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From fundamentals to financial assets: the evolution of understanding price formation in the EU ETS*

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Abstract

Price formation in the EU Emission Trading System (EU ETS) has persistently puzzled economists and policy makers. In recent years, the empirical literature investigating this topic has expanded considerably, but a synthesis of what could be learned about price formation as a whole including the last wave of research is still missing. To fill this gap, we review the empirical literature structured along three categories of price drivers and related econometric methods. For better guidance of the reader, we draw on a simple theoretical model of price formation that we subsequently extend to connect the three different strands of literature: demand-side fundamentals, regulatory intervention and finance. In particular the insights from the second and third strand challenge the widespread view that allowance markets primarily reflect marginal abatement costs. Accordingly, the next wave of research should focus on shedding light on the complex interplay of compliance, regulatory uncertainty and financial trading motives.

JEL classifications: Q48, Q50, Q56, Q58
Keywords: emission trading, EU ETS, price formation, literature review

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1 Introduction

The European Union's (EU) Emissions Trading System (ETS) is the world's largest and longest-lived cap-and-trade program to regulate greenhouse gas (GHG) emissions (ICAP, 2019). It is the flagship instrument of the climate policy of the EU. Now close to its forth compliance period, we can look back at more than 14 years of existence of this market. Since the onset of the second trading period in 2008, the price of allowances (European Emission Allowances, EUAs) as shown in Figure 1 has experienced a downward trend until the end of 2017, which some consider as an indicator for inefficiencies (Fuss et al., 2018), though others think the EU ETS works efficiently and they explain the low prices by the large cap or the low allowance demand (Hintermann et al., 2016). In this paper, we review the empirical literature on the EU ETS to examine which factors have actually determined the price.

In particular, the considerable price decline that started in 2011 came as a surprise. In 2008, when the EU's 2020 climate target was adopted, 2013 EUA futures prices were at a level of around 30€/t (Ellerman et al., 2016). Furthermore, the accompanying regulatory impact assessment pointed to a price of around 40€/t in 2020 (Delbeke et al., 2009; Capros et al., 2011). This suggested that prices would rise rather than decline. The following period of low prices until the end of 2017 gave rise to concern that the EU ETS does not work as intended and it is in need of reform (Edenhofer, 2014). After some smaller reforms[1], the EU ETS for Phase IV (2021-2030) was enacted in early 2018, entailing a tightening of the cap and the strengthening of the Market Stability Reserve (MSR).[2] Presumably as a consequence, prices started to rise by the end of 2017 when the political decision was taken.

Nevertheless, it remains controversial whether the ETS is functioning well, i.e. if price formation is efficient. For instance, the COVID-19 shock led to a massive price decline in March

[1]European Commission (2019): Report on the functioning of the European carbon market https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52019DC0557R(01)).

[2]The MSR is a mechanism within the EU ETS that absorbs allowances if the number of allowances held by market agents (i.e. the allowance bank) exceeds a certain threshold. Based on certain rules, the allowances in the MSR either come back to the market later on or are ultimately cancelled.

2020. A first (theoretical) paper indicates that the recent ETS reform indeed improved the performance of the ETS during such economic crises because the MSR cancels (some of the) allowances that are additionally on the market due the crisis (Gerlagh et al., 2020) and thus, the price quickly recovered until June 2020. However, concerns remain that fundamental flaws still prevail that distort price formation (Flachsland et al., 2020). In fact, our review sheds light on this issue, and we will come back to it in the conclusions.

Figure 1: EUA price development from 2008 to September 2020 (Weekly closing prices based on spot-month continuous contract #1 from ICE via Quandl)

Against this background, this paper aims to answer the question of what actually drives prices in the EU ETS. For this purpose, we conduct an extensive literature review and link empirical results to theory. Christiansen et al. (2005) offers an early analysis of the main price drivers in Phase I (2005-2007) of the EU ETS, structured along policy and regulatory issues, fundamentals, and technical indicators. The long phase of persistently low prices until the end of 2017 motivated new empirical research to explain this development, in particular with

regard to the role of regulation. Moreover, the EU ETS also received more attention of financial economists that analyze EUAs through an asset pricing lens. In parallel, the number of studies that examine fundamental price drivers grew as well. We systematically review this empirical literature with a view on how it can help to explain the price.

Our review is structured according to the three mentioned explanatory factors for the ETS price: In Section 2, we look at studies investigating demand-side fundamental price drivers such as coal and gas prices. In Section 3, we review the literature focusing on the supply of allowances by the regulator and, more broadly, on the impact of political and regulatory events (e.g., announcements about planned changes of the cap). In Section 4, we consider the empirical finance literature devoted to this market. In this vast literature we concentrate on hedging, speculation and behavioral aspects. In each section, we select a representative group of main papers (see Table 1), for which we summarize the methodology before presenting the results. Based on this, we briefly compare the results of other papers. At the end of each of the three sections, we synthesize insights and discuss implications for the EUA price, while also paying attention to methodological limitations of the studies.

We focus on the empirical literature that helps to explain the ETS price level and development and thus, we leave out many related and in other regards highly relevant papers. For instance, we exclude papers that mainly focus on the price behavior itself (e.g., price volatility) for which the implications for the price level or development are hard to grasp (Benz and Trück, 2009; Chevallier, 2011; Dutta, 2018). We also do not consider literature that analyzes the effect of the ETS on other variables as the economic performance of firms (Commins et al., 2011; Mo et al., 2012; Marin et al., 2018), technological innovation (Calel and Dechezleprêtre, 2016; Rogge et al., 2011), emissions abatement (Ellerman and Buchner, 2008; Petrick and Wagner, 2014; Guo et al., 2020) or, more recently, carbon leakage (Borghesi et al., 2020; Koch and Basse Mama, 2019). Furthermore, we ignore the non-empirical literature and papers on other cap-and-trade markets. For one, other ETS markets are much smaller or less mature so that only a very limited number of studies exist, though the Chinese ETS pilots are an exemption (Ji et al.,

2021; Chang et al., 2018; Cong and Lo, 2017; Wen et al., 2020; Zhao et al., 2017). However, because the characteristics of the ETS programs, their maturity and the market environments are fairly different from each other, a comparison is beyond the scope of this paper.

We complement existing reviews not only by considering more recent work and by having a broader topical coverage, but also by linking the different strands through a simple theoretical model of price formation that we extend step by step. The first reviews of the topic conducted by Zhang and Wei (2010) and Bertrand (2014) only covered Phase I. More recent reviews by Zhang (2016) and Hintermann et al. (2016) cover Phase II, but pay limited attention to the finance literature. In this strand particularly, a substantial number of papers has come out over the last years. Furthermore, by extending a theoretical model alongside the empirical literature we develop an incremental understanding of price formation. This gradual approach enhances understanding of the complex interplay of different price drivers in the EU ETS.

2 Demand-side fundamental price drivers

The starting point for this review is a simple theoretical model on intertemporal price formation in emission trading systems based on the classical paper by Rubin (1996). The purpose of referring to this model is to explain how different price drivers influence the price path in theory. It also severs as the backdrop for reviewing the empirical literature investigating the specific price drivers. Initially, the model merely covers demand-side fundamentals, which have been the traditional focus of empirical analyses. In the next section, we extend the model to incorporate further price drivers.

