and, in the case of gold, we roll over the futures contracts to switch from the front month contract that is close to maturity to the nearest monthly futures contract. However, for crude oil futures contracts, following Palao et al. (2020), we take the closing prices of the nearest monthly futures contract 5 days prior to expiration.

## 3. Methodology

This section details the definition of safe haven and describes the methodology used in this study. A safe-haven asset is generally identified by the correlation of its returns with another asset or portfolio only in periods of market turbulence. In particular, Baur and Lucey (2010) describe a safe-haven asset as one that is either uncorrelated or negatively correlated with another asset or portfolio when markets are volatile. They point out that safe-haven assets are characterised by non-positive correlation when

[7] A comprehensive overview and past performance data of the German and the US Treasury 10-year zero-coupon yield is available at https://www.bundesbank.de/en/statistics/time-series-databases and https://www.federalreserve.gov/data/nominal-yield-curve.htm, respectively. (Last accessed in January 2022.)

[8] The specifications regarding the gold futures contract can be seen at https://www.cmegroup.com/markets/metals/precious/gold.contractSpecs.html. (Last visited in March 2022.)

[9] Further information on VSTOXX and VIX can be found at https://www.stoxx.com/index-details?symbol=V2TX and http://www.cboe.com/vix/, respectively. (Last accessed in January 2022.)

market behaviour is extreme, highlighting that the average correlation need not be positive or negative. Baur and McDermott (2010) built on the previous definition by differentiating between strong and weak safe-haven assets, defining them as assets that are negatively correlated or uncorrelated, respectively, with other assets or portfolios during bear markets.

To analyse the safe-haven capacity of the EUA, a multivariate regression analysis has been carried out using the QR approach developed by Koenker and Bassett (1978). Based on the above definitions of safe haven, the lowest quantiles of the dependent variable are of primary interest to us. Specifically, of particular interest is the association between the returns of each market and the performance of the EUA in the lowest return quantiles of the chosen market (from 0.01 to 0.05 and 0.1). The econometric approach rests on a QR model in which the chosen market ($y$) is regressed on EUAs returns ($x$):

$$y_t = x_t\beta_\theta + u_{\theta,t} \text{ with } Q_\theta(y_t|x_t) = x_t\beta_\theta \tag{1}$$

where $Q_\theta(y_t|x_t)$ is the $\theta^{\text{th}}$ conditional quantile of $y$ given $x$ ($0 < \theta < 1$). Therefore, we estimate a QR model for each chosen market with EUA returns. $\beta_\theta$ is estimated by minimising the sum of the asymmetrically weighted absolute error terms, where different weights are given to the positive and negative residuals according to the selected quantile:

$$\beta_\theta = argmin_\beta \tag{2}$$

The use of an unbalanced weighting system in which the weight is equal to $\theta$ for the sum of positive deviations and equal to $(1-\theta)$ for the sum of negative deviations determines, in both cases, a different attraction of points lying above or below the regression line (see Davino et al., 2014, p. 6–8).

Based on the above definitions, if $\beta_\theta < 0$ for the lowest quantiles, the EUA should be considered a strong safe-haven asset. In other words, when the chosen market is experiencing stress, the EUA price should increase. On the other hand, if $\beta_\theta = 0$ for the lowest quantiles, then the asset would be considered a weak safe-haven asset.

It is important to highlight that the above definitions are conditional on the presence of turbulence in the target market. However, we have also estimated the ordinary least squares (OLS) regression to analyse the $\beta$ coefficient that provides information about the trade-off between the performance of the target market and EUA returns on average. In this way, we can identify a hedge as an asset that is uncorrelated (weak hedge, $\beta = 0$) or negatively related (strong hedge, $\beta < 0$) to another asset. If the asset has a positive relationship with the other asset ($\beta > 0$) on average, it would be a diversifier.

To study the impact of safe-haven flows on the carbon market, we have considered the trading volume, the bid-ask spread calculated as the difference between the bid and the ask prices at the end of the trading day and daily estimates of volatility. Specifically, as a proxy for volatility, we have used the measure proposed by Parkinson (1980):

$$\sigma_t = \sqrt{\frac{1}{4log2}\left(logP_{H,t} - logP_{L,t}\right)^2} \tag{3}$$

where $P_{H,t}$ and $P_{L,t}$ are the highest and lowest futures prices traded on day $t$, respectively. Parkinson's volatility measure is widely regarded as an indicator of intraday uncertainty, and it provides more information than the close-to-close standard deviation, as high intraday volatility could be detected by this measure even with two identical consecutive closing prices.[10]

