EU ETS Market Expectations and Rational Bubbles*

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The European Emissions Trading Scheme (EU ETS) was implemented as a fundamental climate protection instrument, intended to mitigate the negative externalities of CO_2 emissions in the European region. Nonetheless, concerns have been raised regarding the recent surge in prices, prompting speculation about the potential emergence of a price bubble. We posit that conventional tests assessing speculative price bubbles, relying on the concept of switching costs, are applicable only under the assumption of market certainty. Given the inherent uncertainty prevailing in economic activities, our study undertakes an investigation of speculative bubbles within the EU ETS, incorporating market expectations as a more robust approach. The results of our empirical analysis indicate that apprehensions over the EU ETS being entangled in a price bubble lack substantive evidence.

Key words: CO_2 emission allowances • carbon finance • EU ETS price expectations • policy uncertainty • market integration • bubbles
JEL classification: Q01 • Q58 • C53 • G14

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* Corresponding author: Christoph Wegener; Note: This is an ongoing research paper, and as such, the empirical findings may evolve in the future. Please refrain from citing this paper without first contacting the authors for permission.

1. Introduction

Climate change and its impacts are the central focus of environmental and economic policy decisions. The compelling evidence that CO_2 emissions are causally related to climate change underscores their importance in the environmental policy context (see IPCC 2021). In economic modeling, climate change is understood as a negative externality. In this context, market actors do not include the social and economic costs of global warming in their actions, so that CO_2 emissions are not adequately priced in the market in terms of their current and future damage.

To internalize this negative externality, the European Union (EU) introduced the European Emissions Trading Scheme (EU ETS) in 2005 as a key climate protection instrument. Alongside other climate policy measures, this cap-and-trade system was initially intended to help reduce greenhouse gas emissions in the EU by at least 40% by 2030 compared to 1990 levels. The EU's current targets are more ambitious: In 2021, for example, all EU member states committed to reducing emissions by at least 55% by 2030 compared with 1990 levels (see European Commission 2011).

Overall, the EU ETS covers around 40% of total greenhouse gas emissions within the European Union. Since 2012, intra-European air traffic has also been integrated into the EU ETS. The participating states issue emission allowances partly free of charge, partly through auctions. One allowance permits the emission of one ton of CO_2 equivalents. The right to freely trade these emission allowances on the spot and futures markets creates a market price for greenhouse gas emissions.

The total amount of greenhouse gas emissions per trading period that may be emitted by the approximately 13,500 production facilities subject to emissions trading in the 27 EU member states, Norway, Iceland and Liechtenstein is determined by a cap. In the first two trading periods (2005-2007 and 2008-2012), there was a massive oversupply of emission rights that were allocated largely free of charge. The resulting market prices were judged by the Organisation for Economic Co-operation and Development (OECD) to be too low to meet the political target in terms of emission reductions within the EU (see OECD 2018).

To reinforce this signal effect, with the EU ETS price at around three euros per metric ton of CO_2 equivalents at the start of the third trading period in 2013, EU policymakers initiated a number of reforms: (i) since the third trading period (2013-2020), a larger share of allowances has been auctioned to market participants, rather than allocated freely as in the second trading period; (ii) during the first and second trading periods, there were national caps – with the third trading period, a uniform cap was set across Europe; (iii) the EU adopted measures to reduce the amount of (surplus) allowances. The focus here is on the Market Stability Reserve (MSR), which will gradually reduce the surplus in emissions trading and transfer it to a reserve from 2019.

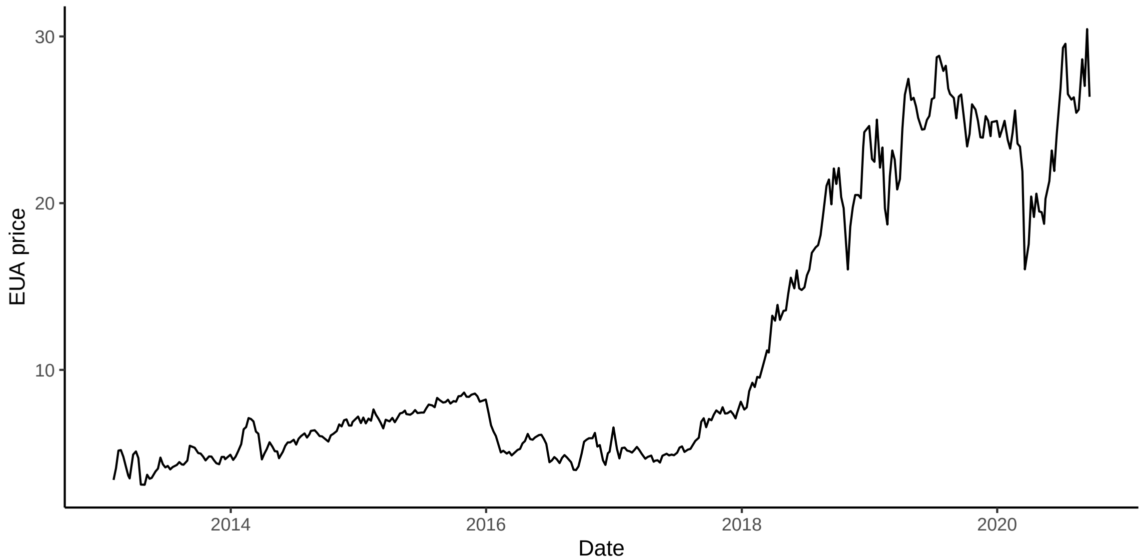

Figure 1 Market price of emission allowances.

Since 2018, there have been rapid price increases for the market price of emission allowances (see Figure 1). According to a 2019 survey by the Leibniz Centre for European Economic Research (see ZEW 2019), 34% of market participants see the expected shortage of allowances due to the MSR as the main driver of the price increase, another 16% attribute it to the expectation of other tighter regulations, and 14% assume that speculation is behind the sharp price increases. (see Friedrich, Fries, Pahle, and Edenhofer 2020) provide empirical evidence for the latter, attributing the massive price increases in part to a price bubble. If this were the case, it would be questionable whether the price increase since 2018 is sustainable or whether a future market correction should be expected. In this case, the incentive created by the EU ETS for cost-effective emission reductions risks becoming ineffective.[1]

The empirical evidence for a price bubble in the EU ETS, on the one hand, could also be attributed to a misspecification of the empirical proxy for the fundamental, i.e., misspecification of the switching costs. On the other hand, the interpretation of bubble test based on switching costs assumes that the market is perfectly competitive and that there is certainty about future energy prices and other factors that affect allowance prices. Firms generally operate under uncertainty, so the price of allowances should reflect market participants' expectations about the scarcity of allowances, including the associated uncertainty (see Seifert, Uhrig-Homburg, and Wagner 2008, Chesney and Taschini 2012, Hitzemann and Uhrig-Homburg 2018).

[1] A price bubble is defined as the decoupling of the price from its fundamental value. Since we assume positive price expectations, the price within a bubble rises above the value of the fundamental (see Tirole 1985, Diba and Grossman 1988a,b).