Emission trading programs work by constraining emissions x to a regulatory defined cap $\overline{G}$

$$\int_0^T x(p)dt \leq \overline{G}, \tag{2.1}$$

where T is the lifetime of the ETS program.[3] The cap is translated into tradable allowances

[3]We disregard expectation operators for simplicity.

Section	Paper	Method	Data
2.1	Koch et al. (2014)	*Linear regression (with dummy variables)*	Jan 2008 - Oct 2013
	Rickels et al. (2014)	*Linear regression (with variable pre-selection)*	Dec 2008 - Jul 2012
	Aatola et al. (2013)	*Linear regression (with instrumental variables)*	Jan 2005 - Dec 2010
2.2	Lutz et al. (2013)	*Markov regime-switching model*	Jan 2008 - Dec 2012
	Creti et al. (2012)	*Cointegration analysis*	Jun 2005 - Dec 2010
	Keppler and Mansanet-Bataller (2010)	*Granger causality analysis*	Mar 2005 - Dec 2009
3	Hitzemann et al. (2015)	*Event study*	Jan 2007 - Dec 2012
	Koch et al. (2016)	*Event study with Dynamic Model Selection*	Mar 2008 - Apr 2014
	Deeney et al. (2016)	*Event study*	Oct 2007 - Feb 2014
4.1	Rittler (2012)	*Cointegration and Granger causality analysis*	May 2008 - Dec 2009
	Trück and Weron (2016)	*Linear regression*	Apr 2008 - Dec 2012
4.2	Kalaitzoglou and Ibrahim (2013)	*Autocorrelated duration model*	Jan 2005 - Dec 2008
	Balietti (2016)	*Trading activity-volatility relation*	Sep 2005 - May 2007
	Palao and Pardo (2017)	*Herding intensity measure*	Dec 2012 - Dec 2015

Table 1: Paper overview per section, with methods and time span of empirical analysis

or certificates which allow firms to emit. For example, in the EU ETS one European Emission Allowance entitles to emit one tonne of CO_2. If allowances are scarce, i.e. equation (2.1) holds with equality, the market establishes the allowance price p. The price reflects marginal abatement costs c' since profit maximization of firms implies, in equilibrium, that $p = c'(\overline{x} - x)$, where $\overline{x}$ are baseline emissions (uncapped emissions) and $\overline{x} - x$ is abatement.

Moreover, in an intertemporal market such as the EU ETS, firms can bank certificates for future use if they hold more allowances than needed for compliance in any period. As long as the market-wide allowance bank is positive, market agents exploit intertemporal arbitrage and therefore the allowance price at time t is given by

$$p_t = p_0 e^{rt}. \tag{2.2}$$

In equilibrium, the allowance price grows at the rate of interest r as it reflects the opportunity costs of banking. For any initial price level p_0, the entire (expected) price path is established.

According to the model, the price is determined by marginal abatement costs and the cap which can be called demand- and supply-side market fundamentals, respectively. In addition, the interest rate determines how allowances are used over time and therefore, it has a important impact on the growth rate and price level. In this section, we present empirical results for several demand-side fundamentals as part of c' while ignoring effects of $\overline{G}$ and r. In Section 3, the focus is on the supply side. Finally, Section 4 concentrates on factors that determine the applied discount rate and other price drivers.

A first challenge for empirical studies is that many price drivers are not directly observable because the current allowance price depends on future abatement costs. For instance, the expected development of low-carbon technologies affects marginal abatement costs (and thus, the price), but neither technological development, nor expectations about it, are observable. Hence innovations in abatement technology can hardly be considered in empirical studies although they clearly influence the EUA price. Empiricists therefore need to rely on observable information variables to analyze the impact on the allowance price. On the demand side, these variables

include past coal and gas prices as main factors. They play a major role for electricity generation which so far was the most important sector covered by the EU ETS. Since coal is emission intensive, the coal price has, in theory, a negative impact on the allowance price. A higher coal price reduces marginal abatement costs. Since gas is a cleaner alternative to coal, the gas price should have a positive impact on the allowance price. Another frequently considered demand-side price driver is economic activity. A higher economic activity has a positive impact on production and thus emissions, leading to increasing marginal abatement cost and, in turn, higher prices.

In addition, factors such as weather conditions including hot or cold periods, wind speed or precipitation can also have an impact, for example via electricity generation from renewables. While extreme temperatures should have a positive impact on the allowance price due to an increase in electricity demand, higher wind speed or more sunny days should have a negative impact due to increased electricity generation from renewable sources. These opposing effects make it hard to empirically investigate. Some papers which directly include data on electricity generation from renewables find a negligible or statistically insignificant effect which might be due to the lack of reliable (Europe-wide) data.

The remainder of this section elaborates on the corresponding empirical findings based on six selected papers. Each paper differs in the applied methods and/or the set of variables it considers. First, we focus on linear regression approaches. Second, we present results of papers using alternative techniques.

2.1 Empirical evidence and challenges using linear models

To empirically investigate the relations identified by economic theory, linear regression analysis is a natural starting point. However, the empirical literature shows that it is a non-trivial task to find a good model for allowance prices. Early evidence is provided by a group of papers investigating the relationship between allowance prices and abatement related fundamentals using Phase I data (e.g., Alberola et al., 2008, Mansanet-Bataller et al., 2007, Alberola and Chevallier, 2009, Chevallier, 2009 and Hintermann, 2010). As a common result, all papers find

the gas price to have a positive and significant influence on the allowance price; other considered variables differ among studies.

While some might argue that the market was not mature enough in Phase I to establish a strong relationship between allowance prices and their fundamentals, Koch et al. (2014) face similar challenges using Phase II data. The authors initially find very limited explanatory power of fundamentals, although the set of included variables is extensive. It consists of coal and gas futures, a stock index as measure of economic activity, renewables generation from two production types (hydro, wind and solar) and the number of issued Certified Emission Reductions (CERs).[4]

The regression exercises reveal that the gas price and economic activity can be identified as clear price drivers. Surprisingly, the coal price does not significantly affect allowance prices. Although the significant factors show the anticipated effect, the overall explanatory power of the models is low. They increase the model fit by accounting for the effect of major policy events using dummy variables. This implies that certain observations disturb or change the estimated relationship such that taking them out improves the findings of a linear model.

A second paper we consider is Rickels et al. (2014), because contrary to most other studies it pays special attention to the multitude of data series that exist. The authors show that empirical papers, whose conclusions regarding the role of fundamentals differ, often use different price series. They point out that, particularly, the coal price can differ quite substantially and it is not obvious which series to choose, as the market lacks transparency. In their empirical study, the authors carefully select each price series by running auxiliary regressions of each candidate series on the allowance price. In the final model specification, they find a significant positive effect of the fuel switching price[5], a significant but negligible effect of renewables and a positive

[4]CERs are so-called carbon credits which can be used instead of emission allowances by covered firms for compliance. They can be earned by companies that engage in certain GHG mitigation projects in developing countries.

[5]The fuel switching price is a linear combination of the coal and the gas price with constants depending on the coal and gas plant's efficiency and emission factor. Hence, using this price can be seen as a restriction which is imposed on the respective coefficients of the coal and gas prices.

effect of economic activity as measured by the oil price and a stock index.