After determining the daily estimates of volatility, trading volume and size of the bid-ask spread, we calculate their median values conditioned by stressful days in the reference market (Sample S1). Then, we compare those values with the medians obtained for the complementary sample (Sample S2). Unlike Smales (2019), who evaluated the volatility and liquidity of the potential safe-haven asset with the volatility and liquidity of other assets under different market scenarios, we study such characteristics only in the carbon market conditioned by extreme situations in the chosen market. Two situations have been defined as "extreme": first, those days on which the return of the target market is equal to or below the value at the 1st, 5th and 10th percentiles for the smallest extreme values of the return distribution in the target market; and second, those days on which the variable of the target market is equal to or above the value at the 90th, 95th and 99th percentiles for the largest extreme values. The idea is to assess the presence of safe-haven flows and their effects on the European carbon futures market by comparing the estimated volatility and liquidity of carbon on days with market stress in the target market with the estimation of such measures on days without such stress. Specifically, we apply the two-sided Wilcoxon rank sum test in order to examine the null hypothesis that data in S1 and S2 are samples from continuous distributions with equal medians, which is against the alternative hypothesis that they are not. In addition, we apply the right-tailed hypothesis test, where the alternative hypothesis states that the median of S1 is larger than the median of S2.

## 4. Empirical analysis

Table 1 presents the summary statistics. The results for BRENT, WTI, MSCI EU, MSCI NA, IBOXX EU, IBOXX NA, BITCOIN and GOLD are expressed in logarithmic returns, while findings for GER ZERO, US ZERO, VSTOXX and VIX are expressed in levels. We see that BITCOIN has by far the highest median return, while corporate bonds (IBOXX EU and IBOXX NA) have the lowest. The EUA has a range that goes from −43.21% to +23.82%. However, the single asset with the widest range is WTI, with a low of −76.98% and a high of +23.89%, both reached during the spring 2020 oil crisis. Corporate bond benchmarks, as expected, as well as stock indices and GOLD, have the lowest standard deviations and the narrowest ranges. Turning to the series expressed in levels, we observe that implied volatility is higher in Europe than in the USA. The opposite is detected in the 10-year zero-coupon sovereign bond yields, where the US benchmark is higher than that in Germany, where the yield exhibits negative values.

[10] It is also possible to use other volatility measures as proxies for intraday uncertainty, which use intraday prices, such as realised volatility or realised range volatility. However, we have observed that, during some sessions in the maturities of 2008 and 2009 ICE EUA December futures contracts, there are intervals of more than five minutes without transactions. In order to avoid possible problems arising from infrequent trading at times of low market liquidity, we have chosen Parkinson's volatility measure as a proxy for intraday uncertainty.

**Table 1.** Summary statistics.

| | EUA | BRENT | WTI | MSCI EU | MSCI NA | IBOXX EU | IBOXX NA | GER ZERO | US ZERO | BITCOIN | GOLD | VSTOXX | VIX |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean | 0.0002 | -0.0001 | -0.0005 | 0.0001 | 0.0004 | 0.0000 | 0.0001 | 1.3190 | 2.5291 | 0.0030 | 0.0003 | 23.4654 | 19.1453 |
| Median | 0.0005 | 0.0009 | 0.0005 | 0.0006 | 0.0008 | 0.0001 | 0.0002 | 0.8350 | 2.4286 | 0.0023 | 0.0005 | 21.4857 | 16.7100 |
| Maximum | 0.2382 | 0.2005 | 0.2389 | 0.0958 | 0.0983 | 0.0087 | 0.0300 | 4.6220 | 4.8355 | 0.2246 | 0.0838 | 87.5127 | 82.6900 |
| Minimum | −0.4321 | −0.3716 | −0.7698 | −0.1231 | −0.1344 | −0.0282 | −0.0420 | −0.8670 | 0.5202 | −0.3120 | −0.0972 | 10.6783 | 9.1400 |
| Std. Dev. | 0.0312 | 0.0239 | 0.0295 | 0.0125 | 0.0134 | 0.0023 | 0.0066 | 1.4580 | 0.9119 | 0.0450 | 0.0129 | 9.5455 | 8.2276 |
| Skewness | −0.8761 | −1.4024 | −5.2516 | −0.4655 | −0.5374 | −1.3621 | −0.1378 | 0.5184 | 0.1766 | −0.3888 | −0.1334 | 2.0552 | 2.1350 |
| Kurtosis | 18.0521 | 30.7400 | 148.8595 | 12.2951 | 14.1090 | 16.5895 | 5.4456 | 2.0248 | 2.5304 | 7.9711 | 7.1210 | 9.5000 | 9.9716 |
| JB statistic | 33115*** | 112104*** | 3083940*** | 12584*** | 17963*** | 25173*** | 817*** | 2746*** | 292*** | 1814*** | 2451*** | 8455*** | 8914*** |
| ADF stat. | −59.10*** | −62.70*** | −23.64*** | −58.82*** | −69.72*** | −49.36*** | −52.90*** | −1.79 | −2.36 | −41.29*** | −37.85*** | −6.20*** | −5.81*** |
| Observations | 3461 | 3461 | 3461 | 3461 | 3461 | 3145 | 3236 | 3461 | 3433 | 1720 | 3449 | 3431 | 3201 |