To test whether the EU ETS has been efficient and free of speculative bubbles in the recent past under uncertainty, we perform the following two steps within our empirical analysis:

First, we decompose the futures prices of the EU ETS, the coal and gas market into time-dependent risk premium and risk-neutral market price expectation. The Hamilton and Wu (2014) affine term structure model is utilized for this purpose. The essential condition for employing this model (which is met in this case) is the availability of at least three liquid continuous futures prices at all times for the relevant market. Similar to interest rate structure models (see Nelson and Siegel 1987), the approach assumes a specific number of factors that influence the term structure of futures prices, typically level, slope, and curvature. These factors are considered stochastic, dynamic, and unobservable. The latter aspect provides a significant advantage, particularly for our paper, as we only need to assume that they follow a vector autoregressive process with normally distributed innovations. No additional data beyond the continuous futures is required.

Second, we use market expectations rather than switching costs to test for a price bubble in the EU ETS. Only if the EU ETS is perfectly integrated into energy markets does it seem reasonable to choose switching costs as an empirical surrogate for the fundamental for this bubble test. However, since it is questionable whether the EU ETS is integrated into energy markets, we use the test procedure of Pavlidis, Paya, and Peel (2017, 2018). This procedure only requires market prices and their expectations. Thereby, it works under uncertainty with respect to the future development of price determinants in the EU ETS and it limits sources of potential misspecification compared to approaches that require the specification of switching costs.

The paper is organized as follows: The next section discusses two different approaches to test against bubbles in the EU ETS. Section three summarizes some useful descriptive facts on the EU ETS and presents the empirical results. The last paragraph proposes policy implications and concludes.

2. Rational Bubbles in the EU ETS

Tests based on Switching Costs Assuming perfect competition and certainty with respect to the future evolution of EU ETS price determinants, producers will shift their production process from dirty-but-cheap to clean-but-expensive as long as the marginal cost of avoiding CO_2 emissions does not exceed the price of allowances. Hence, in market equilibrium and assuming the absence of a speculative price bubble (this will be relaxed in the following), the price in the EU ETS, denoted by $P_t^{(\mathrm{EUA})}$ at time $t = 1, 2, \ldots$, equals the so-called switching costs towards CO_2 efficient energy sources (see Cronshaw and Kruse, 1996; Rubin, 1996), viz.

$$P_t^{(\mathrm{EUA})} = \frac{\eta_{\mathrm{gas}} P_t^{(\mathrm{gas})} - \eta_{\mathrm{coal}}\, P_t^{(\mathrm{coal})}}{E_{\mathrm{coal}} - E_{\mathrm{gas}}}, \tag{1}$$

with $P_t^{(\text{gas})}$ and $P_t^{(\text{coal})}$ as the price of natural gas and the price of coal in euros per megawatt hour (MWh) at time t, respectively. The corresponding heat input coefficient is denoted by η_{gas} for gas and by η_{coal} for coal (in MWh of fuel per MWh of electricity) and E_{gas} and E_{coal} are the corresponding constant average CO_2 emissions (see Chesney and Taschini, 2012).[2]

The relationship in Equation (1) is mirrored by the empirical model

$$P_t^{(\text{EUA})} = \frac{\eta_{\text{gas}}}{E_{\text{coal}} - E_{\text{gas}}} P_t^{(\text{gas})} - \frac{\eta_{\text{gas}}}{E_{\text{coal}} - E_{\text{gas}}} P_t^{(\text{coal})} + \varepsilon_t^{(\text{EUA})}, \tag{2}$$

whereas $P_t^{(\text{EUA})}$, $P_t^{(\text{gas})}$ and $P_t^{(\text{coal})}$ are time series that are assumed to be integrated of order one, i.e., $P_t^{(\cdot)} \sim \mathrm{I}(1)$, and $\varepsilon_t^{(\text{EUA})}$ is integrated of order d with $0 \leq d < 0.5$, i.e., $\varepsilon_t^{(\text{EUA})} \sim \mathrm{I}(d)$. This empirical model implies a cointegration relation with the vector

$$(1, \beta_{\text{gas}}, \beta_{\text{coal}})' = \left(1, \frac{\eta_{\text{gas}}}{E_{\text{coal}} - E_{\text{gas}}}, -\frac{\eta_{\text{coal}}}{E_{\text{coal}} - E_{\text{gas}}}\right)' \tag{3}$$

being constant over time. There are several studies that investigate a cointegration equilibrium between switching costs and emission prices (see Creti, Jouvet, and Mignon 2012, Koch, Fuss, Grosjean, and Edenhofer 2014, Rickels, Görlich, and Peterson 2015).

We relax the assumption that there are no rational bubbles in the EU ETS, i.e., the price can be decomposed as

$$P_t^{(\text{EUA})} = U_t^{(\text{EUA})} + B_t^{(\text{EUA})} \tag{4}$$

whereas $U_t^{(\text{EUA})}$ is the fundamental component and $B_t^{(\text{EUA})}$ is the rational bubble component. Blanchard (1979) suggests to model the bubble component as

$$B_t^{(\text{EUA})} = \begin{cases} \frac{(1+r)}{\pi} B_{t-1}^{(\text{EUA})} + \epsilon_t & \text{with probability } \pi, \\ \epsilon_t & \text{with probability } 1-\pi, \end{cases} \tag{5}$$

whereas r denotes the risk-free rate and ϵ_t is an independent and identically distributed (iid) random variable with zero mean and variance σ_ϵ^2, i.e., $\epsilon_t \sim iid(0, \sigma_\epsilon^2)$. The bubble survives with probability π in period t. In this case, the bubble expands at an increased rate of $(1+r)/\pi$ to compensate investors for the potential bubble collapse. The bubble bursts with probability $1-\pi$. In this case, the bubble collapses to white noise. Since

$$\mathbb{E}_{t-1}\left[B_t^{(\text{EUA})}\right] = \frac{1}{1+r} B_{t-1}^{(\text{EUA})}, \tag{6}$$

$B_t^{(\text{EUA})}$ is explosive whereas $\mathbb{E}_t := \mathbb{E}(\cdot \mid \mathcal{F}_t)$ denotes the conditional expectation given the information set $\mathcal{F}_t$ available at time t. Note that this result holds also for other bubble processes (see Evans 1991). Hence, given that $B_t^{(\text{EUA})} > 0$, the empirical counterpart of Equation (1) reads as

$$\underbrace{P_t^{(\text{EUA})}}_{\mathrm{I}(\infty)} = \frac{\eta_{\text{gas}}}{E_{\text{coal}} - E_{\text{gas}}} \underbrace{P_t^{(\text{gas})}}_{\mathrm{I}(1)} - \frac{\eta_{\text{gas}}}{E_{\text{coal}} - E_{\text{gas}}} \underbrace{P_t^{(\text{coal})}}_{\mathrm{I}(1)} + \underbrace{B_t^{(\text{EUA})}}_{\mathrm{I}(\infty)} + \underbrace{\varepsilon_t^{(\text{EUA})}}_{\mathrm{I}(d)} \tag{7}$$

[2] In Chesney and Taschini (2012), one can find for Europe the value $1.92 MWh_{\text{therm}}/MWh$ for η_{gas}, the value $0.378 \mathrm{t}_{\text{coal}}/MWh$ for η_{coal}, the value $0.388 t_{CO_2}/MWh$ for E_{gas}, and the value $0.897 t_{CO_2}/MWh$ for E_{coal}.

whereas $0 \leq d < 0.5$. The bubble component is explosive and therefore integrated of order $\mathrm{I}(\infty)$. Since the order of integration of a sum is determined by the term with the highest order of integration, i.e., the bubble component, the price process is also explosive in the presence of a rational bubble.