The third paper we would like to review is Aatola et al. (2013). The authors additionally use electricity prices as potential price drivers. The previous two papers do not consider this variable in their empirical analysis due to endogeneity concerns caused by the fact that the relationship between electricity prices and allowance prices might run two-ways: electricity prices drive allowance prices, and allowance prices are likely to have an impact on electricity prices. To address this issue, Aatola et al. (2013) apply a two-stage least squares procedure using appropriate instrumental variables for electricity prices. They find a positive and significant effect of electricity prices. Additionally, they identify significant effects of both coal and gas prices in the direction predicted by economic theory. To the best of our knowledge, this is the only paper which establishes significant effects of both coal and gas prices using Phase II data which is robust throughout all considered specifications.

In Koch et al. (2014), we can see the importance of controlling for political uncertainty, which will be discussed in Section 3. Moreover, all three papers find the residuals of their models to have a non-constant variance. This is addressed by the authors in different ways. Aatola et al. (2013) use a GARCH specification, while Koch et al. (2014) and Rickels et al. (2014) rely on Newey-West robust standard errors. Heteroskedasticity is frequently encountered in empirical studies involving financially traded assets. The allowance price series show several characteristics of financial data which is discussed in more detail in Section 4.

2.2 Alternative approaches

In the previous section, we saw that linear regression approaches need to be adapted to account for time-varying volatility, outliers related to news events as well as possible endogeneity. Here, we present papers that focus on other aspects: time-variation, nonlinearity and instability of the relation between allowance prices and fundamentals.

The first paper is Lutz et al. (2013). It investigates possible nonlinearities in the relationship between the EUA price and its fundamentals during Phase II. They distinguish two different

pricing regimes - one applies during periods of high volatility and the other during periods of low volatility. The model allows for two distinct sets of coefficients. The set of explanatory variables is composed of coal and gas futures, oil prices, a stock index, a commodity price index and deviation from average temperature.

In both regimes, the authors find the same set of relevant price drivers. Coal and gas prices, oil prices and the stock index are statistically significant determinants of the EUA price. In Regime 2, which is characterized by low and constant volatility, all significant price drivers show the anticipated sign. Regime 1, however, shows high uncertainty and time-varying volatility. The results on price drivers are similar in this regime, except for the effect of the coal price, which is now positive. This goes against economic theory which predicts the effect to be negative.[6]

Creti et al. (2012) investigate the question whether the relation between EUA prices and its fundamentals has been stable over the course of Phases I and II and might be evolving towards a long-term equilibrium relationship. Rather than working with stationary data by transforming integrated price series into returns, they analyze the non-stationary price data using cointegration techniques. Previous work finds evidence of a cointegration relationship in Phase II, while evidence for Phase I is mixed. This is confirmed in Bredin and Muckley (2011) who find a cointegration relationship in Phase II but not in Phase I or the whole sample. Hintermann (2010) and Rickels et al. (2007) also find no evidence of cointegration in Phase I.

Creti et al. (2012) consider fuel switching prices, oil prices as well as a stock index. They look at their whole sample (2005-2010) as well as two sub-periods corresponding to the different compliance phases. They find a clear cointegration relationship in Phase II with positive and significant coefficients for all fundamentals. For Phase I, they can only find a relationship if they allow for a break in 2006. The nature of the relationships differ between Phase I and II. They find a negative effect of the stock index in Phase I and an insignificant effect of fuel switching. Overall, these findings indicate an increasing role of fundamentals over time while there is no

[6] A recent paper by Jiao et al. (2018) follows the idea of different regimes by looking at EUA return distributions in two regimes defined by economic states. However, they do not investigate the impact of fundamentals, but use predictions of future economic states together with the past return behavior for Value at Risk forecasting.

clear evidence for a stable long-term relationship.

There is a small body of more recent papers which confirm this conclusion. Rickels et al. (2014) find cointegration relationships to be dependent on the choice of data series. Fell et al. (2015) find cointegration relationships among electricity, EUA, coal and gas prices. The resulting vector error-correction model (VECM) shows, however, insignificant responses of EUA prices to shocks in coal and gas prices. Carnero et al. (2018), who estimate a VECM on Phase III data, find a negative relationship between the allowance prices and gas prices. This is to our knowledge the first paper to find a negative relationship between EUA and gas prices, it is also the first paper which only focuses on Phase III data. Overall, caution should be applied when considering results from cointegration analysis in this market due to the short duration and a potential seasonal pattern caused by European rules.[7]

Keppler and Mansanet-Bataller (2010) analyze the interplay between EUA, electricity, gas and coal prices based on a Granger causality analysis. A time series $\{x_t\}_{t=1}^n$ Granger causes another time series $\{y_t\}_{t=1}^n$, if the past of x has an effect on the present of y. Keppler and Mansanet-Bataller (2010) include both EUA spot and futures prices from 2005 to 2008, as well as gas and coal futures, peak and base load electricity prices, the clean dark and spark spread (CDS, CSS) as well as a stock index and several temperature variables.[8]

For Phase I, Keppler and Mansanet-Bataller (2010) find that returns on EUA futures Granger cause spot returns, while spot returns do not Granger cause futures. In addition, EUA futures are Granger caused by CSS and CDS for peak-load electricity as well as by the temperature index, but not by gas, coal or electricity returns. Conversely, EUA futures Granger cause electricity futures for peak and base load, which, in turn, Granger cause the stock index. Based on the previous causality analysis, the authors decide to run a regression with electricity futures as dependent variable. The allowance price, which is usually the dependent variable, enters as regressor together with the CSS and the gas price. They find positive and significant effects of

[7]We thank an anonymous referee for pointing this out.

[8]CDS refers to the revenue a coal-fired generator makes by selling power after having bought coal and the required number of EUAs. CSS represents the same quantity for a gas-fired generator.

all regressors. Results are different for Phase II, but since the analysis is restricted to one year we do not include the detailed results in our review.

Because econometric analysis is still unavailable, we have to leave out the most recent episode of the EU ETS that has puzzled many market observers: The price plunge and shot-term rebound following the onset of the COVID crisis in March 2020. One can look to work on previous shocks of similar scale for potential explanations. Work by Zhu et al. (2015) finds that the financial crises lead to a structural break point. However, this only makes clear that the relative role of different price drivers changed, but it does not explain why and what the mechanisms behind it could be.

2.3 Insights and implications

The following two main insights can be drawn from the reviewed studies. (1) In general, fundamental price drivers have relatively little explanatory power. Specifically for coal, some studies even find a positive correlation, contradicting the prediction of economic theory. This might be due to the fact that the coal price is location-specific and not uniform across Europe as pointed out by Rickels et al. (2014), or that the relationship between coal and allowance prices might change over time as indicated by the results of Lutz et al. (2013). (2) Methodologically, linear regression models come with the limitation that they can only indirectly account for time variation or important political events by using dummy variables. The reviewed papers indicate that the inclusion of such dummy variables can improve the fit of such models, while the overall explanatory power of abatement-related fundamentals remains low.

These insights have two implications. (1) Price formation in the EU ETS is driven by other drivers than purely by fundamentals. This begs the question what these drivers could be. As mentioned above, some papers point to the role of political decisions and changes in the regulatory framework. In fact, in recent years a literature emerged on this topic, which we will review in Section 3. (2) Alternatively, the fact that the explanatory power of abatement-related fundamentals remains low might be due to data and methodological limitations. This underlines

the need for better data and more flexible approaches.