This table shows the descriptive statistics at a daily frequency of the EUAs and the 12 (US, European and international) benchmarks chosen. EUA is the logarithmic return of the nearby December futures contract on European Union Allowances; BRENT is the logarithmic return of the nearby monthly futures contract on Brent crude oil; WTI is the logarithmic return of the nearby monthly futures contract on West Texas Intermediate; MSCI EU is the logarithmic return of the MSCI Europe Index; MSCI NA is the logarithmic return of the MSCI North America Index; IBOXX EU is the logarithmic return of the IBOXX Euro Corporates AAA Index; IBOXX NA is the logarithmic return of the IBOXX USD Corporates AAA Index; GER ZERO and US ZERO express the yield of the German and US 10-year zero-coupon sovereign bond; BITCOIN is the logarithmic return of the exchange rate Bitcoin/€ (BITCOIN) published by Refinitiv; GOLD is the logarithmic return of the nearby monthly futures contract on gold; VSTOXX is the EURO STOXX 50 volatility index; VIX is the S&P 500 volatility index. The JB statistic stands for the Jarque-Bera statistic, which tests for the null hypothesis of normality for the distribution of the series. The ADF statistic is the augmented Dickey-Fuller test statistic, which tests for the existence of a unit root in the series. The *** indicates rejection of the null hypothesis at the 1% level. The sample period consists of data from December 18, 2007 to October 27, 2021.

All return series are skewed and leptokurtic and the Jarque-Bera statistics confirm the rejection of a normal distribution at the 1% significance level in all cases. This fact supports the use of QR as a suitable methodology to estimate the whole conditional distribution of the dependent variable without the need to previously analyse the error distribution, since the error term does not warrant any parametric distribution assumptions. This feature, together with the least absolute criterion on which the linear QR estimator rests, guarantees robustness to skewed distributions and deviations from normality (Davino et al. 2014, p. 40–42).

Finally, the augmented Dickey-Fuller (ADF) test statistics reject the existence of a unit root at the 1% level in all the series except for the 10-year zero-coupon government bond yields in Germany (GER ZERO) and the USA (US ZERO). In these cases, the null hypothesis of a single unit root is not rejected for the series in levels, but it is rejected after taking first differences at the 1% level with ADF statistics of −56.33 and −59.98 for the German and US series, respectively. Therefore, the regressions for the two sovereign bond yields have been carried out considering the series in differences.

#### 4.1.1. OLS and QR regressions

The results of the estimates of the OLS regression and the QR analysis are presented in Table 2. The traditional OLS regression allows us to study the mean value of the chosen market, while the QR is applied to estimate the relationship between the chosen market and the EUA returns in the lower quantiles of the conditional distribution. The OLS column gives the average effects of EUA returns on the target markets and provides information on the role of EUAs as a diversifier or hedger for these markets. The relationship between the oil (BRENT and WTI) and sovereign bond (GER ZERO and US ZERO) variables and the carbon market is positive and significant at the 1% level. Analogous results were obtained for the stock indices (MSCI EU and MSCI NA), implying that EUAs also behave as a diversifier for oil, sovereign bonds and equity portfolios. Similar results, with different sample periods, were obtained by Gronwald et al. (2011), Mansanet-Bataller and Pardo (2011), Reboredo (2013), Lovcha et al. (2022) and Luo and Wu (2016), among others.

Negative and significant relationships at the 10% level are found with corporate bond benchmarks (IBOXX EU and IBOXX NA) and volatility indices (VSTOXX and VIX), while no significant link is detected for the remaining benchmarks (BITCOIN and GOLD). These results indicate that the EUA acts as a hedge for bond markets and for other assets such as Bitcoin, gold and portfolios that track the implied volatility of European and US stocks. Specifically, the EUA behaves as a weak hedge for Bitcoin and gold, and as a strong hedge for corporate bonds and volatility indices.

