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Master Thesis

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Pricing of carbon emission allowances

An assessment of the pricing relationships and the adequacy of EU ETS as a climate policy tool

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by
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MSc in Business with Major in Finance

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ABSTRACT

The purpose of this study is to shed light on the pricing mechanisms within the EU Emissions Trading System and evaluate the link between the prices of emission allowances and the prices of fundamental drivers of greenhouse gas emission. Through the use of an extensive model framework, we prove that there exists a long-run relationship between the spot and futures prices of emission allowances and make relatively accurate predictions of future spot prices based on historical price information. This implies that futures prices work as a significant information vehicle and that the system exhibits the appropriate risk mitigation characteristics for hedging greenhouse gas emission. Moreover, we identify links between prices of emission allowances and prices of coal, Brent oil and the DAX. Impulse response functions indicate that the system reacts to shocks in these variables but that the shocks are neutralized relatively fast. Overall, we find evidence of a system exhibiting the characteristics of a mature financial market.

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ACRONYMS

ADF Augmented Dickey-Fuller

AIC Akaike information criterion

ARCH Autoregressive conditional heteroscedasticity

DAX Deutscher Aktienindex

ECM Error correction model

EEX European Energy Exchange

EUA European Union allowance

EU ETS European Union Emissions Trading System

GARCH Generalized autoregressive conditional heteroscedasticity

RMSE Root mean squared error

VAR Vector autoregressive

1 INTRODUCTION AND MOTIVATION

In order to assess the adequacy of the EU Emissions Trading System (EU ETS)[1] as a climate policy tool, we will investigate the prices of carbon emission contracts and answer the following research question:

> *"What is the relationship between spot and futures prices of emission allowances, and how do they relate to the fundamental drivers of greenhouse gas emission?"*

As the question is twofold, we structure our analysis into two separate parts. First, we assess the relationship between emission allowance prices. Doing this allows us to shed light on the hedging properties of the futures contracts and the price discovery process in the market. Additionally, discovering that this relationship exists enables us to model future spot prices using historical price data. If we find this to provide satisfactory results, we conclude that the futures prices work as an important information vehicle regarding the future spot prices. Consequently, we may be able to conclude that the system exhibits characteristics of a mature financial market and that the EU ETS is well-designed from a financial perspective.

A successful trading system will work as a significant information vehicle for the direction of the global climate policy. One way to extract information about the system is to consider the prices of both the underlying and its derivatives. Therefore, we consider the price discovery role of the futures prices as they may provide insight regarding the future spot prices. Based on that hypothesis, we ask the following question; are the futures prices a good representation of the expected spot prices in the future? It is reasonable to assume that the spot and futures prices follow a joint distribution, as one should be derived from the other according to financial theory. Hence, a natural first step is to look for a long-run relationship between the spot and

[1] For background information on the Paris Agreement and the EU ETS, see Appendix A.

futures prices. This could allow us to make predictions of one based on the other, and it is also a necessity for the derivatives to function as appropriate risk mitigation tools. If a long-run relationship does not exist, the futures and spot prices would diverge towards independent stochastic paths. The result of this is that no insightful inferences can be made about spot prices when considering historical futures prices, and that any futures position would result in a higher risk exposure. Consequently, we might discover that the system does not work as a mature financial market.

In the second part, we employ additional models, controlling for macroeconomic variables that directly affect the amount of pollution. While a large part of the existing literature on carbon markets provide an overview of both the benefits and drawbacks of the cap and trade scheme, the true effectiveness of the scheme will depend on the market's ability to accurately reflect the marginal cost of greenhouse gas emission reduction in the prices (Milunovich & Joyeux, 2010). In order to investigate the effectiveness, it is therefore essential to understand the price drivers in the carbon markets. We assume that factors affecting the amount of pollution should also relate to the prices of the emissions allowances. Consequently, we include other fundamental variables relating to the actual amount of pollution, and assess whether fluctuations in their prices affect the prices of the permits. Our fundamental belief is that allowance prices need to increase when emissions are high for the governments to provide the impetus necessary for greenhouse gas emissions to be reduced. If this is the case, much indicates that the EU ETS, at least to some extent, leads to reduced emissions. Consequently, it is a tool that may increase our probability of being in compliance with the Paris Agreement, as it properly aligns the incentives of the trading parties and the policymakers.

2 LITERATURE REVIEW

Since the inception of the EU ETS in 2002, carbon emission contracts have been a topic of interest for researchers and companies alike. Studies have been performed based on different models, perhaps most notably through the use of a no-arbitrage cost-of-carry relationship. We discuss findings from these studies as they provide relevant insight regarding the relationship between spot and futures prices, as well as market efficiency in the EU ETS as a whole. Despite this, the starting point for our analysis is the efficient market hypothesis. The amount of existing literature investigating this, in contrast, is rather scarce. Still, we highlight findings from some relevant papers. Finally, we cover some publications about spot price predictions with more complex models, and predictions using fundamental values as price determinants, rather than the futures prices.

2.1 LITERATURE ON PRICE DISCOVERY AND EFFICIENCY IN THE EU ETS

Key findings from the literature indicate that futures prices act as a significant information vehicle for the prices in the EU ETS. Chevallier (2010) launched a study on the relationship between spot and futures prices of CO_2 allowances in the EU ETS during phase II (2008-2012). He made assumptions similar to that of the EMH, namely that spot prices in a period should equal the futures prices of contracts expiring in the same period, plus a white noise error term (ϵ_t). His key finding was that futures prices provide reliable price signals in the market. Similar studies conducted in phase I (2005-2007) also discovered that futures prices were leading the price discovery process (Alberola, Chevallier, & Chèze, 2008; Hintermann, 2010).

When considering cost-of-carry as the starting point, Milunovich and Joyeux (2010) published a thorough study of the market efficiency and price discovery mechanisms in the EU carbon futures market. In an attempt to decide the long-run relationship between spot and futures prices, as well as the interest rate, the authors sought to examine the risk mitigation properties of the carbon emission futures in phase I. They identified a long-run relationship, but rejected that this was due to a no-arbitrage cost-of-carry principle. Their results are in line with those of Charles, Darné, and Fouilloux (2013) who extended the study for phase II, included all three European Markets (BlueNext, EEX and ECX) and used a more considerable amount of futures contracts. Additionally, they consider the carbon trading market to be in contango based on their findings that futures prices, in general, are higher than the spot price. As a result, they disregard the convenience yield in their estimations, being that the convenience yield commonly explains a market that is in backwardation. Their results are backed up by studies done by Borak, Härdle, Trück, and Weron (2006), as they made similar discoveries. Despite their differences, both the studies of Milunovich and Joyeux (2010) and Charles et al. (2013) indicate a well-functioning system, appropriate for hedging. Still, there may exist arbitrage opportunities as a no-arbitrage cost-of-carry relationship is rejected for all maturities and exchanges.

There also exist other studies that provide evidence of the carbon market being mature from a financial point of view. Ibikunle, Gregoriou, Hoepner, and Rhodes (2016) link liquidity to market efficiency by assessing the European Climate Exchange in phase II of the EU ETS. They found that there is a strong relationship between liquidity and efficiency. They also argue that, over the past few years, the EU ETS prices have moved in unity with random walk benchmarks and that the overall trading quality has improved. This is in accordance with previous studies from Frino, Kruk, and Lepone (2010), who found that the long-term liquidity improved over the first phase, and early months of the second phase. Further, Ibikunle and Gregoriou (2011) found evidence of improved liquidity in phase II after enhanced regulations. All of the above-mentioned findings are consistent with a mature market, which further indicates an efficient trading system.

2.2 LITERATURE ON THE PRICE DRIVING MECHANISMS IN THE EU ETS

Since the inception of the EU ETS, the price driving mechanisms and the reaction of carbon prices in response to changes in market fundamentals have been important research topics in order to assess the functionality of the EU ETS. Aatola, Ollikainen, and Toppinen (2013) developed a model with an uncertain permit price where firms are risk-averse and the equilibrium permit price depends on other exogenous variables. They employ OLS, instrumental variables and VAR models with corresponding impulse response functions, on datasets from 2005 to 2010. Their results indicate that there is a clear and stable relationship between fundamental variables and the forward price of EUAs. They argue that approximately 40% of the changes in the forward prices are explained by German electricity prices, UK gas prices and coal prices, German electricity being the most critical determinant. Furthermore, the authors argue that the market is moving towards a mature state where the EU ETS may work as an efficient climate policy instrument. Despite this, their study might be biased as the period they investigate comprise two separate phases, both phase I and II. It is reasonable to assume that there is a structural break present in the time-series at the time of transition between the two phases, which could distort the results.

Similar to the studies by Aatola et al. (2013), Alberola, Chevallier, and Chèze (2007) published a research paper on price drivers and structural breaks in the EU ETS from 2005 to 2007. They find that energy prices, reflected through coal, oil and natural gas, affect the prices of carbon emission allowances. They also argue that EUA spot prices react to temperatures, as they discovered that unexpected temperature changes (extreme weather), affect the spot price. However, this only holds for extremely cold events.