3 Political and regulatory changes

The previous section alluded to regulatory uncertainty as another factor influencing price formation, which has gained more attention in face of the low EUA prices and the difficulty of explaining the price development with the help of demand-side fundamentals.

We follow Salant (2016) to introduce regulatory uncertainty in our theoretical model. In this setting, a regulatory intervention implies that the price will either jump up with probability φ or jump down with probability $(1-\varphi)$. The new expected price p^A is then given by

$$p^A = \varphi p^H + (1-\varphi)p^L, \tag{3.1}$$

where $p^L \geq 0$ and $p^H \geq p^L$ denote the lower and higher price after a jump, respectively. The risk for a regulatory intervention which causes such a jump is ongoing and it is determined by the hazard rate $\alpha > 0$. Salant (2016) shows that no arbitrage considerations cause the price change in anticipation of the jump to be

$$\frac{\dot{p}_t}{p_t} = r + \alpha\left(1 - \frac{p^A}{p_t}\right). \tag{3.2}$$

That is, the growth rate of the price changes from r, as in the previous section, to equation (3.2). Assuming that the downward price jump is more severe than the upward price jump, the new expected price is lower: $p^A < p_t$. Consequently, the growth rate of the allowance price is larger than r because the term in the brackets in equation (3.2) is positive. Given that the cap remains unchanged, the price path can be written as

$$p_t = p_0 e^{(r+\alpha)t} - \frac{\alpha p^A}{r+\alpha}\left(e^{(r+\alpha)t} - 1\right), \tag{3.3}$$

which adds the two new factors, α and p^A, to the price equation (2.2) from the previous section. The higher α and the lower p^A, the faster the price increases. Moreover, for a given cap, a

higher growth rate implies that the current price is lower and the price in the far future is larger compared to the case without regulatory risks. Therefore, even if the regulatory intervention never occurs, current prices are depressed.

There are different plausible causes of the price jumps. For instance, a new policy that reduces the demand for allowances such as coal phase-outs or support schemes for renewable energies. Such policies have already been implemented in the EU, but similar might follow in the future and thus, cause a further reduced allowance demand and associated price drop. A very important cause is certainly also a change in the cap where a higher cap reduces the price and vice versa. Hence, regulatory uncertainty can be included in the model by assuming that the cap is uncertain. The new market balance equation reads

$$\int_0^T x(p)dt \leq \widetilde{G}, \tag{3.4}$$

where the tilde reflects uncertainty compared to (2.1). For example, a news announcement gives market participants new information from which they infer a change of $\widetilde{G}$, leading to price jumps. Such price jumps are in practice reflected by abnormal returns which is the basis for the empirical studies we discuss in the remainder of this section.

The empirical papers focus on the impact of different types of regulatory announcements on allowance prices. They look at supply-side fundamentals as regulatory decisions that may affect the cap or are viewed as signal for the long-term cap setting. Demand-side fundamentals as announcements of realized emissions are considered as well. While many papers discussed in the previous section already incorporated some aspects related to political decisions, the papers discussed here take a more direct approach. Two of them perform an event study and one uses a dummy variable approach.

In general, event studies can uncover price changes caused by a specific event. The main idea relies on a comparison of the price change that would be expected in the absence of the event - the normal return - to the actual change in prices. If the difference aggregated over a pre-specified event window is large enough, there has been a significant price effect caused by the

studied event. This difference between actual and normal returns is called the abnormal return. Formally, the abnormal return at time t can be defined as $AR_t = r_t - \mathbb{E}_t(r_t)$, where r_t denotes the actual return and $\mathbb{E}_t(r_t)$ is the expected normal return at time t. If the event window ranges from t_1 to t_2, cumulative abnormal returns are obtained as $CAR_{t_1,t_2} = \sum_{t=t_1}^{t_2} AR_t$. Those returns are the main quantity of interest and they need to be carefully estimated. Since actual returns are an observed quantity, it is the estimation of normal returns that is crucial. We do not know what the price would have been if the event had not taken place. To obtain estimates of normal returns, the following papers use different approaches.

3.1 Realized emissions

The first paper we present is Hitzemann et al. (2015). The authors look at the effect of emission announcements on EUA returns. Once a year, in April, the quantity of realized emissions of the previous year are publicly announced. This information affects prices if the number of realized emissions differs from expectations of market agents since more emissions imply a higher allowance demand and therefore higher prices and vice versa. In addition, the market may adapt its expectation about future emissions as well if past emissions are considered as indicator for the future which would affect prices accordingly.

In order to capture the news related effect, Hitzemann et al. (2015) define five dummy variables for each announcement. They are designed to capture the effect on the day of the announcement as well as the period before and after the event. The dummy variables are used as explanatory variables in a regression on absolute abnormal returns of EUA futures. This procedure provides an estimate of the immediate effect as well as the effect directly prior to and after the announcement. They are calculated as the difference between actual returns and the overall average return. Using absolute abnormal returns, Hitzemann et al. (2015) run the dummy variable regression which is also carried out on trading volumes and implied as well as realized volatility. The latter two are a measure of intra-day volatility. As a robustness check, Hitzemann et al. (2015) also calculate abnormal returns using average returns over a rolling

window, which yields similar results as using the total average.

Overall, the authors find significant abnormal returns on the event day. They also find increased trading volumes and intra-day volatility on the same day. The return response is particularly high in 2008 and 2012. There is no significant effect on abnormal returns before or after the announcement day. This finding shows an immediate market response and thus the market seems to incorporate new information efficiently into prices. In addition, they observe low trading volumes and low intra-day volatility prior to the announcement. Hitzemann et al. (2015) interpret this as a "calm-before-the-storm" effect. The results are in line with findings from other energy and commodity markets.

3.2 Backloading and cap-updating

A second paper we highlight is Koch et al. (2016). The paper investigates two types of policy events: backloading and updating of the cap. Backloading refers to the decision to postpone the auctioning of allowances. While updating of the long-term cap should lead to a price reaction, backloading is cap-neutral and should not affect allowance prices according to the theoretical model introduced in Section 2. However, if market participants have a short foresight horizon or use allowances for hedging purpose (see Section 4), then backloading can have an effect. In addition, incorporating regulatory risk into the theoretical framework, as in Section 3, says that also backloading announcements may have an effect if they are perceived as indicator for the credibility of the cap.

The analysis in Koch et al. (2016) is a classical event study approach, but instead of simply using average returns as an estimate of normal return, they rely on model predictions. As we saw in the previous section, there is not one preferred model for EUA returns. This complicates the question of model choice. To solve this problem, Koch et al. (2016) rely on a flexible procedure called Dynamic Model Selection. From a vast amount of different models, including potentially different sets of regressors at different time periods, the procedure selects the one with the best fit. For each event, this model is used to predict normal returns for a 7-day event

window. Although the general idea is similar, this approach is substantially more involved than the dummy variables in the previous paper. The set of possible regressors consists of oil, coal, electricity, commodity and stock prices, interest rates, corporate bond spread, CER prices and a volatility index.