One way to test against a rational bubble in the EU ETS is to apply a right-sided unit root test to the difference between the EU ETS price and its fundamental (see Creti and Joëts 2017). Empirical evidence that $P_t^{(EUA)} - U_t^{(EUA)}$ is explosive would argue for the existence of a bubble – but could also be due to the misspecification of the empirical proxy for the fundamental value. Further, a major drawback of this approach is that companies are assumed to operate under certainty. Especially due to dynamic political measures to reduce CO_2 emissions, this assumption appears unrealistic. A way around these limitations is discussed below.

Tests based on Market Expectations Seifert, Uhrig-Homburg, and Wagner (2008) and Chesney and Taschini (2012) study the the price dynamics of emission permits in the case of uncertainty about the future development of the price-determining factors of the EU ETS. In particular, focusing on Chesney and Taschini (2012), the discounted equilibrium fundamental process is a martingale, viz.

$$U_t^{(\mathrm{EUA})} = \beta P \left\{1 - \mathbb{E}_{it}\left[\mathcal{P}_{iT}\right]\right\} \tag{8}$$

whereas β is an appropriate discount factor and P is the penalty that company $i = 1, 2, \ldots, I$ must pay if it cannot provide enough certificates by the compliance date T. Further, $\mathcal{P}_{iT}$ denotes the probability that firm i fails to comply with the regulations at time T and $\mathbb{E}_{it} := \mathbb{E}\left(\cdot \mid \mathcal{F}_{it}\right)$ denotes conditional expectation given the information set $\mathcal{F}_{it}$ available at time t for firm i. In the frameworks by Seifert, Uhrig-Homburg, and Wagner (2008) and by Chesney and Taschini (2012), it holds that the allowance fundamental process does not allow for arbitrage and that the fundamental is uniquely defined by

$$U_t^{(\mathrm{EUA})} = \beta \mathbb{E}_t\left[U_T^{(\mathrm{EUA})}\right], \tag{9}$$

i.e., under uncertainty, the fundamental at time t depends rather on agents' market expectations at time t about the future shortage of allowances than on the switching costs at time t.

Pavlidis, Paya, and Peel (2017, 2018) provide an approach to test against speculative bubbles which is based on market expectation. We adapt this approach to obtain a procedure which, using market price expectations and thus without the specification of an empirical proxy for the fundamental value and under uncertainty, is able to test against the existence of a price bubble in the EU ETS. Pavlidis, Paya, and Peel (2017, 2018) assume that the fundamental process follows a first-order autoregressive process, viz.

$$U_t^{(\mathrm{EUA})} = \phi U_{t-1}^{(\mathrm{EUA})} + \theta_t \tag{10}$$

whereas ϕ is unrestricted and can take values such that $U_t^{(\mathrm{EUA})}$ is stationary, integrated of order one or explosive and $\theta_t \sim iid\,(0,\sigma_\theta^2)$. Thus, this autoregressive model covers the behavior predicted in Equation (9) and also allows for further potential dynamics. Further, Pavlidis, Paya, and Peel (2017, 2018) let the bubble process follow Blanchard's model (see Equation 5). Hence, the bubble process fulfills rational expectations, i.e., $\mathbb{E}_t\left[B_{t+1}\right] = (1+r)B_t$ (see Diba and Grossman, 1988).[3]

The expectation about the price n periods ahead at time t is a linear function of the bubble process, viz.

$$\mathbb{E}_t\left(P_{t+n}^{(\mathrm{EUA})}\right) = \mathbb{E}_t\left(B_{t+n}^{(\mathrm{EUA})}\right) + \mathbb{E}_t\left(U_{t+n}^{(\mathrm{EUA})}\right) = (1+r)^n B_{t+n}^{(\mathrm{EUA})} + \phi^n U_{t+n}^{(\mathrm{EUA})}. \tag{11}$$

Further, the actual spot price at time $t+n$ is given by

$$P_{t+n}^{(\mathrm{EUA})} = \phi^n U_t^{(\mathrm{EUA})} + \left(\frac{1+r}{\pi}\right)^n B_t^{(\mathrm{EUA})} + \epsilon_{t+n}^{\star} \tag{12}$$

whereas $\epsilon_{t+n}^{\star}$ aggregates θ_{t+n} and ϵ_{t+n} and is, therefore, $\epsilon_{t+n}^{\star} \sim \mathrm{I}\,(0)$. Subtracting the expectation formed at time t for the spot rate at time $t+n$ from the actual spot rate at time $t+n$, Pavlidis, Paya, and Peel (2017, 2018) obtain

$$\Delta_{t+n}^{(\mathrm{EUA})} := P_{t+n}^{(\mathrm{EUA})} - \mathbb{E}_t\left(P_{t+n}^{(\mathrm{EUA})}\right) = (1+r)^n\left(\frac{1}{\pi^n} - 1\right) B_t^{(\mathrm{EUA})} + \epsilon_{t+n}^{\star}. \tag{13}$$

Hence, for $B_t^{(\mathrm{EUA})} = 0$, we receive

$$\underbrace{\Delta_{t+n}^{(\mathrm{EUA})}}_{\mathrm{I}(0)} = \underbrace{\epsilon_{t+n}^{\star}}_{\mathrm{I}(0)} \tag{14}$$

and for $B_t^{(\mathrm{EUA})} > 0$, we obtain

$$\underbrace{\Delta_{t+n}^{(\mathrm{EUA})}}_{\mathrm{I}(\infty)} = (1+r)^n\left(\frac{1}{\pi^n} - 1\right)\underbrace{B_t^{(\mathrm{EUA})}}_{\mathrm{I}(\infty)} + \underbrace{\epsilon_{t+n}^{\star}}_{\mathrm{I}(0)}. \tag{15}$$

Since $\Delta_{t+n}^{(\mathrm{EUA})}$ does not depend on market fundamentals, but only on the bubble, this implies that the explosive dynamics of the difference are due solely to the presence of a bubble. Thus it stands to reason to consider the model

$$\Delta_t^{(\mathrm{EUA})} = \mu + \rho\Delta_{t-1}^{(\mathrm{EUA})} + u_t \tag{16}$$

whereas $u_t \sim \mathrm{I}\,(0)$ is an error term, μ is the drift component and ρ is the autoregressive parameter and to test

$$\mathcal{H}_0 : \rho \leq 1 \qquad \text{vs.} \qquad \mathcal{H}_A : \rho > 1.$$

[3] Note that other bubble models would likewise be suitable (see Evans 1991).