Byun and Cho (2013) forecast the carbon futures volatility using three approaches, discovering that a GARCH-type model based on carbon futures prices is the most successful. Furthermore, in an attempt to decide the determining factors of carbon futures volatility, they run a linear regression with volatilities from other energy commodity markets as explanatory variables. In addition to controlling for the volatility of Brent oil, natural gas, coal and electricity, they include a GARCH-component based on their initial studies. They discover that volatilities of Brent oil, coal and electricity have volatility spillover to carbon futures.

2.3 OUR CONTRIBUTION TO THE EXISTING LITERATURE

The existing literature on price discovery, market efficiency and liquidity in the carbon market find varying evidence due to the use of different datasets, research on different phases, different number of contracts and different use of methodology.

To our knowledge, empirical studies on the price predictability during phase III of the EU ETS have never been conducted. It is also worth noting that this period is longer (2013-2020), compared to the other two phases. Previous studies from Brorsen and Fofana (2001) suggest that a less mature futures market lacks important hedging properties that we often see in mature markets. Consequently, we have reason to believe that we will find more robust evidence of price predictability when assessing phase III by utilizing larger and more recent datasets. Additionally, we will use more contracts compared to the previous studies as we utilize futures contracts that expire every December from 2014 to 2019. This study will, therefore, provide an updated review of the EU ETS and its market microstructure.

Additionally, a majority of the existing literature use cost-of-carry as a starting point. In other words, they focus on what drives the futures prices. We alter this to have a primary focus on what drives the future spot prices and consequently base our studies on the EMH. Extending this framework allows us to study the presence of risk premiums. Another key argument is that none of the investigations of the relationship between spot and futures prices through the cost-of-carry relationship conclude that this holds for the EU ETS. This may be due to the fact that there is no common agreement regarding the convenience yield as emission allowances are not a traditional storable good, but rather just an asset on the balance sheet. Another explanation may be that it is not possible to find an appropriate interest rate explaining the relationship as the market participants comprise a wide variety of European countries. Therefore, we believe that assessing the relationship through the EMH may yield different insight compared to previous studies.

In the second part of our analysis, we utilize more recent data on energy prices and other relevant price drivers. However, we also consider the presence of multicollinearity, which was not corrected for in previous studies by Aatola et al. (2013). Consequently, our results may yield different insight regarding the efficiency of the EU ETS as a tool for emissions abatement.

3 THEORY AND RESEARCH METHODOLOGY

3.1 THE EFFICIENT MARKET HYPOTHESIS

In order to provide testable hypotheses regarding the joint distribution of spot and futures prices, our starting point is the efficient market hypothesis (EMH) (Fama, 1970). We further assume risk-neutral market participants, in line with the unbiasedness hypothesis, and absence of storage costs. Under these assumptions, the future spot price should not deviate from the futures price in the absence of unexpected shocks. Combining these allows us to formulate a testable hypothesis where the futures price today, F_t, is equal to the expected spot price when the futures contract matures, given all available information, ϕ_t. The result is the following model for the futures price at time $t-1$:

$$F_{t-1} = E[S_t|\phi_{t-1}] \tag{1}$$

In our case, we consider the available information to be all historical price information, as is also the case for weak-form efficiency in capital markets according to Roberts (1967) and Fama (1970). In other words, Equation 1 should hold for an information set containing only historical prices. We emphasize that we are not testing for market efficiency in this study, but utilizing this testing framework could still yield important insight regarding the market microstructure of the EU ETS. A classical methodology used in several studies is simply to regress futures prices on the spot prices at maturity. In other words, running the following regression:

$$S_t = \alpha + \beta F_{t-1} + u_t \tag{2}$$

According to the unbiasedness hypothesis, the futures price will provide an unbiased prediction of the spot price in the future, under the assumption of risk neutrality and rational expectations. In other words, futures prices represent the expected spot price in future periods, disregarding a potential risk premium. Consequently, the theory predicts that the constant, α, should be statistically insignificant. As the theory assumes risk-neutral market participants, the implication is that the market consists of an equal number of short and long hedgers. In reality, this seems to be unreasonable. Therefore, we extend Equation 1 by implementing the Keynes-Hicks hypothesis presented by Keynes (1923) and Hicks (1939). This hypothesis states that long hedgers are willing to pay a price above the expected spot price for a futures contract, while short hedgers are willing to sell futures contracts below expected spot price. Hence, the long hedgers are willing to pay a risk premium to the participants offsetting their positions. As we expect to discover a surplus of long hedgers in the carbon markets, a natural consequence is that the futures prices will include a positive risk premium. Taking this into account, we introduce a constant term, representing the risk premium, into Equation 1:

$$F_{t-1} = RP_t + E[S_t|\phi_{t-1}] \quad (3)$$

As introduced earlier, there may exist a convenience yield, rather than a risk premium, when storable commodities are studied. This relationship is captured in the cost-of-carry model through the law of one price. As emission allowances are simply an asset on the balance sheet, they may also be storable. However, according to previous research, there is no common agreement regarding the existence of a convenience yield in the EU ETS. Therefore, a risk premium could be a better explanatory factor for the relationship between the spot and futures prices of carbon emission allowances. This can be accounted for by including the constant α in Equation 2.

Consequently, Equation 2 provides the starting point for further hypothesis testing. When introducing our data, we will most likely face a few challenges that are common when running OLS linear regressions on financial time-series. In order to provide meaningful results we, therefore, need to consider the presence of for instance unit roots and cointegration.

3.2 UNIT ROOT TESTING

It is plausible that we encounter spurious regressions, due to time-series that are non-stationary with one or more unit roots. As the EU ETS has experienced a significant price increase since its inception, we have reason to believe that the time-series are not stationary. If they were stationary, we would expect to discover that the prices oscillate around a constant mean. Furthermore, Byrne, Fazio, and Fiess (2013) identified that a majority of the commodity prices are non-stationary, as their time-series possess the characteristics of one unit root. Mizrach (2012) did similar tests on the EUA spot market but also failed to reject the presence of unit roots. To control for this, we run an ADF test (Dickey & Fuller, 1979). A common way to deal with unit roots is to introduce first-differences into the equation, so we formulate the following model:

$$S_t - S_{t-1} = \alpha + \beta(F_{t-1} - F_{t-2}) + u_t \tag{4}$$

3.3 COINTEGRATION

In the case of all variables being I(1), i.e. integrated of first order, we might encounter difficulties when there is a long-run relationship between them, i.e. when they are cointegrated. This is the case when the error terms of the cointegrating relationship (Eq.2) are I(0) (stationary), which we investigate by employing the Johansen's multivariate cointegration test (Johansen, 1988). We run the test controlling for up to p and q lags of both the relevant variables. The optimal number of lags to include is decided by specifying a VAR model and minimizing the AIC (Akaike, 1974) and a log-likelihood function. We specify one VAR of general form for each of the contract periods, where Y is a matrix containing all relevant decision variables. In this case, Y consists of spot price (S) and futures price (F), and we allow for up to 12 lags while testing. This yields the following general model:

$$Y_t = \alpha + \beta_1 Y_{t-1} + \beta_2 Y_{t-2} + ... + \beta_n Y_{t-n} + \epsilon_t \quad (5)$$

We test for cointegration by allowing for the models to include a constant term, reflecting the potential risk premium in the market. However, we also test for cointegration without including a constant term to see if this changes any results.

3.4 ERROR-CORRECTION MODEL

A common approach to avoid spurious results when studying time-series with a cointegrating relationship is to formulate an error correction model (ECM). As discovered by Granger (1986), we control for the cointegrating properties by formulating a model where we introduce an error correction term, expressed as the error terms, $\hat{u}_t = S_t - \hat{\beta} F_{t-1}$, from Equation 2. Additionally, we control for unit roots by specifying a model with terms that are first-differenced. This results in the following model:

$$\Delta S_t = \alpha + \theta \hat{u}_{t-1} + \beta \Delta F_{t-1} + v_t \quad (6)$$

As previously mentioned, we consider all historical price information in order to make valid predictions of the future spot prices. This is done through the inclusion of p and q lags of the first differences of both spot and futures prices. When deciding p and q, we look at the results provided by AIC and the log-likelihood function from the VAR-model specified during the cointegration test. The result is a model of the following form:

$$\Delta S_t = \alpha + \theta \hat{u}_{t-1} + \beta_1 \Delta F_{t-1} + \sum_{i=2}^{p} \beta_i F_{t-i} \sum_{j=1}^{q} \gamma_j S_{t-j} + v_t \quad (7)$$

3.5 ECM WITH A GARCH-COMPONENT

A common flaw in the general ECM is that it assumes homoscedasticity, meaning a constant variance of errors. Consequently, the model does not consider time-varying volatility. This may eventually provide price predictions that are highly inaccurate as the historical prices of emission allowances indicate some periods of higher volatility. Most notably, the early parts (2013-2014) of phase III of the EU ETS had highly fluctuating prices which may be due to the fact that the market was relatively immature with low liquidity. In the following years, volatility appears to decline as volumes and liquidity increases. Additionally, events impacting the public's view of global warming, like for instance extreme weather, might lead to temporary volatility peaks in more recent years as well.