They find that events related to backloading explain many jumps in the data. Four backloading events cause a significant price drop and two a significant price increase, while only two events related to long-term cap changes trigger a statistically significant price effect. The latter are the agreement on 2020 targets and the Green Paper on 2030 targets - both having a positive effect. In summary, they conclude that policy events can explain the existence and timing of jumps in EUA prices. However, many events do not cause an effect in the anticipated direction. The goal to increase the price by backloading has not been achieved, because there is an overall negative effect on prices. Koch et al. (2016) argue that expectations about the degree of commitment plays an important role in allowance pricing.

3.3 Decisions by the European Parliament

The third paper in this section is Deeney et al. (2016). The authors look at the effect of announcements of the European Parliament (EP) on EUA returns. They categorize events according to three main criteria. First, they distinguish between "party-political" and "non-party-political". Party-political decisions concern resolutions put forward by the seven political groups of the EP. Non-party-political decisions come from the European Commission or the European Council. Second, they construct a measure of EUA market sentiment and label events as high or low sentiment according to the resulting index. Third, they measure market attention, or news exposure, which leads to the third and final category. The events are divided between high and low news exposure.

The event window is chosen to consist of 11 days, the day of the Decision by Parliament as well as five days before and after this day. To calculate abnormal returns, they use a zero log return model as well as a constant log return model. In the first model, normal returns are

assumed to be zero during the event window, $\mathbb{E}_t(r_t) = 0$. In this case, $AR_t = r_t$. In the second model, normal returns are constant and equal to the mean return during the estimation window, which consists of the 20 days before the start of the event window. Both models are easy to implement and yield very similar results in this application. In addition, the authors investigate volatility effects using a GARCH model equipped with dummy variables for the period before the event, the event day itself and the period after the event.

Deeney et al. (2016) find significant negative abnormal returns as well as an increase in volatility due to the announcements related to EP decisions. Looking at the different categories, these findings seem driven by non-party-political events. Most party-political events have no significant effect. A possible explanation according to Deeney et al. (2016) is that party-political decisions get more media coverage and attract more attention in advance than non-party-political resolutions. This suggests that the party-political decision does not come as a surprise and that prices already reflect this information. Additionally, they find the same effects after events in times of low market sentiment and when market attention is low. When market attention is high, there is no significant abnormal return, but a decrease in volatility after the announcement. Both findings are relevant for the timing and extent to which political decisions are revealed to market participants.

3.4 Other related papers

Other studies in this direction are e.g., Mansanet-Bataller and Pardo (2009), Mansanet-Bataller and Sanin (2014) and Fan et al. (2017). The first paper shows that news announcements during Phase I had an influence on allowance prices on both the announcement day and on previous days, while they find no effects on the volatility of returns. Mansanet-Bataller and Sanin (2014) find a strong impact of announcements by the European Commission, in particular, regarding the Phase II announcements of National Allocation Plans and the global cap for Phase III. Fan et al. (2017) look at a wide range of announcements regarding regulatory updates in an event study using adjusted mean returns as a measure of normal returns. They find 24 out of the 50

events they consider to have caused significant abnormal returns. Moreover, according to this study, impacts of events having negative impacts are higher than those having positive impacts. Another recent contribution is Creti and Joëts (2017) who also use an event study. However, before the event study, they test for periods of exuberance in the allowance price data and find evidence for several short periods of explosive behavior. Events that offer possible explanations for these episodes are then used in an event study in which no abnormal returns are found.

In addition, Conrad et al. (2012) find that decisions regarding the allocation of allowances has a strong and immediate impact on EUA prices. This finding is based on high-frequency data and the use of surprise variables which are constructed with the help of market expectations obtained from surveys.

Sanin et al. (2015) apply a different approach which is, in essence, a combination of methods used by papers in the previous section on fundamentals. The authors use an ARMA model for allowance prices with fundamentals as exogenous regressors and a GARCH component. To the GARCH model they add a jump component that allows for sudden jumps in volatility which they relate to supply announcements by the European Commission. The fact that their focus lies on volatility dynamics rather than prices is due their focus on financial market aspect of the EU ETS.

3.5 Insights and implications

The following insights can be drawn from the reviewed studies. (1) There is clear evidence that, in general, the market reacts to a variety of regulatory news with changes in returns and volatility. However, some events triggered a response in a direction contradicting theoretical predictions. Offered explanations are that the information has already been priced in (party-political EP decisions), or that it more profoundly signaled a lack of commitment (backloading). (2) Methodologically, core to all approaches is the notion of abnormal returns. There exists a plurality of ways how to estimate this unobserved quantity, e.g., zero or constant returns and Dynamic Model Selection. Respective results can differ substantially and some methods may

find significant effects where others do not. Moreover, all studies employ time windows spanning over several days. Accordingly, it remains unanswered how persistent the effects are.

These insights have two implications. (1) The way in which the market responds to news alludes to the potential role of information processing and belief formation. Prices may not respond to an event because it has been anticipated, or they respond indirectly by means of adapted beliefs. This implies that identifying the true underlying cause of the market response remains challenging. (2) Information processing and belief formation also imply that market reactions depend on capabilities and access to information of different trader types. This is reflected in their trading behavior, which is covered by the finance literature that we review in the next section.

4 Emission allowances as a financial asset

Besides its role as a compliance market, the EU ETS is also a financial market. The main purpose of such a financial commodity market is risk reduction (hedging), speculation and price discovery. Moreover, a financial market introduces new agents to the ETS: financial traders or speculators who aim to make profit from trading allowances or derivatives such as options and futures. This raises the question in how far speculation, hedging and (in)efficient price discovery affect the price formation in the EU ETS. Analyzing the EU ETS from a financial market perspective thus offers useful insights into the functioning of the market.

We focus on two different aspects. The first strand of literature (Section 4.1) considers market frictions and the price discovery processes. Financial economic theory suggests that markets are efficient if prices reflect all available information such that there are no arbitrage opportunities. Typical inefficiencies which impair information transmission are transaction costs. Other market frictions are convenience yields and risk premiums that may lead to under- or overvalued prices, compared to the idealized first-best market solution. In this case, the temporal availability of allowances and the hedging demand of firms can affect prices.

The second strand of literature (Section 4.2) that we discuss is on behavioral aspects of the

EU ETS. By now, non-regulated actors make up a large share of the overall trading volume in the market. Given that trading accounts held by financial actors tend to be more active than those of compliance traders (Berta et al., 2017; Betz and Schmidt, 2016), their behavior is potentially an important factor for price formation. Consequently, during the last years, the behavior of these actors and possible differences in their trading strategies have become a major interest in the literature.

Although the relationship of interest is different, it is worth noting that many of the methods which we saw in Section 2 reappear in this section. Previously, they were applied to analyze the allowance price and its relationship to fundamentals. In particular, cointegration analysis, Granger causality tests and (variations of) GARCH models are popular also in this strand of the literature. The main difference is that the methods are applied to different data series. Studies in the section analyze, for example, the price volatility, bank volume or the duration of trades.