However, market expectations $\mathbb{E}_t\left(P_{t+n}^{(\mathrm{EUA})}\right)$ are not observable. For the risk neutral case only, $F_{n,t} = \mathbb{E}_t\left(P_{t+n}^{(\mathrm{EUA})}\right)$ holds, whereas $F_{n,t}$ is the futures price at time t with respect to the delivery date $t+n$. In the general case, however, $F_{n,t} = \mathbb{E}_t\left(P_{t+n}^{(\mathrm{EUA})}\right) + \varrho_t$ where ϱ_t is a time-varying risk premium. Negative risk premia, i.e., $\varrho_t < 0$, indicate that agents expect higher prices, whereas positive risk premia, i.e., $\varrho_t > 0$, indicate expected price reductions (see Trück and Weron 2016). Since we might take into account the time-varying nature of expectations, we decompose $F_{n,t}$ into the time-varying estimated risk premium $\hat{\varrho}_t$ and the resulting market expectation using the approach of Hamilton and Wu (2014).

Pavlidis, Paya, and Peel (2017, 2018) apply the Generalized Supremum Augmented Dickey Fuller (GSADF) test of Phillips, Shi, and Yu (2015a,b) to the differences between (estimated) market expectations and spot prices. In addition to that, we use the bootstrap procedure for the Backward Supremum Augemented Dickey Fuller (BSADF) test of Phillips and Shi (2020) to account for heteroskedasticity and multiplicity and we apply this methodology to

$$\delta_{t+n}^{(EUA)} := \log P_{t+n}^{(\mathrm{EUA})} - \mathbb{E}_t\left(\log P_{t+n}^{(\mathrm{EUA})}\right) \tag{17}$$

as the method of Hamilton and Wu (2014) provides an estimator of log market expectations.[4]

3. Data and Empirical Results

Data We use EUA futures traded on the *Intercontinental Exchange* (ICE). At any time, there are the front month, and as well as 2 months and 3 months futures, the quarterly, the December contracts. In order to construct continues futures, we fit futures curve with differing spline points as maturities are not constant. Therefore, we use 135 contracts across three phases traded on the ICE for the sampling period from 1st Feb 2008 to 29th Sep 2020. In total there are 58 329 price quotations observations across contracts including price, trading volume, and open interest. We focus on those contracts with trading volume larger than zero. Hence, we receive 23 024 settlement prices for liquid futures contracts. Figure 2 indicates that there are at least three liquid futures contracts at any point in time, so HW's procedure can be applied. Therefore, we construct the continuous futures contracts for the next three months and apply the procedure of Hamilton and Wu (2014), that is, we obtain risk premium and market expectations for the next three months at each point in time t. Further, we obtain spot prices for the EU ETS for the sampling period from Bloomberg.[5]

[4] The derivation of the market expectations estimator by Hamilton and Wu (2014) is presented in the appendix.

[5] The Bloomberg identifier is `EEXX03EA Index`.

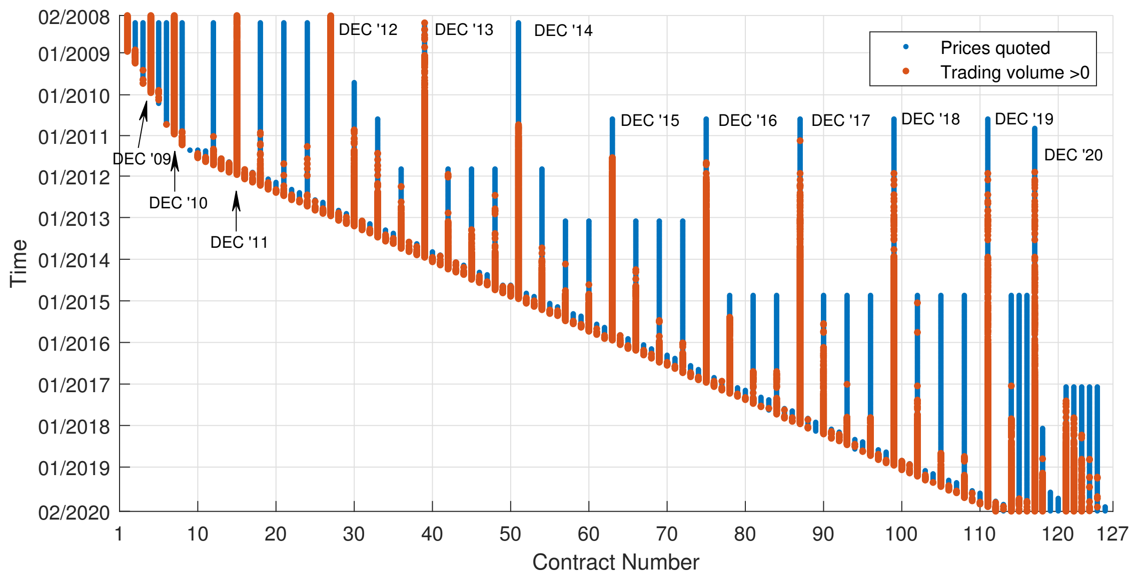

Figure 2 **EUA futures availability 2008 - 2020.**

Empirical Results Figure 3 presents the estimated time-varying risk premium. Following the approach by Hamilton and Wu (2014), it reveals a positive risk premium up to 2018, suggesting that market participants anticipated higher EU ETS prices in the future, i.e., in one, two and three month. Coincidently with the price surge in 2018, the risk premium declined, signifying that agents now hold the belief that the market price within the EU ETS will not experience further increases.