3.5.1 ENGLE'S TEST FOR ARCH EFFECTS

In order to decide if our ECM in fact exhibit ARCH effects, we run the Engle test (Engle, 1982) for ARCH effects on lags of the squared residuals of Equation 7. Including 12 lags allows us to test for ARCH of 12^{th} order. Consequently, we run the following regression:

$$\hat{v}_t^2 = \gamma_0 + \sum_{i=1}^{12} \gamma_i \hat{v}_{t-i}^2 \tag{8}$$

Then we test the null hypothesis that $\gamma_1 = 0$, $\gamma_2 = 0, \ldots,$ and $\gamma_{12} = 0$, against the alternative hypothesis that $\gamma_1 \neq 0, \gamma_2 \neq 0, \ldots,$ or $\gamma_{12} \neq 0$. Rejection of the null hypothesis means that there are ARCH effects that are unaccounted for in the ECM specified in Equation 7.

3.5.2 SPECIFICATION OF THE MODEL

The Engle's test confirms that there exists ARCH-effects and that the squared residuals for all error correction models are autocorrelated. Through extensive residual analysis and minimizing AIC, we see that an ECM-GARCH(1,1) is able to capture all the ARCH effects, and that this holds for all the futures contracts. The new model is specified below:

$$\Delta S_t = \alpha + \theta \hat{u}_{t-1} + \beta_1 \Delta F_{t-1} + \sum_{i=2}^{p} \beta_i F_{t-i} \sum_{j=1}^{q} \gamma_j S_{t-j} + \sigma \sqrt{C_t} + v_t \quad (9)$$

In this case, C_t is the conditional variance of ΔS_t:

$$C_t = \eta + \sum_{l=1}^{L} \tau_l C_{t-l} + \sum_{m=1}^{M} \rho_m v_{t-m}^2 \quad (10)$$

3.6 PREDICTIVE POWER

We validate the predictive power of the ECM and ECM-GARCH through measuring out-of-sample prediction accuracy. In order to make meaningful inferences regarding the determinants of the emission allowance prices and the future price development, we re-estimate the models specified above using in-sample data from January 1st 2013 to 12 months before the contract expires. This is done for any given contract. Subsequently, we make predictions based on the estimated models for the remaining 12 months. Since our models will estimate the first-differenced logarithmic spot prices, we need to transform the predictions back to levels of the spot price. Finally, we assess the out-of-sample prediction accuracy, using RMSE as our metric for goodness-of-fit, as it penalizes large errors more severely than small errors.

3.7 VAR ANALYSIS – IMPULSE RESPONSE FUNCTIONS

In order to answer the second part of our research question, we also need to assess whether there is a link between fundamental variables and the prices of carbon emission allowances. Firstly, we specify one general model with spot prices of emission allowances against spot prices of Brent oil, electricity, natural gas, the DAX and coal. Since we suspect at least some of the variables to be highly correlated, we may encounter multicollinearity. We, therefore, run five separate OLS regressions where we include only the spot price and one relevant variable. These models, albeit simple, will provide some insight regarding the relationship between spot prices and other fundamental variables.

Furthermore, we extend this analysis by defining a VAR-model similar to the general form specification in Section 3.3. Now, Y represents log first-differenced spot prices for carbon emission allowances, Brent oil, electricity, natural gas, the DAX and coal. To obtain results that are comparable to the analysis above, we assess the impulse response functions of the VAR-model. That is, we look at how a shock in all the relevant variables affects the variables itself, and the prices of emission allowances over time, i.e. how shocks propagate through the system. By extending the models above to a VAR model, we are also able to study the price determination process with a dynamic model rather than with static models.

4 DATA DESCRIPTION AND PRELIMINARY ANALYSIS

In the following section, we provide a description of all relevant data. We begin with assessing the spot and futures prices, as they provide the starting point for our analysis. Subsequently, we present other relevant variables that need to be considered when addressing whether the EU ETS can lead to a reduction in greenhouse gas emissions. Finally, we provide a preliminary analysis of the data by investigating important characteristics and statistics of the relevant time series.

4.1 SPOT PRICES

In our analysis, we use daily spot EUAs, retrieved from Bloomberg. The quoted prices represent the price in euros for one carbon contract, each one providing the right to emit 1 tonne of CO_2. The original source of this data is the EEX, which provides daily updated closing prices of the spot. The dataset contains daily observations from the 1^{st} of January 2013 until 30^{th} of December 2019, a total of 1709 observations throughout the period.

4.2 FUTURES PRICES

Bloomberg provides extensive data on futures prices from EEX as well, with different maturities. For the prices to be efficient and provide some transparency, the total trading volumes must be sufficiently high. Additionally, there need to be a sufficient number of market participants, requesting both long and short positions. Consequently, we extract price data for futures contracts that mature every December, from 2014 to 2019. These contracts are traded at the highest frequency, and in the highest volumes. A reason for this can be identified by considering the way the cap and trade scheme is designed. Since permits for a full calendar year need to be surrendered on an annual basis, it makes sense for participants to hedge their need for greenhouse gas emission by year-end. This provides the ones with excess permits the incentives to enter short positions with the same maturity as well, to satisfy the demand.

As highlighted in Section 2.3, including contracts from 2014 to 2019 yields more contracts than what has previously been studied within the existing literature, and will hopefully provide a more comprehensive view of the current market characteristics. Additionally, we use daily closing prices to obtain a sufficiently large dataset. The spot and futures prices for all contracts are illustrated below.

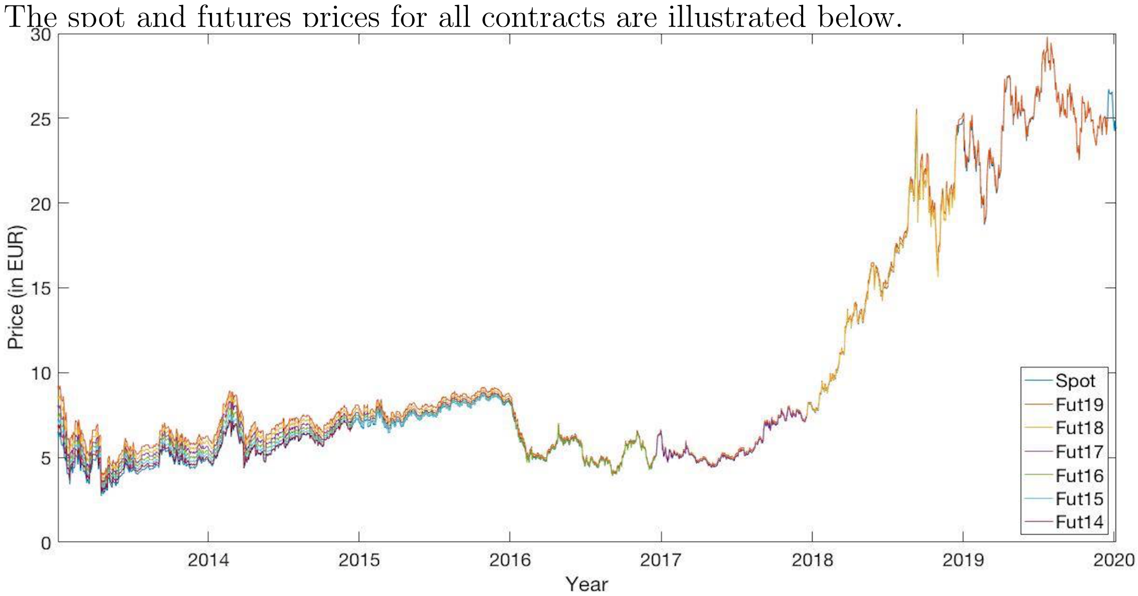

Figure 1: Illustration of historical spot and futures prices

4.3 OTHER FUNDAMENTALS AFFECTING CARBON EMISSION PRICES

Utilizing historical spot and futures prices can yield insightful results in terms of predicting future price movements. Additionally, it might indicate that the EU ETS is working as an efficient trading platform from a financial point of view. When attempting to decide whether the system is providing the incentives to reduce emissions, however, a mature financial market is far from sufficient. We believe that the spot prices of emission allowances need to be related to fundamental drivers of pollution as well. If this is not the case, it is unlikely that the system alone provides the incentives needed for emissions to be reduced.

There are several relevant price drivers to be considered. Based on previous studies within the field, as well as logical reasoning, we argue why the following variables are of relevance. A significant portion of the total global emission stems from electricity production and consumption. Therefore, we include historical spot prices of electricity in the North European markets, extracted from the Nord Pool exchange. As the Nordic countries stand for the majority of the European power consumption, due to variations in climate, among other things, this data should represent the majority of the greenhouse gas effects of electricity production. We also include historical data on prices of coal, Brent oil and natural gas, due to their undeniable impact on greenhouse gas emissions. As increased prices of these commodities could reflect increased demand, and consequently increased consumption, we see a clear link between the prices of these commodities and the prices of emission allowances. Prices are extracted from Bloomberg and S&P Capital IQ. Additionally, we include the DAX as an indicator of overall economic growth in Europe, extracted from Yahoo Finance. Prices for the above-mentioned fundamentals are quoted in euros to match the currency of the emission allowances.