**Table 2.** Quantile regression**.**

| Panel A | | OLS | 0.01 | 0.02 | 0.03 | 0.04 | 0.05 | 0.10 |
|---|---|---|---|---|---|---|---|---|
| BRENT | Coefficient | 0.1508 | 13.4383 | 8.7436 | 11.0975 | 9.0078 | 8.5201 | 9.5355 |
| | Prob. | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| WTI | Coefficient | 0.1805 | 12.5451 | 4.7235 | 6.6513 | 12.3506 | 10.2917 | 11.2922 |
| | Prob. | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| MSCI EU | Coefficient | 0.0848 | 0.2560 | 0.2065 | 0.1850 | 0.1784 | 0.1721 | 0.1243 |
| | Prob. | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| MSCI NA | Coefficient | 0.0515 | 0.1909 | 0.1697 | 0.1545 | 0.1232 | 0.1061 | 0.0616 |
| | Prob. | 0.0001 | **0.1828*** | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| IBOXX EU | Coefficient | −0.0039 | 0.0039 | 0.0025 | 0.0010 | −0.0017 | −0.0006 | −0.0022 |
| | Prob. | 0.0822 | **0.5497*** | **0.5667*** | **0.7217*** | **0.6821*** | **0.8913*** | **0.1475*** |
| IBOXX NA | Coefficient | −0.0218 | −4.7072 | −2.6829 | −1.2023 | −0.4076 | −1.2889 | −2.7287 |
| | Prob. | 0.0002 | **0.0000**** | **0.0073**** | **0.2293*** | **0.6836*** | **0.1975*** | **0.0064** |
| GER ZERO | Coefficient | 0.1455 | 0.4431 | 0.4749 | 0.4045 | 0.3737 | 0.2905 | 0.2176 |
| | Prob. | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| US ZERO | Coefficient | 0.1653 | 0.7641 | 0.6463 | 0.5799 | 0.5435 | 0.4203 | 0.2779 |
| | Prob. | 0.0001 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 | 0.0000 |
| BITCOIN | Coefficient | 0.0360 | 0.2614 | 0.2104 | 0.3352 | 0.2392 | 0.2904 | −0.0209 |
| | Prob. | 0.4047 | 0.0835 | **0.1395*** | 0.0442 | **0.1048*** | 0.0016 | **0.8067*** |
| GOLD | Coefficient | −0.0106 | 0.1134 | 0.0446 | 0.0326 | 0.0051 | 0.0137 | −0.0060 |
| | Prob. | 0.2800 | 0.0425 | **0.1812*** | **0.2955*** | **0.8736*** | **0.6645*** | **0.7082*** |
| VSTOXX | Coefficient | −24.8642 | −4.4936 | −9.7634 | −7.6412 | −4.8712 | −4.7040 | −9.8782 |
| | Prob. | 0.0041 | **0.3139*** | **0.0256**** | **0.0979**** | **0.3124*** | **0.3308*** | **0.0053**** |
| VIX | Coefficient | −13.7484 | −0.3907 | −0.5425 | −4.0383 | −1.5479 | −0.1990 | −2.3999 |
| | Prob. | 0.0943 | **0.9272*** | **0.9153*** | **0.2350*** | **0.6692*** | **0.9469*** | **0.1284*** |

| Panel B | | OLS | 0.90 | 0.95 | 0.96 | 0.97 | 0.98 | 0.99 |
|---|---|---|---|---|---|---|---|---|
| VSTOXX | Coefficient | −24.8642 | −63.5001 | −45.8317 | −47.5469 | −56.7276 | −89.3671 | −136.0560 |
| | Prob. | 0.0041 | **0.0025**** | **0.1115*** | **0.0150**** | **0.0048**** | **0.0068**** | **0.0000**** |
| VIX | Coefficient | −13.7484 | −32.0649 | −58.5040 | −67.7881 | −42.3105 | −23.3246 | −22.2053 |
| | Prob. | 0.0943 | **0.0127**** | **0.1046*** | **0.0001**** | **0.0141**** | **0.1261*** | **0.1531*** |

Notes: This table shows the coefficients of the OLS regression and the quantile regressions for some extreme quantiles (from 0.01 to 0.05 and 0.10 in Panel A and 0.90 and from 0.95 to 0.99 in Panel B) in accordance with Eq (1) for each target market as the dependent variable, and for EUA returns as the explanatory variable. BRENT, WTI, MSCI EU, MSCI NA, IBOXX EU, IBOXX NA, BITCOIN and GOLD are expressed in logarithmic returns. VSTOXX and VIX are expressed in levels, while GER ZERO and US ZERO are expressed in first differences. P-values in bold type indicate that the coefficient of the quantile regression is non-positive. The * stands for a non-rejection of the null hypothesis at the 10% level (weak safe-haven asset), and the ** denotes a rejection of the null hypothesis at the 10% level (strong safe-haven asset). The sample period consists of data from December 18, 2007 to October 27, 2021.