4.1 Financial market frictions

Financial market frictions as considered in this section do not directly affect the demand- and supply-side fundamentals of the previous sections. Instead, they affect how allowances are evaluated over time. Accordingly, empirical papers in this field typically analyze the relationship between ETS spot and futures prices. There are two (non-exclusive) theoretical views on this relationship (Fama and French, 1987). First, according to the theory of storage, price differences should reflect the forgone interest due to investing in a commodity, its storage costs and a convenience yield (Kaldor, 1939; Working, 1949; Brennan, 1958). Since storage costs for EUAs are virtually zero, price differences should be only due to the interest rate and the convenience yield. The latter arises because of a potential benefit of holding EUAs rather than futures. This benefit exists due to potential stock-outs (i.e. a zero allowance bank) in the future which can lead to positive price shocks because firms cannot borrow from future compliance periods. The second view on the relationship between spot and futures prices is the hedging pressure theory (Keynes, 1930, Hicks, 1939, Hirshleifer, 1990). In this case, futures prices consist of the expected

spot price and a risk premium. The latter has to be paid by producers to financial traders that take the contrary position in the market. The risk premium reflects the producers' demand for risk reduction (due to risk aversion). They thus accept a lower return which is the profit of speculators. Both theories can be incorporated in a standard cost-of-carry model implying no-arbitrage between spot and futures prices. Specifically, the futures price is

$$p_t^{fut} = p_t e^{(r-\gamma+\lambda)(S-t)} \tag{4.1}$$

where p_t is the ETS spot price, S is the expiry date of the futures contract, γ is a convenience yield and λ is a risk premium. Due to arbitrage this relationship holds for allowances prices in general and thus we can write the allowance price path as

$$p_t = p_0 e^{(r-\gamma+\lambda)t}. \tag{4.2}$$

Hence, similar as the hazard rate in the previous section, the risk premium and the convenience yield change the price path and enter the original equation (2.2) through an additional term in the exponential function. A positive risk premium leads to a steeper price path and thus lower prices initially and higher prices in later periods. A negative risk premium and the convenience yield, in contrast, have opposing effects since they flatten the price path.

The empirical papers presented in this section often test whether the relationship between futures and spot prices hold as in equation (4.1) with $\gamma = \lambda = 0$. If this is not the case, it is interpreted as indicator for non-zero convenience yields γ or risk premiums λ that prevent a perfect arbitrage. An alternative interpretation is that the information transmission between spot and futures markets is inefficient due to transaction costs, implying also that the price discovery process is distorted.

The first paper we consider is Rittler (2012). In a first step, he derives the theoretical futures prices from observed spot prices based on the cost-of-carry model given by equation (4.1) assuming no convenience yields and risk premiums, $\gamma = \lambda = 0$. Theoretical and observed

futures prices are then used to estimate a vector error correction model (VECM) to analyze cointegration of long-run prices. Subsequently, Rittler (2012) computes common factor weights as price discovery measures for the markets and conducts Granger causality tests for the short-term relationship.

Using daily data, the author finds no cointegration between prices, indicating the absence of a stable long-run relationship. This confirms the result by Chevallier (2010a) who also finds no cointegration for similar data. It is also consistent with Joyeux and Milunovich (2010), who provide results for Phase I. In contrast, Uhrig-Homburg and Wagner (2009) find evidence of a long-run relationship with daily data for Phase I. More recent studies by Charles et al. (2013) and Bredin and Parsons (2016) also conduct conintegration tests with daily data. The former find a significant relationship between spot and futures prices using data from March 2009 to January 2012. Bredin and Parsons (2016) use data from 2005 to 2014, and find only cointegration between observed and theoretical cost-of-carry futures in Phase I, while for Phases II and III, there is no cointegration. Overall, the results for the relationship between daily spot and futures prices are mixed and suggest some frictions preventing a perfect arbitrage. However, when using 10 or 30 minutes intra-day data, Rittler (2012) finds strong support for cointegrated prices. He suggests that markets are indeed closely linked but this can only be observed when exploiting information in high frequency rather than daily data. Furthermore, Rittler (2012) finds common factor weights of about 70% for the futures market, which means that it contributes more to the price discovery process than the spot market. Regarding short-term causality, he finds a bidirectional impact. Rittler (2012) concludes that the price discovery process is similar to other mature markets. This result is confirmed by Schultz and Swieringa (2014) who also use high frequency data. In addition, Schultz and Swieringa (2014) find that transaction costs are an important market friction that prevents faster price adjustments for some EU ETS securities. The study by Mizrach and Otsubo (2014) confirms the cointegration between EUA futures and spot prices, where the more liquid futures market leads the price discovery.

While Charles et al. (2013) find cointegration between spot and futures prices (see above),

they reject the cost-of-carry model with zero convenience yield. They interpret this as market inefficiency because it implies arbitrage opportunities. A related strand of literature considers the presence of profitable trading strategies which should not exist in an efficient market when arbitrage is exploited. Daskalakis (2013) examines the EUA futures market and analyzes the relative performance of different trading strategies that aim at identifying price trends by looking at past prices. The results hint both at the failure of the efficient market hypothesis in the period from 2008 to 2009 as well as at an increase in efficiency from 2010 onwards. However, even for 2011, the trading strategies produced positive returns, although these were lower than those of the reference sell and hold strategy. This implies that the market became more mature over the years and thus closer to being in line with weak market efficiency. Related to this, Crossland et al. (2013) consider the daily EUA spot prices in Phase II and analyze the presence of profitable trading strategies based on momentum (price trend continuing) and overreaction (price trend reversing). They find the occurrence of momentum in the short-term and overreaction in the medium-term, both phenomena that contradict the efficient market hypothesis. Mizrach and Otsubo (2014), Narayan and Sharma (2015), Niblock and Harrison (2013) and Aatola et al. (2014).

Trück and Weron (2016) explicitly take non-zero convenience yields and risk premiums into account that may explain profitable trading strategies of other studies. They calculate the implied convenience yield using observed spot and futures prices based on equation (4.1), yielding

$$\gamma = r - \frac{\ln(p_t^{fut}) - \ln(p_t)}{(S - t)} \tag{4.3}$$

where γ may also include a risk premium λ. They find that after a short positive period in 2008, the convenience yield turns highly negative between -2% and -7%. In a second step, Trück and Weron (2016) regress the implied convenience yields on several factors by applying a pooled OLS regression. They use the allowance surplus in the market and risk measures as independent

variables. They find that a higher allowance surplus decreases the convenience yield and interpret this result as consistent with the theory of storage, since generally more allowances should lead to lower risk of a stock-out. They also find a negative effect of the EUA price variance on the convenience yield. This is seen as evidence for the impact of the hedging demand: firms are willing to pay higher prices for futures to reduce their risk exposure.

Other papers that empirically consider risk premiums are Chevallier (2010b, 2013), Kamga and Schlepper (2015) and Pinho and Madaleno (2011). They find on average positive risk premiums and suggest that this indicates that investors want to hedge against rising prices. The role of hedging is also confirmed by Hintermann (2012). He derives an option pricing formula in which the price depends on the penalty for non-compliance and the probability of a non-binding cap. He applies it to Phase I data and finds that it can explain large parts of the price development. Therefore, he concludes that hedging against paying the penalty was an important price driver in Phase I.

4.2 Behavioral aspects

This section sheds light on how the behavior of different market actors affects ETS prices. An important question in this context is how market participants form their expectations and beliefs about how the price will evolve. Behavioral aspects covered here comprise the existence of different trading types, non-rational behavior such as herding, and the use of trading strategies aiming at exploiting price patterns. Two important theoretical papers in this context are Barberis et al. (1998) and De Long et al. (1990). Both derive price formulas for assets in which they distinguish between the fundamental value of the asset and the actual price distorted by the behavior of a part of the market participants.