We expect to identify a clear relationship between all of these variables and the carbon spot price. One way of assessing this relationship is to run a simple multivariate regression, including all of the identified fundamentals as independent variables. However, many of these variables ought to be at least moderately correlated with one another. For instance, fossil fuel is one of the largest sources of energy production worldwide. The U.S. Energy Information Administration (2020) reports that more than 80% of the nation's primary energy consumption originates from fossil fuels, while the European Commision (2018) reports that 40% of the electricity consumed in the EU is fossil. Increased prices of these commodities as a result of increased demand, could indicate that more electricity will be generated. Although there is not a one-to-one relationship between demand for fossil fuel and electricity production, it is reasonable to assume that some of it will be converted to electricity. By holding output from other electricity sources constant, the increased supply will decrease prices of electricity as more is available to the consumers. It is difficult to conclude about the causality between the variables, but there is bound to be correlation at least. Additionally, the DAX might be correlated to several of the other independent variables, as it can be considered a proxy for economic growth in Europe. Economic growth might be of relevance as it is closely related to industrial production, where one of the primary input factors is electricity. When creating a correlation matrix between the variables, we get the following results:

Table 1: Correlation matrix for all relevant variables

	Spot	**Brent oil**	**Electricity**	**Coal**	**DAX**	**Natural gas**
Spot	**1.00**	-0.05	0.46	0.35	0.53	-0.20
Brent oil	-0.05	**1.00**	0.35	0.74	-0.47	0.52
Electricity	0.46	0.35	**1.00**	0.65	0.06	0.16
Coal	0.35	0.74	0.65	**1.00**	0.60	0.51
DAX	0.53	-0.47	0.06	0.60	**1.00**	-0.25
Natural gas	-0.20	0.52	0.16	0.51	-0.25	**1.00**

4.4 UNIT ROOT TESTING

Before conducting our main analysis, we need to determine whether the time series are non-stationary. Consequently, we apply an ADF test on both the log-levels and log-differences of the spot and futures prices for all the relevant carbon emission contracts. In line with previous research conducted on the pricing mechanisms in the EU ETS, we find that all time series are integrated of first order (i.e. are non-stationary and contain one unit root). The ADF test statistics are tabulated below.

Table 2: Results from unit root testing

	Log levels			**Log first differences**		
	No Drift or trend	Drift	Drift and trend	No drift or trend	Drift	Drift and trend
Spot	1.1738	-0.2872	-1.7638	-13.2141***	-13.2811***	-13.4019***
$F_{t,Dec19}$	0.9336	-0.2297	-1.6920	-12.8673***	-12.9074***	-13.0659***
$F_{t,Dec18}$	1.0871	0.1668	-0.8924	-11.7478***	-11.7949***	-12.0344***
$F_{t,Dec17}$	-0.1375	-2.5436	-2.5772	-11.1639***	-11.1589***	-11.2723***
$F_{t,Dec16}$	-0.4460	-2.2462	-2.2568	-10.1485***	-10.1425***	-10.2678***
$F_{t,Dec15}$	0.2768	-1.3904	-5.2144***	-9.6294***	-9.6332***	-9.8018***
$F_{t,Dec14}$	0.1053	-1.7487	-4.1712***	-7.8674***	-7.8619***	-8.1043***

When conducting the ADF test, we controlled for drifts and time trends in the time series. The optimal lag length was chosen by minimizing AIC. ***,**,* indicates rejection at the 1%, 5% and 10% significance level. In this case, the null hypothesis, H_0, is: "The time series are characterized by one unit root".

4.5 DESCRIPTIVE STATISTICS ON THE RISK PREMIUM

The descriptive statistics for the historical risk premiums are presented in Table 3. We see that all of the contracts exhibit a positive mean and are positively skewed with respect to their risk premium. Generally, this implies that the market participants believed that the marginal cost of greenhouse gas emission was to increase across the entire third phase of the EU ETS. Hence, they were willing to pay a premium today to hedge their future emissions. Another way of interpreting the positive means is that the market may have an overweight of actual hedgers (buy-side traders), rather than speculative traders. Moreover, we see that the standard deviation of the risk premium in the market declines as we approach the time of maturity for each contract. This is in line with a well functioning financial system, where there exists a long-run relationship between the futures and spot prices. Thus, our preliminary analysis of the risk premium shows that the EU ETS may provide an appropriate system for risk mitigation.

Table 3: Descriptive statistics on the risk premium

Contract	Observations	Mean	Std.dev	Skewness	Kurtosis
$F_{t,Dec19}$	1699	0.568	0.569	1.145	0.650
$F_{t,Dec18}$	1454	0.456	0.485	0.981	0.125
$F_{t,Dec17}$	1207	0.382	0.376	0.798	-0.365
$F_{t,Dec16}$	983	0.306	0.275	0.641	-0.614
$F_{t,Dec15}$	729	0.225	0.176	0.597	-0.171
$F_{t,Dec14}$	485	0.137	0.109	0.977	0.672

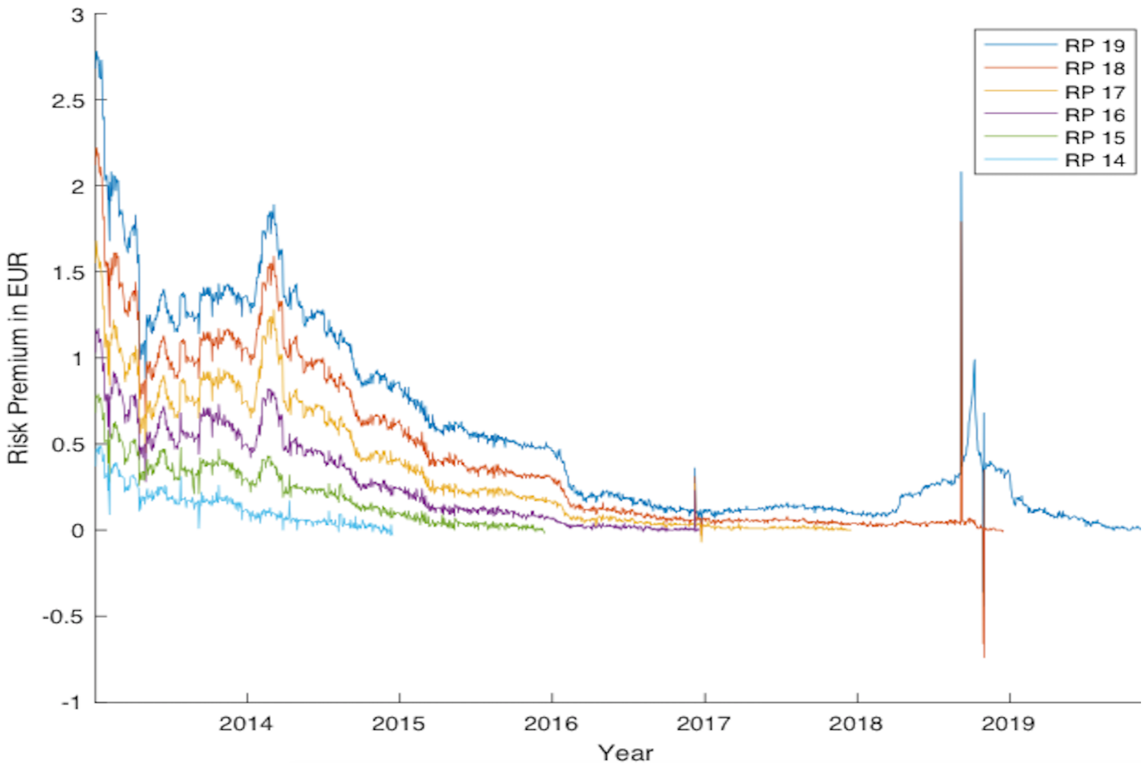

Figure 2: Illustration of historical risk premiums

5 RESULTS AND MAIN ANALYSIS

This section is twofold and presents the empirical findings from the application of the methodologies previously specified. The first part is dedicated to the assessment of whether the EU ETS works as an efficient trading system from a financial perspective. We begin with presenting findings regarding the relationship between the spot and futures prices. Subsequently, we formulate different models to describe the pricing relationship and assess their validity by testing out-of-sample prediction accuracy.

In the second part, we assess whether the EU ETS is an efficient policy tool to reduce emissions. We identify factors that should be of relevance for global greenhouse gas emissions and investigate whether there is a link between these and the prices of emission allowances. To further elaborate on this relationship, we investigate how shocks to the fundamental variables propagate through the system over time. Finally, we synthesize the results and see if we can find evidence of a functioning trading system that provides the incentives necessary for greenhouse gas emissions to be reduced.

5.1 ANALYSIS OF THE PRICE RELATIONSHIP

Having proved that the time series of spot and futures prices possess non-stationary characteristics, we already know that we need to include first-differenced terms of both variables in our prediction models. As the fundamental assumption in our thesis is based on there being a long-run relationship between the futures and spot prices, we test this hypothesis by assessing whether there is cointegration between the two variables. The assessment is done through pairing each time-series of the individual futures contracts and the spot prices into a VAR model. Following this, we test the subsequent null hypotheses that there are 0 and 1 cointegrating relations ($r = 0$ and $r = 1$). As Table 4 reveals, we reject that $r = 0$ at a 5% significance level, for all but the 2014 contract. However, by including a constant term, we reject this too at a 1% level (Table 5). Considering test statistics and their corresponding p-values from the $r \leq 1$ tests, we conclude that all contracts are cointegrated with the price of emission allowances at minimum a 10% level.