In order to study the movement of EUA prices when the target market is experiencing stress, we have estimated the QR coefficients across several extreme low quantiles. Specifically, Panel A of Table 2 shows the coefficients of the QR for quantiles from 0.01 to 0.05 and 0.10 in accordance with Eq (1) for each target market as dependent variables, and under the condition of taking EUA returns as the explanatory variable. The relationship between the oil variables (BRENT and WTI) and the carbon market is positive and significant and homogeneous across the different quantiles. The same is true for government yields (GER ZERO and US ZERO). Regarding the stock market indices (MSCI EU and MSCI NA), all coefficients are positive and significant at the 1% level, except for the coefficient of the 1st quantile in the case of the MSCI NA, which is not different from zero. These results reinforce the role of the EUA as a diversifier in crude oil, government bonds and equity portfolios.

With regard to corporate benchmarks (IBOXX EU and IBOXX NA), no significant link is detected across the lowest quantiles for IBOXX EU. However, the relationship with the IBOXX NA is either null (0.03, 0.04 and 0.05 quantiles) or negative, and it is significant at the 1% level (0.01, 0.02 and 0.10 quantiles), suggesting that the EUA acts as a weak safe haven for European corporate bonds, and as a weak or strong safe haven in the North American corporate case.

Regarding BITCOIN, although the coefficients are non-significant in quantiles 0.02 and 0.1, the rest of the coefficients are significantly positive at the usual levels of significance. Therefore, unlike Yang and Hamori (2021), we cannot conclude that EUAs behave as a safe-haven asset for BITCOIN. As for GOLD, we observe that we cannot reject the null hypotheses in all quantiles, except the first one, where the null hypothesis is rejected at the 5% level, implying that EUAs act as a weak safe haven on extreme GOLD returns conditions, with the exception of the most stressful scenario. Finally, the link between EUAs and volatility indices is null across all quantiles in the case of VIX, and null or significantly negative at the 10% level for VSTOXX, suggesting that the EUA acts as a safe-haven asset when European or North American volatility is extremely low.

In Panel B, we show the findings for volatility indices in the upper quantiles. Given that both indices are expressed in levels, safe-haven properties should be investigated not only in the lower quantiles, but also in the upper ones. In this way, we analyse the behaviour of these assets at other times of market stress, such as high levels of volatility. Both the European (VSTOXX) and the US (VIX) volatility indices behave similarly. They are uncorrelated or negatively correlated at the 5% level, implying that the EUA has safe-haven properties when volatility levels are bullish.

Taken together, the findings in Table 2 suggest that investors can rely on carbon assets as an alternative asset that provides refuge during times of stress in some markets. Specifically, the EUA shows signs of acting as a safe-haven asset for corporate bonds and gold. Furthermore, the EUA may act as a potential safe haven when European or North American equity volatility is extremely low or high.[11]

### 4.1.2. Volatility and liquidity

Previous analysis has demonstrated that the EUA may help to limit losses in portfolios that invest in gold, bond markets or those that track the implied volatility of European and US stocks. If the EUA is considered a safe-haven asset by some traders, following the idea suggested by Kaul and Sapp (2006),

[11] In order to gain robustness, the role of EUAs as a refuge asset has been estimated only for Phase III (from January 2, 2013 to October 27, 2021). The results remained qualitatively similar in all cases except for the case of IBOXX NA, where EUA retains the role of a weak safe-haven asset in two quantiles (0.04 and 0.1). These results are not included in the paper for the sake of brevity, but they are available from the authors upon request.

we should observe abnormal behaviour in the European carbon futures market on days of stress in the target markets. Although carbon market makers and other liquidity providers can manage these flows through changes in their inventories and by modifying the spreads, we can investigate the effects of these inflows indirectly through the analysis of some carbon market variables, such as volatility, trading volume and the size of the bid-ask spread. Specifically, in this section, we present a detailed analysis of the EUA market, with a particular focus on carbon volatility and liquidity, in order to test whether safe-haven flows into the carbon market on days of stress in the above-mentioned markets can significantly impact carbon market conditions.

In this subsection, we have selected only those benchmarks that are uncorrelated or negatively correlated with the EUA in times of market stress. The estimated findings are presented in Tables 3, 4 and 5. All of these tables show the results of the tests for equality of the medians between days with stress in the reference market (S1) and all other days (S2). On the one hand, stressful times for the variables presented in Panel A have been defined as the days on which the return of the target market is equal to or below the value at the k$^{th}$ percentile; the percentiles considered are the 1$^{st}$, 5$^{th}$ and 10$^{th}$ percentiles of the return distribution. On the other hand, stressful times for the benchmarks shown in Panel B have been defined as the days on which the variable of the target market is equal to or above the value at the k$^{th}$ percentile. In this case, the percentiles considered are the 90$^{th}$, 95$^{th}$ and 99$^{th}$ percentiles of the return distribution.