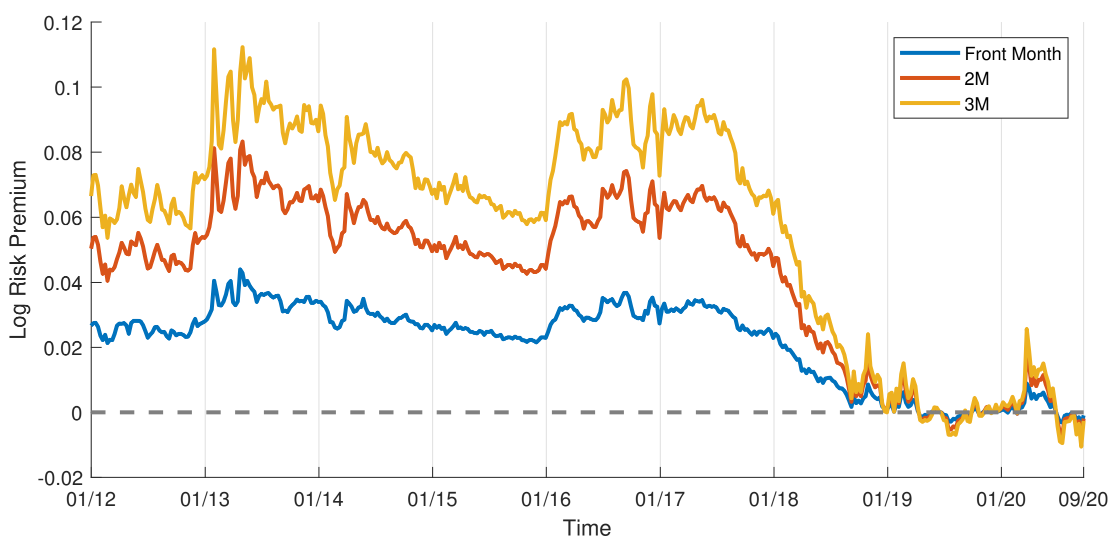

Figure 3 **Estimated time-varying risk premium in the EU ETS.**

Subsequently, we apply the GSADF and BSADF test to the spot price of the EU ETS. The GSADF test yields a test statistic of 2.748, surpassing the simulated critical values as shown in Table 1. The critical values for the GSADF test are generated through 10,000 repetitions, employing a minimum window size of 38 observations, following the rule proposed by Phillips et al. (2015a). Hence, the GSADF test points towards the existence of explosiveness in the EU ETS spot price. In order to identify the specific period of explosiveness, we employ the BSADF test statistic alongside bootstrapped critical values (also presented in Table 1), utilizing 5,000 bootstrap replications. Figure 4 illustrates the test statistic and the corresponding critical values. If the test statistic

Test Statistic		Critical values (90%, 95%, 99%)	
Variable	GSADF	simulated	bootstrap
$\log P_t^{(\mathrm{EUA})}$	2.748	(1.885, 2.022, 2.363)	(0.887, 1.328, 1.747)
$\delta_{t+1}^{(EUA)}$	1.120		(1.145, 1.413, 1.951)
$\delta_{t+2}^{(EUA)}$	2.375		(0.866, 1.151, 1.778)
$\delta_{t+3}^{(EUA)}$	2.208		(0.981, 1.275, 1.779)

Table 1 The table provides an overview of the GSADF test statistic results for the EU ETS spot price, as well as for the spread between EU ETS spot prices and their expected values in one, two, and three months. Additionally, the table includes the simulated critical values for the GSADF test and the bootstrapped critical value for the BSADF testing procedure.

exceeds the critical value, we mark the beginning of the explosive regime, and if the test statistic falls below the critical value, we indicate the end of the explosiveness. We disregard the first regime indicating explosiveness due to its short duration. However, the second regime aligns with the price surge as expected. Although the GSADF test identifies explosiveness in the spread between the spot price and the expected spot price (as indicated in Table 1), Figures 5 to 7 demonstrate that this test result does not pertain to the price surge observed since 2018. It appears more conclusive that this result can be attributed to a few observations in 2008, which we do not intend to further interpret here.

The result that there is no bubble but explosiveness in the EU ETS since 2018 is further supported by the fact that the autocorrelation function of the price decays very slowly, while the autocorrelation of the spreads between prices and price expectations decays rapidly. Additionally, the partial autocorrelation functions indicate stationary behavior of the spreads between prices and price expectations (see Appendix B).

Figure 4 BSADF test statistic with bootstrapped critical values for the EU ETS spot price.

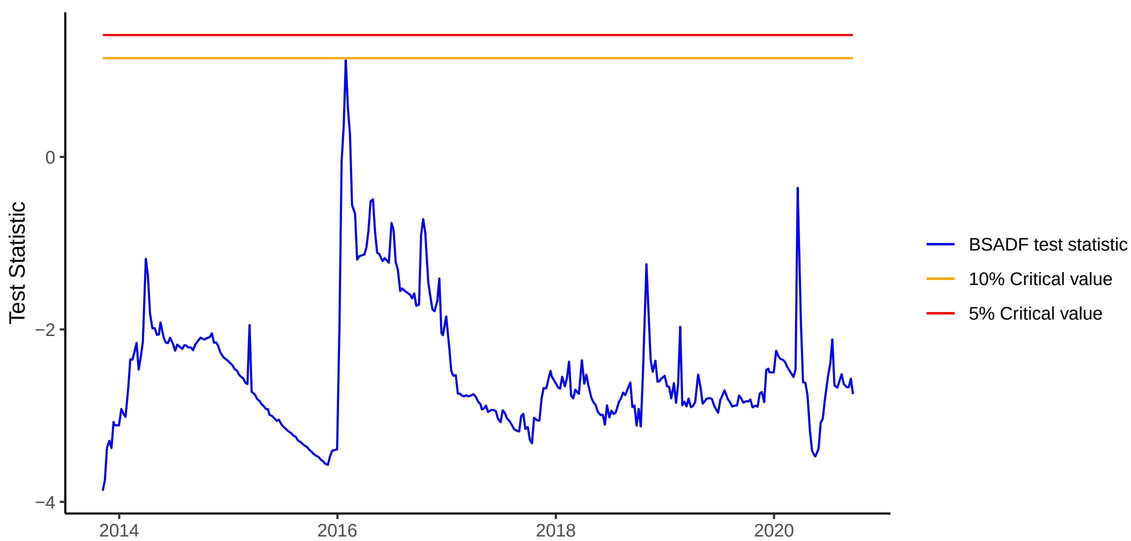

Figure 5 BSADF test statistic with bootstrapped critical values for the spread between EU ETS spot price and EU ETS market expectations one month ahead.

4. Discussion and Conclusion

Friedrich, Fries, Pahle, and Edenhofer (2020) use a time-varying coefficient model, a testing procedure against explosiveness, i.e., the GSADF test, and crash-odds modelling to analyze the EU ETS (see Fries 2022). The authors conclude that the recent price increase, i.e., the upward trend since 2018, cannot be attributed to movements in the considered price determinants, viz. coal, gas and oil prices. Moreover, Friedrich et al. (2020) deduce that explosive phases can be ascribed to