Table 4: Results from cointegration test without intercept

	$r = 0$		$r \leqslant 1$	
	λ_{trace}	λ_{max}	λ_{trace}	λ_{max}
$F_{t,Dec19}[12]$	0.001	0.001	0.333	0.333
$F_{t,Dec18}[8]$	0.001	0.001	0.210	0.210
$F_{t,Dec17}[12]$	0.014	0.008	0.994	0.994
$F_{t,Dec16}[7]$	0.020	0.013	0.785	0.785
$F_{t,Dec15}[10]$	0.017	0.011	0.774	0.774
$F_{t,Dec14}[7]$	0.171	0.134	0.746	0.746

All values displayed are p-values. Number of lags are shown in brackets, based on the AIC from the corresponding VAR model

Table 5: Results from cointegration test with intercept

	$r = 0$		$r \leqslant 1$	
	λ_{trace}	λ_{max}	λ_{trace}	λ_{max}
$F_{t,Dec19}[12]$	0.001	0.001	0.648	0.648
$F_{t,Dec18}[8]$	0.004	0.001	0.696	0.696
$F_{t,Dec17}[12]$	0.017	0.046	0.106	0.106
$F_{t,Dec16}[7]$	0.013	0.076	0.042	0.042
$F_{t,Dec15}[10]$	0.001	0.001	0.007	0.007
$F_{t,Dec14}[7]$	0.001	0.001	0.063	0.063

All values displayed are p-values. Number of lags are shown in brackets, based on the AIC from the corresponding VAR model

Overall, the results indicate that the futures and spot prices do not follow individual paths, but move together with a long-run equilibrium. This, in turn, provides evidence that market participants may, in fact, hedge greenhouse gas emission by trading futures contracts in the carbon markets. We have yet to decide the specifics of this relationship. However, as the prices will move together, we should be able to discover that the spot price can be predicted to some extent using historical futures prices.

In order to control for the discovered cointegrating relations, we formulate an individual ECM for each contract, using the error terms from Equation 2 as the error correction term. Additionally, we include the appropriate number of lags. This, in turn, provides us with the first model we use in order to predict spot prices. Here, the coefficient θ indicates the rate of adjustment towards the long-run equilibrium. The relatively small coefficients displayed in the table indicates that the model only corrects for a tiny amount of previous periods' disequilibrium. We also note that all the models seem to exhibit positive risk premiums, reflected through the constant terms. This is in line with our preliminary hypothesis emphasized in Section 3.1.

Table 6: Parameter estimates from ECM

$$\Delta S_t \quad = \quad \alpha + \theta \hat{u}_{t-1} + \beta_1 \Delta F_{t-1} + \sum_{i=2}^{p} \beta_i F_{t-i} \sum_{j=1}^{q} \gamma_j S_{t-j} + v_t$$

Parameter	$F_{t,Dec19}$[12]	$F_{t,Dec18}$[8]	$F_{t,Dec17}$[12]	$F_{t,Dec16}$[7]	$F_{t,Dec15}$[10]	$F_{t,Dec14}$[7]
α	0.0013	0.0012	0.0010	0.0005	0.0014	0.0014
θ	0.0054	0.0099	-0.0002	-0.0160	0.2775	0.2682
β_1	-	0.2960	-	-	0.7879	1.1145
β_2	0.6527	0.6903	0.6617	0.8479	1.1740	1.1971
β_3	0.6569	0.7047	0.8485	0.9096	1.3872	1.3764
β_4	-	-	0.4889	0.7981	1.2711	1.5513
β_5	-	-	0.3805	0.7470	1.1157	1.4669
β_6	-	-	-	-	0.7097	-
β_7	-0.5427	-0.4850	-	-	-	-
β_{11}	0.2337	-	-	-	-	-
β_{12}	0.4259	-	0.3581	-	-	-
γ_1	-	-0.2761	-	-	-1.0546	-1.3638
γ_2	-0.6833	-0.7589	-0.7666	-0.9855	-1.3288	-1.3638
γ_3	-0.6379	-0.6887	-0.8177	-0.8955	-1.4270	-1.4352
γ_4	-	-	-0.4258	-0.7153	-1.1465	-1.4377
γ_5	-	-	-	-0.6507	-1.0391	-1.3790
γ_6	-	-	-	-	-0.6322	-0.7475
γ_7	0.4961	0.4274	-	-	-	-
γ_{11}	-0.2909	-	-	-	-	-
γ_{12}	-0.4511	-	-0.4222	-	-	-
ARCH-test	110.21***	146.39***	60.65***	90.12***	46.83***	31.34***

Values reported are coefficient estimates significant at a 10% level. Values in brackets are number of lags from minimizing AIC. For the ARCH-test, the test statistics are reported. (*), (**) and (***) represents rejection of the null hypothesis at a 10%, 5% and 1% significance level respectively. Here, the null hypothesis, H_0, is: "There are no ARCH effects in our model".

Following this, we extend the model. By performing Engle's ARCH test, we reveal that there exist ARCH effects in our data (all significant at the 1% level). Hence, our current ECM might be misspecified. This leads us to introduce GARCH-components as it enables us to encompass the discovered ARCH-characteristics. This model may better capture the conditional, time-varying volatility we encounter in our data[2]. As

[2]Modeled volatility from the GARCH-components are plotted against first differenced spot prices in Appendix D

a result, we have identified the second framework for our predictions. Estimating ECM-GARCH(1,1) models for each contract yields the following results:

Table 7: Parameter estimates from ECM-GARCH(1,1)

$$\Delta S_t = \alpha + \theta \hat{u}_{t-1} + \beta_1 \Delta F_{t-1} + \sum_{i=2}^{p} \beta_i F_{t-i} \sum_{j=1}^{q} \gamma_j S_{t-j} + \sigma \sqrt{C_t} + v_t$$

Parameter	$F_{t,Dec19}$[12]	$F_{t,Dec18}$[8]	$F_{t,Dec17}$[12]	$F_{t,Dec16}$[7]	$F_{t,Dec15}$[10]	$F_{t,Dec14}$[7]
α	0.0028	0.0025	0.0021	-0.0003	-0.0025	-0.0039
θ	0.0024	0.0070	-0.0039	0.0200	0.3409	0.3535
β_1	-	0.2865	-	-	0.7790	1.1210
β_2	0.6401	0.6737	0.6519	0.8561	1.2313	1.3015
β_3	0.6427	0.6864	0.8361	0.9192	1.4506	1.4815
β_4	-	-	0.4760	0.8084	1.3371	1.6451
β_5	-	-	0.3708	0.7554	1.1823	1.5536
β_6	-	-	-	-	0.7700	0.9041
β_7	-0.5531	-0.4941	-	-	-	-
β_9	-	-	0.2629	-	-	-
β_{12}	0.4192	-	0.3525	-	-	-
γ_1	-	-0.2653	-	-	-1.1103	-1.4538
γ_2	-0.6727	-0.7443	-0.7582	-0.9926	-1.3784	-1.4603
γ_3	-0.6259	-0.6725	-0.8067	-0.9037	-1.4831	-15310
γ_4	-	-	-0.4144	-0.7241	-1.2058	-1.5221
γ_5	-	-	-	-0.6574	- 1.0968	-1.4550
γ_6	-	-	-	-	-0.6826	-0.8093
γ_7	0.5046	0.4347	-	-	-	-
γ_{11}	-0.2839	-	-	-	-	-
γ_{12}	-0.4459	-	-0.4180	-	-	-
σ	-0.0472	-0.0402	-0.0365	0.0270	0.1210	0.1330
η	-0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
τ_l	0.1109	0.1294	0.1085	0.1234	0.1015	0.1584
ρ_m	0.8891	0.8706	0.8915	0.8766	0.8985	0.8416

Values reported are coefficient estimates significant at a 10% level. Values in brackets are number of lags from minimizing AIC.

From the models above, we see that the parameters for conditional volatility (σ) are larger for the contracts maturing in December 2014, 2015 and 2016. This is because the volatility in these periods have been higher and therefore yields larger effects (seen from the size of the coefficients) to spot price changes. We also see that the parameter estimates are smaller when we estimate the models for the long-term contracts (maturing December 2017, 2018 and 2019), which implies that the market has become less volatile throughout the period and perhaps, therefore, more mature. Overall, from the number of significant variables in our models and the size of their coefficients, it seems like both historical spot and futures prices are indeed important when determining future spot prices. This further suggests that the market is maturing.

TESTING THE VALIDITY OF OUR MODELS - OUT-OF-SAMPLE PREDICTION ACCURACY

To assess the validity of our models and the futures prices' predictive power, we re-estimate all the models stated above and predict daily spot prices for the last twelve months before the contracts mature. The RMSE for all contracts are tabulated below.