Barberis et al. (1998) ask how market participants form beliefs about the probability of future changes – or rather how these beliefs are updated in response to new information. Standard models implicitly assume that updating happens instantaneously and with full confidence about the effect on prices in equilibrium. Yet it is known that there is both overreaction and under-

reaction of stock prices to new information. Barberis et al. (1998) propose a model of investor sentiment based on psychological evidence to explain this behavior. While earnings from the asset actually follow a random walk, investors believe that earnings are either following a trend or reverting to the mean. With every new information, investors are updating their beliefs. Barberis et al. (1998) show that their framework can explain both under- and overreaction. They link both phenomena to concepts from psychology: conservatism (hesitance to update model in view of new information) and representativeness (a small part of a process is interpreted as being representative for the overall process).

De Long et al. (1990) analyze the effect of noise traders in financial markets. They assert two types of traders in the market: sophisticated investors and noise traders, whereby the latter falsely believe they have special information about the future price of the risky asset and misperceive the true expected price. This misperception leads to persistent irrational trading behavior that distorts prices. This in turn creates a noise-trading induced risk for sophisticated traders, which even further distorts prices.

Applying such behavioral aspects to allowance price models is an interesting avenue for future research. For this paper we simply denote by p_t^F the original price path determined by fundamentals, as in the previous equations (2.2), (3.3) and (4.2) and add an additional behavioral term to our model

$$p_t = p_t^F + \mathcal{B}_t. \tag{4.4}$$

That is, $\mathcal{B}_t$ represents any changes from the fundamental allowance price p_t^F due to behavioral aspects such as herding behavior, different trading strategies or even speculative bubbles. From an empirical perspective it is challenging to distinguish the two parts in equation (4.4). This is because, as we have seen in previous sections, p_t^F is difficult to determine since demand- and supply-side fundamentals as well as financial frictions affect the price but are hardly observable. Nonetheless a number of empirical papers analyze behavioral aspects in the EU ETS which we

present in the following.

Kalaitzoglou and Ibrahim (2013) identify different types of agents active in the EU ETS futures market that can be clearly distinguished by their trading behavior. The authors analyze the duration of trades examining in how far clustering of duration characteristics correlates with the trading behavior of market participants.

The duration between single transactions is modeled with a smooth transition mixture autocorrelated duration (STM-ACD) model. By incorporating smooth transitions into the model, the dynamics between two regimes (where a regime is dominated by a certain type of trader) can be captured. The presence of three different trader types in the market is examined: The informed traders receive private information to which they react by trading in large volumes. The uninformed have no access to this information and hence initiate their trades randomly. Lastly, while the fundamental traders are also uninformed, they are able to extract information from the market by examining past trades.

The trader types associated with the three regimes are identified by analyzing the shape of the hazard rate, which measures the probability of a trade being initiated after the arrival of exogenous information as a function of time. In the case of the informed traders, the hazard rate is decreasing, for the uninformed it is flat. For the fundamental traders, who extract information with a delay by analyzing informed trades, the hazard rate is increasing. Regarding the smooth transition mechanism included in the model, the findings suggest smoother transitions between the informed and the fundamental regime in Phase II compared to Phase I. This implies that learning by the uninformed happened faster in later stages of the EU ETS and, as a result, greater market depth.

Balietti (2016) also considers the presence of different trading behaviors. Specifically, the author estimates in how far the relation between trading activity and volatility varies with different trader types. In contrast to Kalaitzoglou and Ibrahim (2013), the author differentiates between different trader types according to the specific design of the EU ETS as a compliance market. This market is characterized by actors who are regulated by the EU ETS, and hence

obliged to participate, and financial actors, who participate either as intermediaries or to make profit from speculation. Moreover, actors are exposed to different (product) markets depending on whether they are active in the energy, industry, or financial sector. The initial endowment of certificates relative to their baseline emissions is also taken into account.

In order to examine how the specific characteristics of the market actors translate into differences in their trading behavior, Balietti (2016) regresses the volatility on the trading activity of the different participants. The trading activity-volatility relation is estimated by simultaneously estimating returns and volatility. Therefore, two equations are iterated: Equation 1 estimates the price changes conditional on autoregressive terms and lagged volatilities, while equation 2 estimates the conditional standard deviation based on lagged volatilities, lagged price changes, and trading activity. As a proxy for trading activity, Balietti (2016) uses both the daily transferred EUA volumes (fitted by an ARIMA process) and the number of daily permit transfers.

The regression on the daily spot price differences hints at a lack of market efficiency in Phase I of the EU ETS: The coefficients of the lagged price differences are significant and negative, i.e. large price differences in the past come along with smaller price changes in the present. The regression on price volatility and permit trading shows that when distinguishing between the three sectors (energy, industry, finance), the trading activity-volatility relation differs with trader type. While the energy sector trades more when volatility is high, the industry sector tends to be more active when volatility levels are low. The financial sector seems to act as a flexible counterpart, trading more with the energy sector when volatility is high and more with the industry sector when volatility is low. However, all in all, many actors seem to have remained inactive during Phase I especially when volatility was high, suggesting that a large share of actors was unwilling to trade when a lot of information arrived in the market.

Also concerned with the microstructure of the carbon futures market is Ibrahim and Kalaitzoglou (2016). In the light of certain findings in the literature, such as autocorrelation in the price level and order flow (Benz and Hengelbrock, 2008) and the presence of intra-day price patterns (Ibikunle et al., 2016), they propose an asymmetric information microstructural model of intra-

day price changes in order to analyze the effect of expected trading intensity on intraday price changes. In their model, the price responds dynamically to information and liquidity with every transaction, as traders form their expectations about subsequent trades based on trading activity and characteristics of previous trades. Specifically, when formulating price quotes, traders take into account trading intensity, information content, and volatility of previous trades. The authors find that the autocorrelation of returns and of the volatility of returns can be explained to a large extent by the predictability in the persistence of trading intensity. A similar positive autocorrelation in the trade sign has been found by Benz and Hengelbrock (2008), Mizrach and Otsubo (2014), Medina et al. (2014).

Herding behavior is one possible explanation for the autocorrelation in trade sign (Tóth et al., 2015). Palao and Pardo (2017) analyze the presence of herding behavior in the EU ETS in three parts: (i) detecting herding behavior in the futures market, (ii) identifying factors that influence herding behavior and (iii) analyzing the impact of herding behavior on the market.

Herding behavior can be detected by looking for persisting upward and downward runs in the price development: sequences of buy or sell trades. Palao and Pardo (2017) use the Herding Intensity Measure developed by Patterson and Sharma (2006) to identify the occurrence of such runs. They find that the herding effect decreases over time but is higher on days where price clustering is strong. Moreover, herding increases during speculative periods and when ETS-related news are published. Similarly, herding is positively correlated with trading frequency, uncertainty (as measured by intraday volatility) and the occurrence of extreme returns. The presence of herding, in turn, increases price volatility and entails overreaction.