**Table 3.** EUA volatility on days with market stress.

| Panel A | 1$^{st}$ Percentile | | | | 5$^{th}$ Percentile | | | | 10$^{th}$ Percentile | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 |
| IBOXX EU | 0.0152 | 0.0145 | 0.4210 | 0.2105 | 0.0161 | 0.0145 | 0.1473 | **0.0736** | 0.0150 | 0.0145 | 0.4632 | 0.2316 |
| IBOXX NA | 0.0170 | 0.0144 | 0.1061 | **0.0531** | 0.0147 | 0.0144 | 0.7450 | 0.3725 | 0.0146 | 0.0144 | 0.9525 | 0.5238 |
| GOLD | 0.0173 | 0.0144 | 0.0385 | **0.0193** | 0.0160 | 0.0143 | 0.0367 | **0.0183** | 0.0148 | 0.0144 | 0.2448 | 0.1224 |
| VSTOXX | 0.0140 | 0.0145 | 0.4045 | 0.7978 | 0.0139 | 0.0145 | 0.3447 | 0.8276 | 0.0137 | 0.0146 | 0.0649 | 0.9676 |
| VIX | 0.0150 | 0.0146 | 0.9607 | 0.4803 | 0.0143 | 0.0146 | 0.4422 | 0.7789 | 0.0150 | 0.0145 | 0.2490 | 0.1245 |

| Panel B | 90$^{th}$ Percentile | | | | 95$^{th}$ Percentile | | | | 99$^{th}$ Percentile | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 |
| VSTOXX | 0.0183 | 0.0141 | 0.0000 | **0.0000** | 0.0191 | 0.0142 | 0.0000 | **0.0000** | 0.0209 | 0.0144 | 0.0000 | **0.0000** |
| VIX | 0.0178 | 0.0143 | 0.0000 | **0.0000** | 0.0211 | 0.0143 | 0.0000 | **0.0000** | 0.0324 | 0.0145 | 0.0000 | **0.0000** |

Notes: This table shows the results of the test for the equality of medians between the days with market stress in the reference market and the rest of the days. Stressful times in each market in Panel A have been defined as those days on which the return of the target market is equal to or below the value at the k$^{th}$ percentile. The percentiles considered are the 1$^{st}$, 5$^{th}$ and 10$^{th}$ percentiles of the return distribution. Stressful times in each market in Panel B have been defined as those days on which the return of the target market is equal to or above the value at the k$^{th}$ percentile. The percentiles considered are the 90$^{th}$, 95$^{th}$ and 99$^{th}$ percentiles of the return distribution. S1 indicates the median of the EUA volatility on days with market stress in the target market; S2 refers to the median of the EUA volatility on days with no stress in the target market. In both panels, "S1 ≠ S2" indicates the p-value of a two-sided Wilcoxon rank sum test that compares the equality of medians between S1 and S2 against the alternative hypothesis that they are not equal. "S1 > S2" indicates the right-tailed Wilcoxon rank sum test that compares the equality of medians between S1 and S2, where the alternative hypothesis states that the median of S1 is greater than the median of S2. P-values in bold type indicate the rejection of the right-tailed Wilcoxon rank sum test at the 10% level. The sample period consists of data from December 18, 2007 to October 27, 2021.

Table 3 provides the results for the EUA volatility conditioned by bearish (Panel A) or bullish (Panel B) times in the chosen market. Parkinson's volatility has been calculated by following Eq (3). "S1" indicates the median EUA volatility on days with stress in the target market; "S2" refers to the median EUA volatility on days with no stress in the target market. In both Panels A and B, "S1≠S2" indicates the p-value of a two-sided Wilcoxon rank sum test that compares the equality of medians between S1 and S2, against the alternative hypothesis that they are not equal, and "S1>S2" indicates the right-tailed Wilcoxon rank sum test that compares the equality of medians between S1 and S2, where the alternative hypothesis states that the median of S1 is greater than the median of S2. P-values in bold type indicate the rejection of the right-tailed Wilcoxon rank sum test at the 10% level. The results of Panel A in Table 3 show more volatility during stressful times in all of the cases except in the volatility indices, suggesting that extreme bearish movements in the other benchmark indices lead to abnormally high volatility in the carbon market. Similar findings are observed in Panel B in the case of bullish markets for the VSTOXX and VIX indices.