Table 8: Root mean squared error for out-of-sample spot price predictions

Model	$F_{t,Dec19}[12]$	$F_{t,Dec18}[8]$	$F_{t,Dec17}[12]$	$F_{t,Dec16}[7]$	$F_{t,Dec15}[10]$	$F_{t,Dec14}[7]$
ECM	0.4428	0.9025	0.0137	1.5499	0.4360	0.5835
ECM-GARCH(1,1)	0.0965	0.9623	0.0544	1.6832	0.7238	1.4928

We see that both models yield a relatively low RMSE taking into consideration that we have estimated daily spot prices for an entire year. This further implies that all the futures contracts seem to work as efficient tools for predicting future spot prices. It seems like both the ECM and ECM-GARCH(1,1) model for the December 2017 contract provides the most accurate predictions, a contract that is long-term relative to the time period we are studying. However, the fact that long-term contracts provide the most accurate predictions is not consistent. We see this by comparing the errors of the ECM-GARCH(1,1) for December 2018 and 2015 contracts. Regardless, the futures contracts provide important and relatively precise information about future spot prices. The predicted spot prices are illustrated in Appendix B.

Thus, we have shown that there indeed is a long-run relationship between spot and futures prices in the EU ETS. This implies that the futures prices work as a significant information vehicle and that the system exhibits characteristics of a mature financial market. In other words, the system is well designed from a financial point of view.

5.2 THE LINK BETWEEN CARBON PRICES AND FUNDAMENTALS

In order for the EU ETS to work as an efficient climate policy tool, the prices of allowances need to be related to fundamentals affecting the actual amount of greenhouse gas emissions. This could, for instance, be the consumption of fossil fuels. As the prices for such commodities are based on supply and demand, a natural assumption is that high consumption is correlated with high demand, which could yield higher prices.

5.2.1 ASSESSMENT OF RELEVANT PRICE DRIVERS

In Section 4.3, we identified several potentially relevant drivers for the prices of emission allowances, some of them exhibiting relatively strong correlation. Consequently, we might get biased results when regressing prices of emission allowances on all of the independent variables due to multicollinearity. However, we start our analysis by running the simple regression below. All variables are log first-differenced as they should be according to the ADF tests in Appendix C.

$$S_t = \alpha + \beta_1 Oil_t + \beta_2 Elec_t + \beta_3 Coal_t + \beta_4 DAX_t + \beta_5 Ngas_t + \epsilon_t \tag{11}$$

When using first-differenced variables instead, the problem of multicollinearity seems to be less significant, as the correlation between the variables decreases. We use variables from corresponding periods as we want to capture the instant effect of shocks to the fundamental variables on the spot price of carbon emission allowances. It is a reasonable assumption that a well-functioning system should capture these effects immediately. Even though the regression might be spurious due to the potential problem of multicollinearity, it provides some insight and a good starting point for our analysis. The results from the regression are summarized in Table 9.

As seen from Table 9, all variables except electricity and natural gas are significant at a 10% level, and all but DAX are significant at a 5% level. However, we cannot

Table 9: Results from multivariate regression

$$S_t = \alpha + \beta_1 Oil_t + \beta_2 Elec_t + \beta_3 Coal_t + \beta_4 DAX_t + \beta_5 Ngas_t + \epsilon_t$$

	Estimate	**P-value**
Constant	0.0016	0.0502
Brent oil	0.1125	0.0032
Electricity	0.0046	0.5473
Coal	0.6151	0.0000
DAX	0.1406	0.0534
Natural gas	-0.0272	0.1147
Adjusted R^2	0.1520	
RMSE	0.0263	
F-statistic	39.2	

conclude solely on the basis of this, due to the presence of multicollinearity. For instance, the price of oil is highly correlated with the price of natural gas, so it may be that this effect is captured through the oil variable in this model, even though natural gas alone may be significant. Therefore, we run five individual regressions to avoid the multicollinearity problem. That is, we run the following general model for each variable:

$$S_t = \alpha + \beta X_t + \epsilon_t \tag{12}$$

X_t is either Brent oil, electricity, coal, DAX or natural gas. In this case, both X_t and S_t are on the log first-differenced form. The results from these regressions are tabulated below.

Table 10: Results from univariate regression

$$S_t = \alpha + \beta X_t + \epsilon_t$$

	α	β	R^2	$RMSE$
Brent oil	0.0010	0.2333***	0.033	0.0286
Electricity	0.0011	0.0008	0.000	0.0291
Coal	0.0012	0.6858***	0.146	0.0269
DAX	0.0010	0.3339***	0.017	0.0288
Natural gas	0.0014	-0.0163	0.001	0.0285

BRENT OIL

We see that increased oil prices ought to reflect an increase in the spot price of emission allowances. By comparing results from the two regressions, we see that this result is consistent, despite the coefficient being larger in the latter regression.

The results are in line with our fundamental hypothesis, as an increase in the oil price may reflect increased demand and thus higher consumption, resulting in higher emissions. Therefore, to incentivize companies to emit less, the price of emission allowances increases. However, it is not obvious that the sign of this coefficient is positive. For instance, if there is a decrease in the supply side of oil, prices may increase as it becomes more of a scarce resource. In this case, the consumption of oil does not necessarily increase. Consequently, the exact effect of increasing oil prices is unclear.

Another element that might further distort the interpretation is the natural cyclicality of the oil prices. In short, increasing prices might stimulate decision-makers to ramp up production to exploit the increased profitability they may achieve. As global extraction increases, we might eventually experience a significant supply surplus as producers are flooding the markets to some extent. The result is a structural price decline, eventually incentivizing decision-makers the put extraction on halt as the lower prices might render their facilities unprofitable. When this is the case, supply decreases, and we might experience a demand surplus. The result is that prices, once again, are forced upwards. As this cycle tends to repeat itself, the key takeaway is that price changes of oil could be interpreted as a force that will fluctuate regardless of policies and climate change. Consequently, findings might be distorted as decision-makers interpret price changes as something natural, rather than a representation of the consumption of oil, and consequently greenhouse gas emissions.

ELECTRICITY

Running the simple regression provides conflicting results when comparing it to our hypothesis. The relationship is slightly positive, but insignificant, indicating that no such relationship is identified.

As stated earlier, common sense dictates that there should be some kind of relationship between the amount of electricity generated and consumed, and the prices of the emission allowances. According to the International Energy Agency (2019), global electricity demand increased by 4% in 2019. Clean energy such as nuclear power and renewable sources satisfied a major portion of the increased demand, but unclean sources increased significantly as well. Backing up this argument, the agency also states that the global energy-related CO_2 emissions increased by 1.7% relative to 2018 levels, yielding a historic high of 33.1 Gt CO_2. This reflects that electricity is, in fact, a highly relevant source for greenhouse gas emissions, albeit clean energy is manifesting itself as the future. Consequently, we would expect to identify a statistically significant, positive relationship between the prices of electricity and prices of emission allowances. However, we cannot say that increased prices of electricity is at all responsible for increased prices of emission allowances, and no inferences about causality can be made. This is also true for the first model specification with all the fundamental variables. Hence, we cannot prove a direct effect of electricity prices on the spot prices of emission allowances.

COAL

The statistically significant and positive coefficient for coal prices indicates that when prices of coal increase, so do the prices of emission allowances. Different energy sources yield highly varying amounts of greenhouse gas emission, based on the actual carbon content of the fuel. By comparing the conventional energy sources used globally, we see that coal emits the largest amount of pollution per British thermal unit (Btu) of energy. For instance, it emits approximately twice as much CO_2 as natural gas and around 50% more than Gasoline (without ethanol) (U.S. Energy Information Administration, 2019). With coal being the most significant source of pollution of the energy sources, it is only natural for us to expect it to be related to the prices of emission allowances. As the purpose of the EU ETS is to reduce emissions, it makes sense for it to penalize those who are dependent on unnecessary consumption of coal. However, the results might be misleading as coal is still the largest source of electricity worldwide. Consequently, increased demand for electricity will often manifest itself as increased demand for coal. So although there seems to be a correlation, inferences about causality can hardly be made. Electricity might be an omitted variable that leads to biased results. As a consequence, it is near impossible to conclude if one of the variables is, in fact, responsible for the price movement of the others. For instance, coal, being correlated with electricity as well as the amount of greenhouse gas emissions, might seem highly significant when, in fact, the effect stems from somewhere else entirely. Still, recent studies indicate that despite being the largest source of electricity, coal's role in the global energy mix continues to decline. Additionally, the demand for coal in Europe declines as cheaper renewables and environmental policies are on the verge of taking over (International Energy Agency, 2019).

DAX

When running the simple regression of DAX on spot prices, we identify a positive relationship, significant at a 1% level. By comparing this to, for instance, the coefficient on oil for the individual regression (oil against emission allowance spot prices), DAX seems to be more critical as the coefficient is larger. This is also true for the regression including all the fundamental variables (only significant at a 10% level). If we interpret an increase in the DAX as an increase in the economic activity across Europe, the results may support a functioning cap and trade scheme for reducing emissions. When looking at the companies included in the index, we see that approximately 33% of the companies are either in the industry of manufacturing, aviation, energy or chemicals, contributing to approximately 36% of the weight in the index. Increased economic activity in these companies, which could result in higher valuations, could also lead to more pollution as these industries traditionally have been considered emission-intensive. However, in recent years, there has been an increased focus on ESG-perspectives of the business, making both operating activities and end products more environmentally friendly. For instance, car manufacturers, such as BMW and Volkswagen, are moving towards production of electric and hybrid cars, so the economic growth in itself may not be driven by the traditional emission-intensive end products we have seen in the past decade. Hence, it is not apparent that the price relationship is always positive.