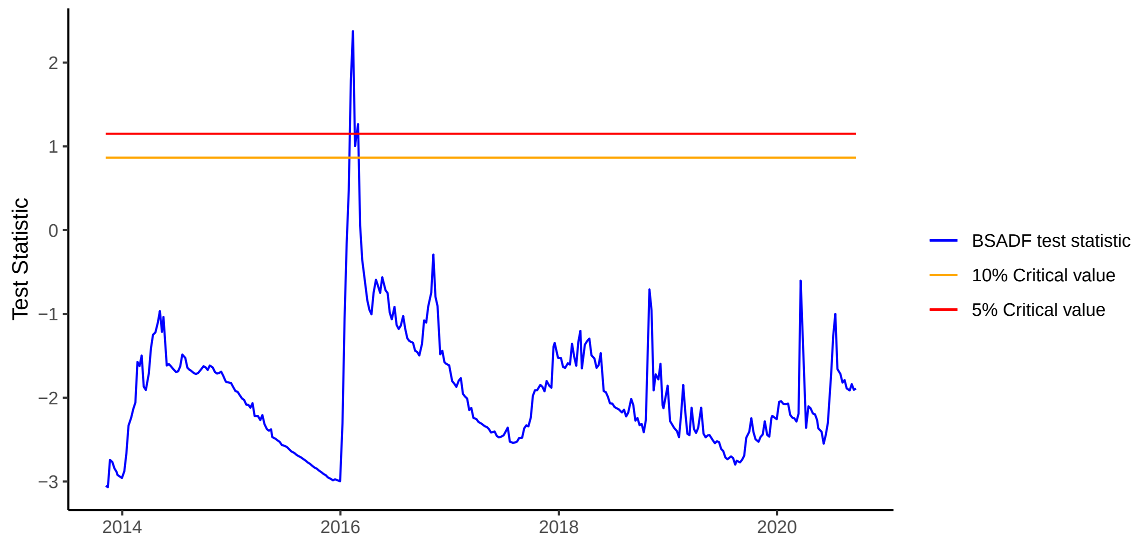

Figure 6 **BSADF test statistic with bootstrapped critical values for the spread between EU ETS spot price and EU ETS market expectations two months ahead.**

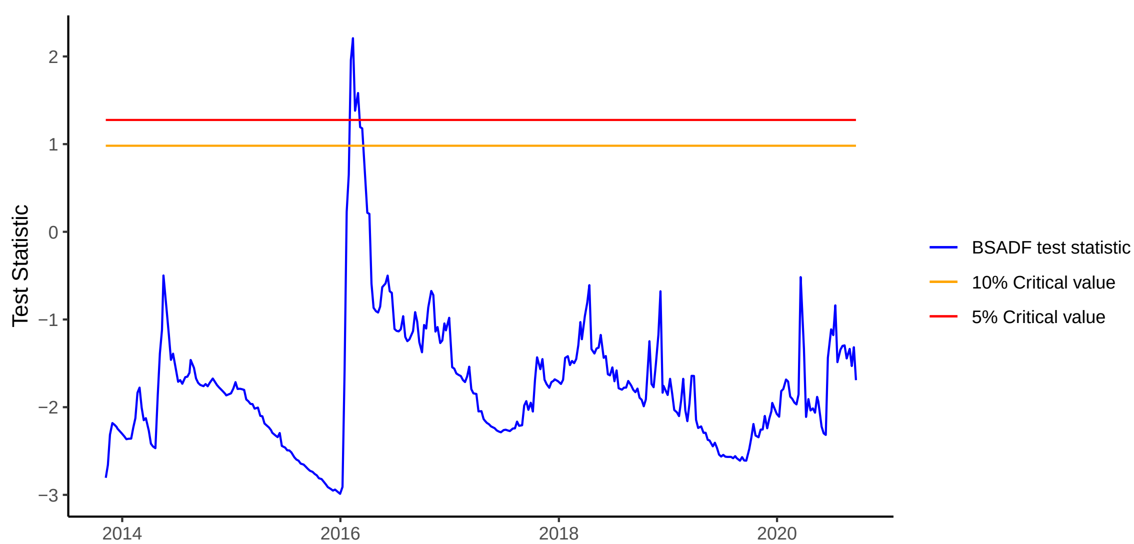

Figure 7 **BSADF test statistic with bootstrapped critical values for the spread between EU ETS spot price and EU ETS market expectations three months ahead.**

speculation and, consequently, to price bubbles, as they did not identify any simultaneous explosive phases corresponding to potential fundamental values.

While we confirm the explosive time period in the EU ETS price series, we come to another conclusion by using market expectations rather than fundamental price drivers for testing against bubbles. We find that the difference in prices and associated price expectations does not exhibit explosive phases. This suggests that although prices exhibit explosive phases, these cannot be attributed to bubbles, as price expectations contain the same explosive phases.

Our approach, in contrast to methods based on the switching costs from dirty-but-cheap to clean-but-expensive energy sources, has the advantage that it is suitable under uncertainty and that the sources of misspecification of the fundamental value are more limited. This is in line with the theoretical results by Seifert, Uhrig-Homburg, and Wagner (2008) and Chesney and Taschini (2012) and the empirical result of Lutz, Pigorsch, and Rotfuß (2013) that in particularly uncertain times (i.e., when volatility in the EU ETS is high), fundamentals have a weak explanatory power for price developments in the EU ETS. On the other hand, our approach is subject to the limitation that only three continuous futures price time series can be constructed due to data limitations. At most, we can obtain the market expectations over the next three months. Here, it would be desirable to also obtain longer-term market price expectations for more robustness of our results.

The question of whether the EU ETS is free of speculative bubbles has real-world implications. Policy makers might consider alternative measures like a Pigouvian tax if the EU ETS is found to be characterized by financial bubbles. This is because bubbles collapse, leading to significant price declines, and hence, the EU ETS might fail to internalize sustainably the externalities of CO_2 emissions. However, our results suggest that this concern is unwarranted. On the contrary, our results indicate that the market reforms of the EU ETS have had the desired effect of pricing-in a decline of allowances in the future at the present time. According to our analysis, this measure has not led to an overreaction in the market.

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Appendix A: Technical Appendix

Derivation of Expected log Market Prices

Hamilton and Wu (2014) model the total wealth W_t of a speculator at time $t+1$ as

$$W_{t+1} = \sum_{j=0}^{J} q_{jt} R_{j,t+1} + \sum_{n=1}^{N} z_{nt} \frac{F_{n-1,t+1} - F_{nt}}{F_{nt}}$$

and assume an affine structure of the forward curve, viz.

$$f_{nt} = \log F_{nt} = \alpha_n + \beta_n' x_t \qquad \text{for} \qquad n = 1, \ldots, N$$

whereas α_n is a constant, β_n' is a vector of coefficients and x_t contains stochastic, dynamic, and unobservable factors as level, slope, and curvature. The returns on all other assets $1, \ldots, J$ than futures contracts is given as $R_{j,t+1}$ and $R_{0,t+1}$ is assumed to be risk-free. With $r_{jt} := \log R_{j,t+1}$, we receive

$$r_{jt} = \xi_j + \psi_j' x_t \qquad \text{for} \qquad j = 1, \ldots, J$$

whereas ξ_j is a constant, ψ_j' is a vector of coefficients. Further, Hamilton and Wu (2014) assume that x_t follows a Vector AutoRegression with one lag, i.e., VAR(1), viz.