**Table 4.** EUA volume on days with market stress.

| Panel A | 1st Percentile | | | | 5th Percentile | | | | 10th Percentile | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 |
| IBOXX EU | 10701.0 | 12040.5 | 0.8590 | 0.5706 | 12380.0 | 11969.0 | 0.5856 | 0.2928 | 11889.0 | 12071.0 | 0.1169 | 0.9415 |
| IBOXX NA | 6846.0 | 11035.5 | 0.0088 | 0.9956 | 8925.5 | 11079.0 | 0.0036 | 0.9982 | 9579.5 | 11117.5 | 0.0061 | 0.9970 |
| GOLD | 3970.0 | 11181.0 | 0.0021 | 0.9989 | 9109.0 | 11213.0 | 0.0010 | 0.9995 | 9508.0 | 11221.0 | 0.0004 | 0.9998 |
| VSTOXX | 11707.5 | 11223.0 | 0.6731 | 0.3365 | 13570.0 | 11077.0 | 0.0000 | **0.0000** | 13379.0 | 10942.5 | 0.0000 | **0.0000** |
| VIX | 9861.0 | 11887.0 | 0.0493 | 0.9754 | 9713.0 | 12102.0 | 0.0000 | 1.0000 | 10053.0 | 12242.5 | 0.0000 | 1.0000 |

| Panel B | 90th Percentile | | | | 95th Percentile | | | | 99th Percentile | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 |
| VSTOXX | 7331.0 | 11653.0 | 0.0000 | 1.0000 | 5272.5 | 11437.0 | 0.0000 | 1.0000 | 3512.0 | 11269.0 | 0.0003 | 0.9999 |
| VIX | 9074.0 | 12070.0 | 0.0000 | 1.0000 | 8208.5 | 11945.0 | 0.0000 | 1.0000 | 22032.5 | 11856.0 | 0.0378 | **0.0189** |

Notes: This table shows the estimates for the EUA trading volume conditioned by stressful times in the chosen market. This table shows the results of the test for the equality of medians between the days with market stress in the benchmark market and the rest of the days. Stressful times in each market in Panel A have been defined as those days on which the return of the target market is equal to or below the value at the $k^{th}$ percentile. The percentiles considered are the 1st, 5th and 10th percentiles of the return distribution. Stressful times in each market in Panel B have been defined as those days on which the return of the target market is equal to or above the value at the $k^{th}$ percentile. The percentiles considered are the 90th, 95th and 99th percentiles of the return distribution. S1 indicates the median of the EUA volatility on days with market stress in the target market; S2 refers to the median of the EUA volatility on days with no stress in the target market. In both panels, "S1 ≠ S2" indicates the p-value of a two-sided Wilcoxon rank sum test that compares the equality of medians between S1 and S2 against the alternative hypothesis that they are not equal. "S1 > S2" indicates the right-tailed Wilcoxon rank sum test that compares the equality of medians between S1 and S2, where the alternative hypothesis states that the median of S1 is greater than the median of S2. P-values in bold type indicate the rejection of the right-tailed Wilcoxon rank sum test at the 10% level. The sample period consists of data from December 18, 2007 to October 27, 2021.

Turning to liquidity measures, if some traders consider the EUA to be a safe-haven asset, we should observe higher-than-normal liquidity in the European carbon futures market on days of stress in the chosen markets. Specifically, we should observe significant increases in the trading volume of EUA futures contracts and/or a reduction in the size of its bid-ask spread on days of stress in bond, gold, or volatility markets. Tables 4 and 5 present the results for the EUA trading volumes and bid-ask spreads, as conditioned by stressful times in the chosen market. Panel A of Table 4 indicates that carbon trading volume increases significantly at the 10% level for bearish movements in VSTOXX. A significant increase can be observed in Panel B when EUA trading volume is conditioned by bullish markets in VIX. Finally, Table 5 provides the findings for the behaviour of carbon bid-ask spreads when the benchmarks are bearish. We observe abnormally high spreads in IBOXX EU, GOLD and VIX when markets are bearish (Panel A), and the same is observed when the VIX benchmark is bullish (Panel B).

**Table 5.** EUA bid-ask spread on days with market stress.

| Panel A | 1st Percentile | | | | 5th Percentile | | | | 10th Percentile | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 |
| IBOXX EU | 0.0100 | 0.0100 | 0.9887 | 0.5060 | 0.0100 | 0.0100 | 0.7101 | 0.6451 | 0.0100 | 0.0100 | 0.9847 | **0.0307** |
| IBOXX NA | 0.0100 | 0.0100 | 0.4933 | 0.7536 | 0.0100 | 0.0100 | 0.9666 | 0.4833 | 0.0100 | 0.0100 | 0.5722 | 0.8558 |
| GOLD | 0.0300 | 0.0200 | 0.2313 | 0.1157 | 0.0200 | 0.0200 | 0.2021 | 0.1010 | 0.0200 | 0.0200 | 0.0439 | **0.0879** |
| VSTOXX | 0.0200 | 0.0100 | 0.2498 | 0.1249 | 0.0200 | 0.0100 | 0.3439 | 0.1719 | 0.0100 | 0.0100 | 0.4302 | 0.8604 |
| VIX | 0.0100 | 0.0100 | 0.0987 | 0.9507 | 0.0100 | 0.0100 | 0.1124 | 0.9439 | 0.0100 | 0.0100 | 0.9965 | **0.0070** |