NATURAL GAS

Both the simple regression and the one including all relevant variables seem to agree on the fact that the natural gas price is statistically insignificant, with a parameter estimate close to zero. It is slightly negative for both the regression models defined in this section. As natural gas as an energy source is the least carbon-intensive amongst all the fossil energy sources, we hypothesized this to be the most likely regression to provide insignificant results. Furthermore, as discussed in studies published by the MIT Energy Initiative (2011) and Weissman (2016), natural gas is commonly characterized as a "bridge fuel", as it may play an essential part in the reduction of greenhouse gas emissions, and work as a bridge to low-carbon future. This theory is backed up by evidence of an estimated 4.6% growth in consumption in 2018, with more than one-fifth of this increase accounted for by the substitution of coal in favor of natural gas (International Energy Agency, 2019).

The somewhat positive view of natural gas as a significant advocate for a low-carbon future leads us to believe that increased consumption should not be heavily penalized, although it is a fossil fuel and an apparent source of greenhouse gas emissions. This might be the reason for the insignificance of natural gas prices when determining prices of emissions allowances.

5.2.2 VAR ANALYSIS - IMPULSE RESPONSE FUNCTIONS

As mentioned in Section 3.7, we extend the model from 5.2.1 and define a matrix system that contains all relevant variables. This analysis also allows us to see how previous values of the fundamental drivers affect the current spot price as we are including lags. By minimizing AIC and the log-likelihood function, we end up with a system of two lags. The results from the VAR(6,2)-model is summarized below.

Table 11: Summary of VAR(6,2) model

	$Spot_t$	Oil_t	$Elec_t$	$Coal_t$	DAX_t	$Ngas_t$
$Constant$	0.0013	0.0006	-0.0011	-0.0003	0.0001	-0.0002
$Spot_{t-1}$	0.0267	-0.0324	-0.0105	-0.0152	-0.0134	-0.0002
$Spot_{t-2}$	-0.0070	-0.0028	0.1340	0.0052	-0.0091	-0.0208
Oil_{t-1}	-0.0518	-0.0195	-0.1363	-0.0163	-0.0098	0.0238
Oil_{t-2}	0.0051	**-0.0592**	0.2347	**-0.0621**	0.0078	0.0336
$Elec_{t-1}$	-0.0053	0.0052	-0.1605	-0.0040	**-0.0095**	-0.0081
$Elec_{t-2}$	-0.0064	**-0.0253**	**-0.1193**	**-0.0091**	**-0.0087**	-0.0071
$Coal_{t-1}$	**-0.1908**	**0.0854**	0.0592	0.0423	0.0075	-0.1472
$Coal_{t-2}$	-0.0141	-0.0440	-0.1620	-0.0308	0.0292	0.0793
DAX_{t-1}	0.0592	0.0721	-0.3632	-0.0405	-0.0007	-0.1076
DAX_{t-2}	0.0558	**0.1464**	-0.2478	**0.1192**	-0.0238	-0.1139
$Ngas_{t-1}$	-0.0003	0.0205	-0.1041	-0.0054	0.0043	**0.1369**
$Ngas_{t-1}$	-0.0140	-0.0119	-0.0086	-0.0004	-0.0009	**-0.1765**

Values reported are coefficient estimates, bold ones are significant at a 10% level.

We see that few of the variables are significant at a 10% level, and the estimates of fit are not particularly high. However, the interpretation of the VAR model is not straightforward. To find comparable results for Section 5.2.1, we run different impulse response functions to see how the system works as a whole. In this analysis, we try to determine how shocks in all the relevant variables (Brent oil, electricity, coal, DAX and natural gas) affect the variables itself, and the spot price of carbon emission allowances over time, i.e. how shocks propagate through the system.

From Figure 3, we see that a positive shock in the spot price of emission allowances is followed by an immediate price increase that is downward trending up until period two, but zero already after period three. Hence, it implies that shocks in spot prices do not contribute to increased volatility in the system as it stabilizes relatively quick, and the shock only yields substantial price changes immediately (at $t = 0$).

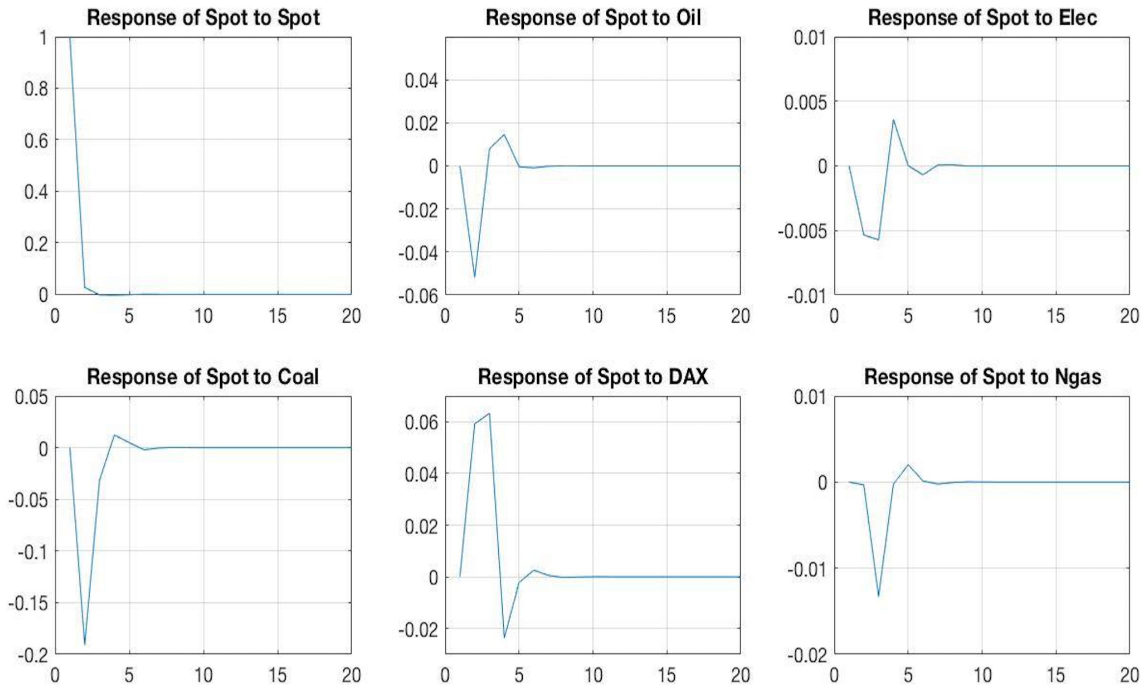

Figure 3: Illustration of impulse response functions

We see that the response of the spot price to shocks in the oil price is in line with the results and discussion presented in Section 5.2.1. However, the immediate response to a positive shock, according to the VAR model, is decreasing prices the first two periods. Following this, it increases significantly from period two to four, before dying out. Consequently, it is difficult to interpret the effect of increased oil prices. Regardless, we see that the system stabilizes and the shock is almost completely neutralized after five periods. This is in line with a well-functioning and efficient system, as it reacts to a shock in the variable, but also stabilizes after a short period of time.

Shocks in electricity prices seem to have a small effect on the price of emission allowances. The price adjustments are very small (almost neglectable); however, the signs of adjustment are contradicting our initial hypothesis that there may be a positive relationship, as we see that a shock in electricity prices yields both negative and positive responses. Either way, the results are more or less in line with findings from the previous sections, where we could not identify a significant relationship. As discussed earlier, this may be because electricity prices are hard to interpret, being that the energy mix consists of electricity generated from multiple sources. Consequently, the prices reflect both electricity from carbon-intensive sources as well as green sources, which may explain why the effect from an electricity price shock is close to zero and stabilizes quickly, i.e. why it is insignificant.

Shocks in coal prices seem to contribute to the most considerable change in the price of emission allowances. This is in line with the results presented in the previous section. However, the sign of the price adjustments is similar to what we found for oil prices. Firstly, spot prices react negatively until period two, before trending upwards and stabilizing around period five. This contradicts the hypothesis that a positive shock should manifest itself as a price increase. An interpretation is that decreasing prices of coal will lead to increased demand, as the energy source turns relatively cheaper compared to the alternatives. Consequently, decreasing prices may be a sign of increased demand to come and more pollution, which again will lead to increased price pressure on the emission allowances. This may explain the initial negative effect of a shock in coal prices. If this line of reasoning holds, then prices are bound to start increasing eventually as we experience increased demand. We will then encounter a period of both increasing prices of coal and emission allowances, which could explain why the impulse responses turn positive after the initial shock. Another explanation for the initial negative shock is that a shock in coal prices makes participants more eager to transition to less carbon-intensive energy sources, such as natural gas.