$$x_{t+1} = c + \Gamma x_t + \Sigma e_{t+1}, \qquad e_t \sim \text{ i.i.d. } N(0, I)$$

whereas c is a vector of constants, the matrix Γ contains coefficients, Σ denotes the covariance matrix and I is the unit matrix with appropriate dimension. The speculator maximizes

$$\mathbb{E}_t(W_{t+1}) - (\gamma/2)\mathbb{V}_t(W_{t+1}) \qquad \text{s.t.} \qquad \sum_{i=0}^{J} q_{jt} = W_t,$$

whereas $\mathbb{V}_t := \mathbb{V}(\cdot \mid \mathcal{F}_t)$ denotes the conditional variance given the information set $\mathcal{F}_t$ available at time t,

$$\begin{aligned}
\mathbb{E}_t(W_{t+1}) \approx\; & q_{0t}(1 + r_{0,t+1}) \\
& + \sum_{j=1}^{J} q_{jt}\left[1 + \xi_j + \psi_j'(c + \Gamma x_t) + (1/2)\psi_j' \Sigma \Sigma' \psi_j\right] \\
& + \sum_{n=1}^{N} z_{nt}[\alpha_{n-1} + \beta_{n-1}'(c + \Gamma x_t) - \alpha_n - \beta_n' x_t + (1/2)\beta_{n-1}' \Sigma \Sigma' \beta_{n-1}]
\end{aligned}$$

and

$$\mathbb{V}_t(W_{t+1}) \approx \left(\sum_{j=1}^{J} q_{jt}\psi_j' + \sum_{n=1}^{N} z_{nt}\beta_{n-1}'\right) \Sigma\Sigma' \left(\sum_{j=1}^{J} q_{jt}\psi_j + \sum_{n=1}^{N} z_{nt}\beta_{n-1}\right),$$

by choosing $\{q_{0t}, \ldots, q_{Jt}, z_{1t}, \ldots, z_{nt}\}$ as the exposure of the speculator in other assets and in futures contracts. It follows that the first-order conditions for the speculator positions are

$$\xi_j + \psi_j'(c + \Gamma x_t) + (1/2)\psi_j' \Sigma\Sigma' \psi_j = r_{0,t+1} + \psi_j' \lambda_t$$

and

$$\alpha_{n-1} + \beta'_{n-1}(c + \Gamma x_t) - \alpha_n - \beta'_n x_t + (1/2)\beta'_{n-1}\Sigma'\beta_{n-1} = \beta'_{n-1}\lambda_t$$

with

$$\lambda_t = \gamma\Sigma\Sigma' \left(\sum_{j=1}^{J} q_{jt}\psi_j + \sum_{n=1}^{N} z_{nt}\beta_{n-1} \right).$$

Further Hamilton and Wu (2014) assume that the positions q_{jt}, z_{nt} chosen by arbitrageurs in equilibrium can be represented as affine functions of the vector of factors, so that $\lambda_t = \lambda + \Lambda x_t$. Then

$$\beta'_n = \beta'_{n-1}\Gamma - \beta'_{n-1}\Lambda$$

and

$$\alpha_n = \alpha_{n-1} + \beta'_{n-1}c + (1/2)\beta'_{n-1}\Sigma\Sigma'\beta_{n-1} - \beta'_{n-1}\lambda.$$

The parameters c, Γ, Σ, λ and Λ are estimated by the approach by Hamilton and Wu (2012). We obtain the log futures prices for risk-neutral speculators, which are equal to the expectations about future log spot prices, by recursion and setting $\lambda = \Lambda = 0$.

Appendix B: Further Empirical Results

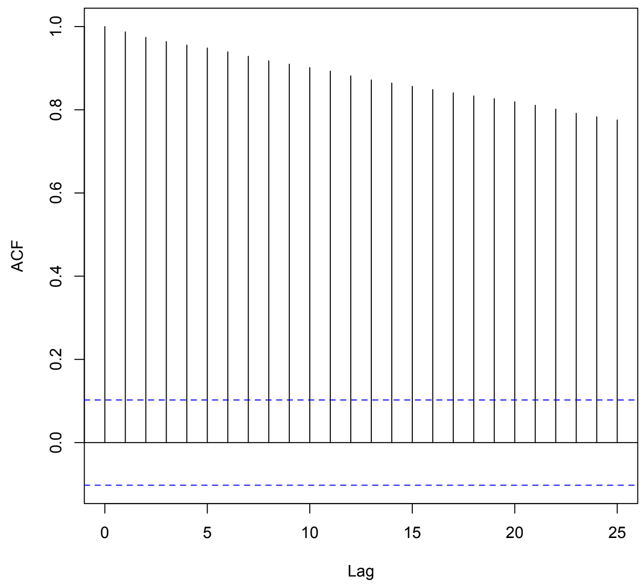

Figure 8 Autocorrelation function of the EU ETS spot price.

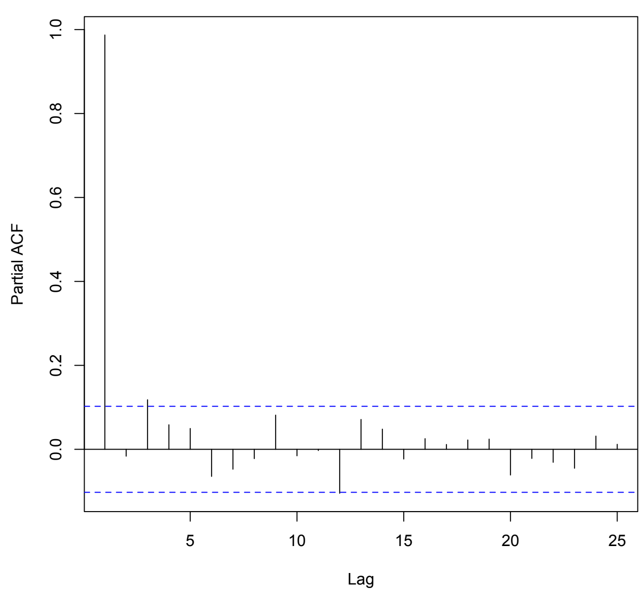

Figure 9 Partial autocorrelation function of the EU ETS spot price.

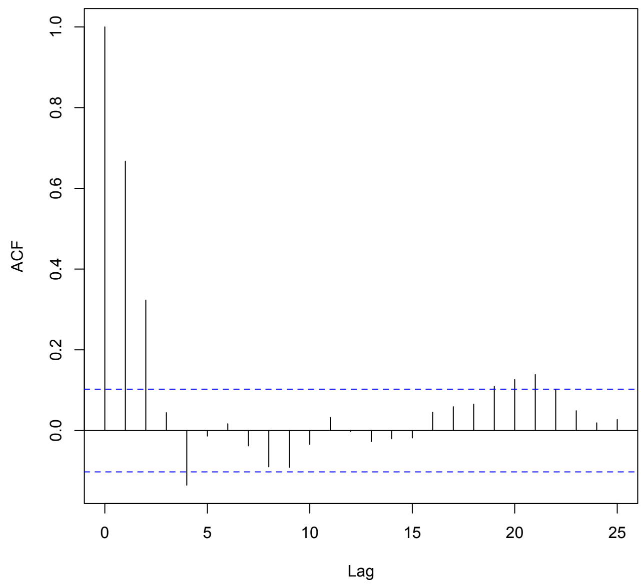

Figure 10 Autocorrelation function of the spread between EU ETS spot price and EU ETS market expectations one month ahead.