| Panel B | 90th Percentile | | | | 95th Percentile | | | | 99th Percentile | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Benchmark | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 | S1 | S2 | S1 ≠ S2 | S1 > S2 |
| VSTOXX | 0.0100 | 0.0100 | 0.0628 | 0.9686 | 0.0100 | 0.0100 | 0.5789 | 0.2895 | 0.0200 | 0.0100 | 0.2979 | 0.1490 |
| VIX | 0.0200 | 0.0100 | 0.0611 | **0.0306** | 0.0100 | 0.0100 | 0.3274 | 0.1637 | 0.0200 | 0.0100 | 0.5702 | 0.2851 |

Notes: This table shows the estimates for the EUA bid-ask spread conditioned by stressful times in the chosen market. This table shows the results of the test for the equality of medians between the days with market stress in the benchmark market and the rest of the days. Stressful times in each market in Panel A have been defined as those days on which the return of the target market is equal to or below the value at the $k^{th}$ percentile. The percentiles considered are the 1st, 5th and 10th percentiles of the return distribution. Stressful times in each market in Panel B have been defined as those days on which the return of the target market is equal to or above the value at the $k^{th}$ percentile. The percentiles considered are the 90th, 95th and 99th percentiles of the return distribution. S1 indicates the median of the EUA volatility on days with market stress in the target market; S2 refers to the median of the EUA volatility on days with no stress in the target market. In both panels, "S1 ≠ S2" indicates the p-value of a two-sided Wilcoxon rank sum test that compares the equality of medians between S1 and S2 against the alternative hypothesis that they are not equal. "S1 > S2" indicates the right-tailed Wilcoxon rank sum test that compares the equality of medians between S1 and S2, where the alternative hypothesis states that the median of S1 is greater than the median of S2. P-values in bold type indicate the rejection of the right-tailed Wilcoxon rank sum test at the 10% level. The sample period consists of data from December 18, 2007 to October 27, 2021.

In summary, volatility increases during times of stress in several markets and, in some of them, this occurs alongside increases in trading volume and/or bid-ask spreads in carbon markets. These results are in line with the observation of Quemin and Pahle (2022), who note that, as new financial actors in the EU ETS participate in various other markets, emission allowances become increasingly connected to the economy at large, making the carbon market more vulnerable to imported cross-market risks.

## 5. Conclusions

This study investigates whether the EUA can be considered a safe haven for a range of assets. We considered 12 daily benchmarks across six markets (carbon, oil, stocks, bonds, precious metals and cryptocurrencies) and concluded that EUAs can help limit losses in falling markets along with corporate bonds or gold. Furthermore, we have detected that carbon allowances can also act as a safe haven when volatility levels in Europe or North America are too low or too high. Therefore, EUAs can be considered a safe-haven investment when corporate bonds, gold or volatility-related assets experience market turmoil.

In addition, we have also studied whether carbon volatility and liquidity are driven by demand pressure from investors who rely on carbon assets as an alternative asset that provides a safe haven from turbulent markets. Specifically, we have compared measures of carbon volatility and liquidity conditioned by extreme movements in the specific target market (European corporate bonds, US corporate bonds, gold market and European and US volatility-related assets) to these measures on days when the target market is calm. Extremely bearish and bullish movements in benchmark indices that can potentially use the EUA as a safe haven induce excess volatility in carbon markets. Furthermore, we have found evidence of higher trading volumes and larger-than-normal bid-ask spreads that coincide with extreme fluctuations in returns/levels in some of these markets.

These findings support the idea that some traders, viewing carbon futures as a refuge asset, trigger safe-haven flows into the carbon market. It is important to highlight that the existence of these flows contributes to the financialisation of the European carbon futures market. These findings are of interest not only to portfolio managers, who may consider adding EUAs to their portfolios in times of market stress, but also to carbon market players, such as policy-makers, market-makers and carbon traders, who can expect increases in carbon volatility and volume, and higher-than-normal bid-ask spreads in the EUA December futures contract, triggered by safe-haven flows.

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## Conflict of interest

All authors declare no conflict of interest regarding this paper.

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