A recent analysis of the price rally following the 2018 EU ETS reform also alludes to overreactions (Friedrich et al., 2020). The analysis suggests the shock (reform) has triggered the market into speculation about its price impacts, leading to an overreaction indicated by an episode of explosive price behavior. After the recent COVID shock in March 2020 the price plummeted, but quickly recovered until June 2020. This may also be explained by overreactions in response to the negative supply shock caused by COVID.

Further behavioral aspects examined in the EU ETS that are not in line with informational efficiency are the presence of price and size clustering as well as feedback trading (i.e. buying after a price rise and selling after a price fall). Palao and Pardo (2012) find that transactions are concentrated on prices ending on digits 0 and 5, tracing this back to the attraction theory (the preference for certain numbers without any rational explanation) and the negotiation hypothesis (where price clustering is used to limit transaction costs). Palao and Pardo (2014) complement this analysis by showing that not only prices, but also order sizes are rounded up in times of high uncertainty. While Chau et al. (2015) do not find significant feedback trading in emissions markets, Crossland et al. (2013), as mentioned beforehand, find short-term momentum and medium-term overreaction in the European carbon market.

4.3 Insights and implications

The following main insights can be drawn from the reviewed studies. (1) The idealized cost-of-carry model is violated by market frictions which affect the price level and its growth rate. Such frictions could be transaction costs, hedging demand of firms (and related risk premiums) as well as convenience yields. The latter are resulting from potential stock-outs because allowance borrowing from the future is not allowed in the EU ETS. (2) Methodologically, it is difficult to directly attribute these frictions to the violation of the cost-of-carry model. Frictions are typically not observable and therefore, deviations from the theoretically ideal predictions are open to several interpretations. However, the relatively large allowance bank over the past years suggests that the likelihood of a stock-out was low and thus convenience yields probably did not play an important role. This alludes to other frictions, such as hedging demand, as important price drivers. (3) Studies on behavioral aspects reveal the presence of different trader types with distinct trading strategies. Moreover, the results point to possibly non-rational behavior such as size and price clustering, herding as well as under- and overreaction to new information. Taking into account these trader types and behaviors sheds light on several observations about the EUA market: price jumps, persisting price trends including the occurrence of crashes and

bubbles, excessive volatility and inadequate (or insufficient) intertemporal trading strategies by compliance actors.

These insights have the following implications. (1) In light of the relevance of frictions, the recently introduced Market Stability Reserve (MSR) may have a significant impact on the permit price beyond its effect through lowering the cap.[9] As the MSR reduces the allowance bank level in the coming years, it might affect the costs of hedging reflected by risk premiums. A smaller bank implies that less permits are available for hedging purposes. However, the lower bank should not significantly increase the relevance of convenience yields because allowances leave the MSR and enter the market again when the bank level becomes lower. (2) In view of the political nature of the EU ETS and the ongoing reform process, the question of how actors form expectations and beliefs about the future and how they respond to new information may be even more important than in other financial markets. For example, if investors tend to overreact to regulatory announcements, and shocks in general, then stabilizing expectations might be essential for the efficiency of the ETS.

5 Discussion and conclusion

Covering three different strands of empirical literature on the EU ETS, the structure of this review mirrors the different angles to analyze price formation in the EU ETS. Our findings challenge the widespread view that short-term price formation in the EU ETS is primarily driven by observable marginal abatement costs: Some important explanatory factors do not show a significant effect, or, in some cases, the effect is opposite to what is predicted by theory (Section 2). As shown in Section 3, price explanation in the EU ETS can be improved by considering regulatory or political events. Yet, the price response to such events is not always in line with theoretical considerations, which raises the question how market participants process information or form their beliefs. For instance, some may perceive a political decision as support

[9]The MSR has two main effects: (1) It lowers the allowance bank level by shifting the supply of EUAs to the future and (2) it reduces the overall cap ($\overline{G}$ in our model) by cancelling EUAs. While (2) clearly raises the price level, (1) has no effect on the price in an idealized market without frictions (Salant, 2016).

for the EU ETS (price), whereas others expected an even stronger supportive decision and thus, adjust their price expectations downwards. The finance literature, reviewed in Section 4, alludes to different trader types and different reactions to new information. Specifically, the market exhibits herding behavior and over- or underreaction to new information that may cause bubbles. To conclude, in order to understand price formation in the allowance market, it must (also) be viewed as a financial market – and analyzed and regulated as such.

This has important implications for policy design and the further evolution of the EU ETS. Speculation fueled by regulatory uncertainty and affected by financial market flaws could imply a substantial – and potentially persistent – deviation of prices from their fundamental value. Such deviations would impair the functioning of the system, in particular its dynamic cost-effectiveness. Moreover, theory suggests that such speculation could also destabilize the market by inducing excess volatility (De Long et al., 1990). According to our review, regulatory uncertainty could be a major source for this. Accordingly, avoiding speculation on changes of the design of the system including its targets – or creating uncertainty about future changes in the first place – seems key for policy design. Obviously, this can be accomplished through stable market rules, whose impact on prices is well predictable.

Specifically for the EU ETS, this suggests that the Market Stability Reserve (MSR) does not actually stabilize the market. First, it considerably increases the complexity of the market (Perino, 2018). Notably, cancellation depends on the expectation of future prices, leading to the counter-intuitive effect that future complementary policies may reduce cancellations (Rosendahl, 2019) – contrary to what policy maker and market participants had expected it to do. In addition, the MSR opens up the door for price manipulations and the magnitude of future cancellations is highly uncertain (Osorio et al., 2020; Quemin, 2020). In contrast, a price collar may be a more suitable option; see Flachsland et al. (2020) for a short review for the literature and design options. In particular, by clarifying ex-ante that the price will never surpass (ceiling) or fall below (floor) a certain level, price expectations can be substantially stabilized. In face of that, EU policy makers should seriously consider replacing the MSR with such a price control

mechanism.

Finally, echoing the call by Hintermann et al. (2016), this review also identifies promising fields for future research in two additional directions. Firstly, in all strands of the empirical literature, it is evident that findings heavily depend on the method used and its specific restrictions. The fact that the market is maturing together with the existing empirical evidence calls for more flexible methods in the analysis of classical price drivers. Such methods should be able to identify and capture potential structural changes. So far, the analysis often keeps the relationship between the allowance price and its price drivers constant over time or it relies on restrictive assumptions which limit the form of potential transitions. Future approaches could, for example, include a thorough analysis of break points or smooth transitions in the relationship. Alternatively, it could be modeled nonparametrically or with a local trend model from the state-space literature.

Secondly, the theoretical finance literature emphasizes the importance of considering different trader types and points out the implications for price formation. While some work in this direction exists, e.g. on the role of banks (Cludius and Betz, 2020), the presence and impact of speculation is a particularly promising topic for future research. Analyzing other allowance market data beyond prices offers opportunity for such work. To begin with, Open Interest (OI) data together with volume data could be used to measure speculative and hedging activities in the futures market. This approach is quite common for other markets (Lucia and Pardo, 2010), but to the best of our knowledge there is just a single analysis of this type for the EU ETS (Lucia et al., 2015) so far. Moreover, pursuant to stronger financial market regulations such as MiFID II and MiFIR, Commitment of Traders (CoT) reports became mandatory for the EU ETS in 2018. They break down positions by types of traders and trading motives at the end of each business week for each market place (Bohl et al., 2019). Analyzing this new source of data promises even more accurate insights into hedging and speculation activities.

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