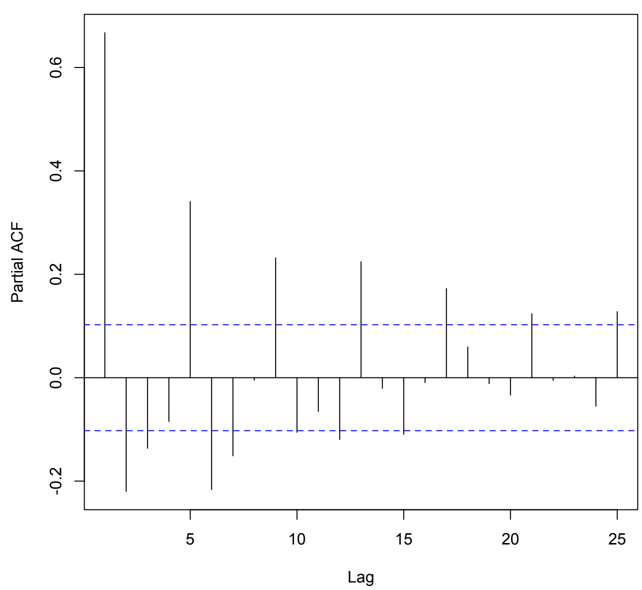

Figure 11 Partial autocorrelation function of the spread between EU ETS spot price and EU ETS market expectations one month ahead.

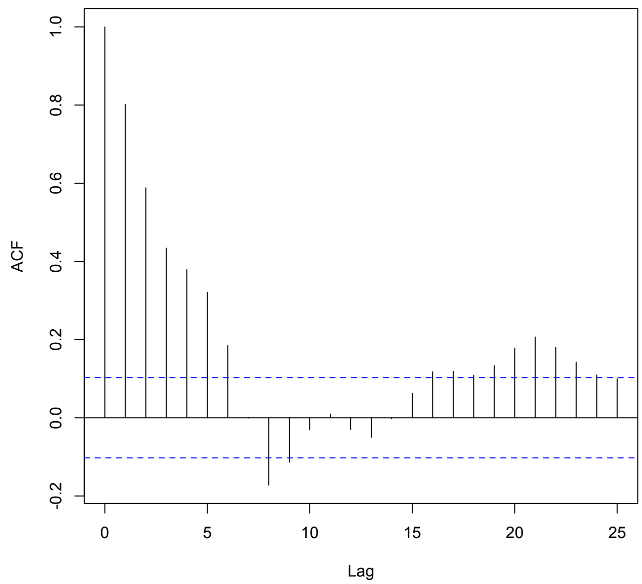

Figure 12 Autocorrelation function of the spread between EU ETS spot price and EU ETS market expectations two month ahead.

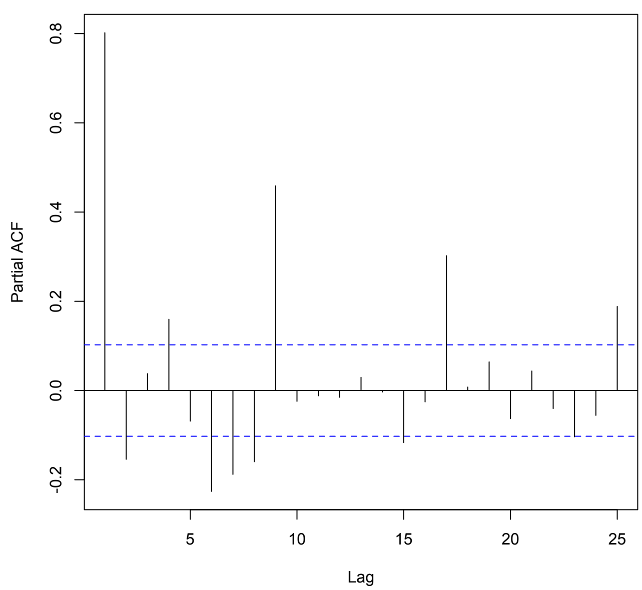

Figure 13 Partial autocorrelation function of the spread between EU ETS spot price and EU ETS market expectations two month ahead.

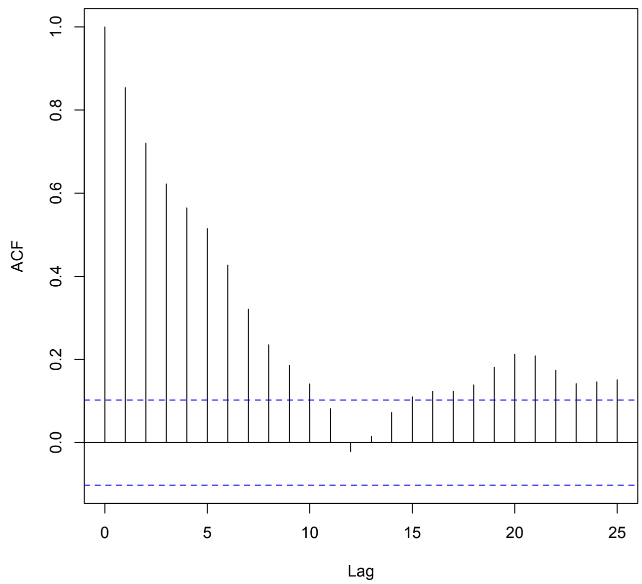

Figure 14 Autocorrelation function of the spread between EU ETS spot price and EU ETS market expectations three month ahead.

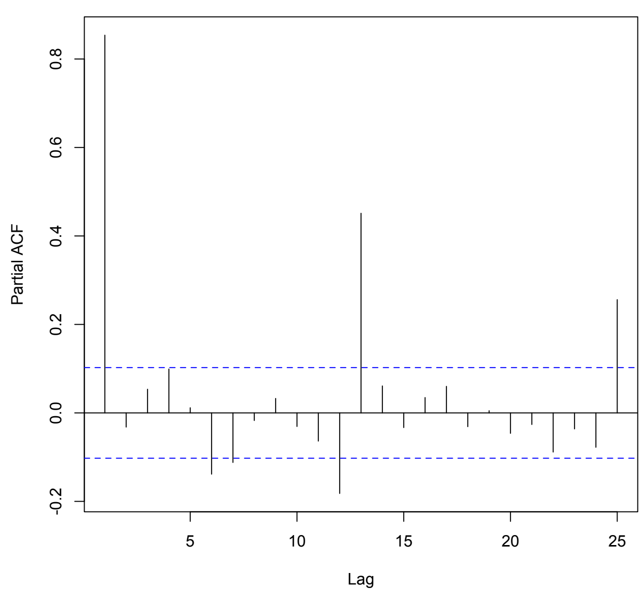

Figure 15 Partial autocorrelation function of the spread between EU ETS spot price and EU ETS market expectations three month ahead.