The impulse response function for shocks in DAX is also consistent with the findings in the previous section. A shock in the variable seems to have a significant and positive effect on the spot prices, and the system stabilizes around period six. As previously mentioned, if the DAX variable is a good proxy for economic activity and growth, a positive relationship is expected. That is the case both here and in the previous section. A positive shock is also followed by a price reduction between period four and five, but this is relatively low compared to the instant response. Overall, it seems like the system stabilizes fairly quick when shocks to the DAX occur.

Similar to the shocks in the electricity prices, shocks in natural gas seem to be less significant due to their relatively small size. This is consistent with the fact that we could not prove significance for the variable in the previous section. It is also hard to interpret the sign and its effect on spot prices between period zero and five since the effect is varying. However, overall, the effect is weak and stabilizes relatively fast. As previously mentioned, the direction of the relationship between natural gas and emissions is a bit unclear as it is a fossil fuel, but can also be considered a bridge to a less carbon-incentive future. This may explain why the results from both models indicate that the effect is insignificant.

Overall, by analyzing the impulse response functions of the VAR system, we see that several of the fundamental variables are indeed affecting the prices of emission allowances. Most of the price effects have the signs we would expect from the previous discussion and analysis, and shocks to the variables seem to die out relatively fast in the system. Thus, it seems like the VAR system is stable which supports our previous findings of a mature financial market. Furthermore, prices in the EU ETS are responding to fundamental variables in a way that could imply that it is an efficient climate policy tool.

6 CONCLUSION

In the first part of our analysis, we prove that there exists a cointegrating relationship between the spot and futures prices of carbon emission allowances. Hence, the prices do not diverge towards independent stochastic paths in the long-run. A consequence of this is that the carbon futures exhibit the appropriate risk mitigation characteristics for market participants to hedge greenhouse gas emission. Another consequence is that we are able to model future spot prices using historical prices. Through our models, we see that that futures prices indeed work as an important information vehicle when considering prices in the EU Emissions Trading System. An interpretation is that current spot prices comprise a majority of the information stored in historical price data, which is in line with the theories proposed by Fama (1970). Taking all of this into account, we conclude that the system exhibits characteristics of a mature financial market. This result is not surprising, being that the market has experienced drastically increasing volumes and higher liquidity. Consequently, supply and demand from the market participants are the driving forces of the prices, leading to a marketplace that provides indications of efficiency, in accordance with financial theories of no-arbitrage.

When considering other fundamental drivers of pollution, we discover that coal, Brent oil and the DAX are the most significant variables. Despite significant results, we cannot say much about causality. A more extensive model framework might be needed to make meaningful interpretations of the relationship between fundamental drivers of pollution and carbon prices. Still, the VAR analysis and impulse response functions suggest that the EU Emissions Trading System indeed reacts to shocks in several of the fundamental variables defined above. In line with the results from the simple regression models, shocks in the prices of Brent oil, coal and the DAX seem to be the main drivers of price instability of emission allowances. However, even though the shocks may be substantial and the signs are not easily interpreted, all of them seem to die out relatively quick. These findings also support our previous view of a mature financial market.

While results provide clear indications of financial maturity, it is more difficult to provide clear interpretations of how the EU Emissions Trading System incentivizes participants to reduce their emissions. The prices of emission allowances are linked to some fundamentals, but the actual nature of this link is somewhat unclear. Conclusively, the link between fundamental drivers of emission and carbon prices indicates that changed behavior of energy consumers could influence the prices of emission allowances, albeit the robustness of the relationships still needs to be further investigated.

6.1 SUGGESTIONS FOR FURTHER RESEARCH

Having discovered that the EU ETS seems to behave as a mature financial market and exhibits appropriate hedging properties, a potential next step could be to assess various hedging strategies and attempt to detect an optimal hedge ratio. One way to assess this is through a comparative performance study of traditional emission-intensive companies versus more recently developed, green, companies.

Even though we have identified a relationship between the prices of carbon emission allowances and the prices of some fundamental drivers of greenhouse gas emission, our models are not able to capture all the effects. Additionally, we were not able to identify a relationship between electricity prices nor the prices of natural gas which was the case in the studies of Aatola et al. (2013). They utilized German electricity prices and studied phase I and II of the the EU ETS. Our results might differ as we utilize electricity prices from Nord Pool which reflects electricity prices for North European countries and the Baltic region. Another reason may be that these price effects are reflected through some of the other fundamental variables in phase III. Alberola et al. (2007) also found a clear relationship between extreme weather temperatures and the prices of carbon emission allowances. We were not able to collect sufficient datasets to control for these effects, but it is natural to assume that there should exist a link between these variables as global warming resulting from pollution is a leading cause of more extreme weather. Hence, both German electricity prices and extreme weather temperatures, given sufficient datasets, should be controlled for in future studies of the the carbon markets.

Furthermore, if future studies aim to assess the probability of reaching global climate goals, an event studies approach might be an efficient way of assessing the adequacy of the EU ETS as a climate policy tool. As we highlighted in our analysis, the interpretation of signs is not straightforward in any static OLS model or dynamic VAR model unless we know the underlying reason for a price change in the fundamental variable. Therefore, by focusing on specific events like, for instance, an increase in the oil prices due to a reduction in the global supply, we can look at how the prices of emission allowances have reacted historically.

BIBLIOGRAPHY

Aatola, P., Ollikainen, M., & Toppinen, A. (2013). Price determination in the EU ETS market: Theory and econometric analysis with market fundamentals. *Energy Economics*, *36*, 380–395.

Akaike, H. (1974). A new look at the statistical model identification. *IEEE transactions on automatic control*, *19*(6), 716–723.

Alberola, E., Chevallier, J., & Chèze, B. (2007). European carbon prices fundamentals in 2005-2007: the effects of energy markets, temperatures and sectorial production.

Alberola, E., Chevallier, J., & Chèze, B. (2008). Price drivers and structural breaks in European carbon prices 2005–2007. *Energy policy*, *36*(2), 787–797.

Borak, S., Härdle, W. K., Trück, S., & Weron, R. (2006). Convenience yields for CO2 emission allowance futures contracts.

Brorsen, B. W., & Fofana, N. F. (2001). Success and failure of agricultural futures contracts. *Journal of Agribusiness*, *19*(345-2016-15191), 129–145.

Byrne, J. P., Fazio, G., & Fiess, N. (2013). Primary commodity prices: Co-movements, common factors and fundamentals. *Journal of Development Economics*, *101*, 16–26.

Byun, S. J., & Cho, H. (2013). Forecasting carbon futures volatility using GARCH models with energy volatilities. *Energy Economics*, *40*, 207–221.

Charles, A., Darné, O., & Fouilloux, J. (2013). Market efficiency in the European carbon markets. *Energy Policy*, *60*, 785–792.

Chevallier, J. (2010). A note on cointegrating and vector autoregressive relationships between CO2 allowances spot and futures prices. *Economics Bulletin*, *30*(2), 1564–1584.

Dickey, D. A., & Fuller, W. A. (1979). Distribution of the estimators for autoregressive time series with a unit root. *Journal of the American statistical association*, *74*(366a), 427–431.

Engle, R. F. (1982). Autoregressive conditional heteroscedasticity with estimates of the variance of United Kingdom inflation. *Econometrica: Journal of the*

Econometric Society, 987–1007.

European Commision. (2018). Shedding light on energy in the EU. A guided tour of energy statistics. (https://ec.europa.eu/eurostat/cache/infographs/energy/bloc-3b.html. Retrieved 2020-05-28)

Fama, E. F. (1970). Efficient capital markets: A review of theory and empirical work. *The journal of Finance*, *25*(2), 383–417.

Frino, A., Kruk, J., & Lepone, A. (2010). Liquidity and transaction costs in the European carbon futures market. *Journal of Derivatives & Hedge Funds*, *16*(2), 100–115.

Granger, C. J. (1986). Developments in the study of cointegrated economic variables. *Oxford Bulletin of economics and statistics*, *48*(3), 213–228.

Hicks, J. R. (1939). Value and capital: an inquiry into some fundamental principles of economic theory. *Oxford: Clarendon Press*.

Hintermann, B. (2010). Allowance price drivers in the first phase of the EU ETS. *Journal of Environmental Economics and Management*, *59*(1), 43–56.

Ibikunle, G., & Gregoriou, A. (2011). European Union Emissions Trading Scheme (EU-ETS) futures liquidity effects: Evidence from the European Energy Exchange (EEX). In *8th international conference on advances in applied financial economics* (pp. 245–252).

Ibikunle, G., Gregoriou, A., Hoepner, A. G., & Rhodes, M. (2016). Liquidity and market efficiency in the world's largest carbon market. *The British Accounting Review*, *48*(4), 431–447.

International Energy Agency. (2019). Global energy CO2 status report. the latest trends in energy and emissions in 2018. *Paris, France*.

Johansen, S. (1988). Statistical analysis of cointegration vectors. *Journal of economic dynamics and control*, *12*(2-3), 231–254.

Keynes, J. M. (1923). Some aspects of commodity markets. *Manchester Guardian Commercial: European Reconstruction Series*, *13*, 784–786.

Lütkepohl, H., & Poskitt, D. S. (1991). Estimating orthogonal impulse responses via vector autoregressive models. *Econometric Theory*, *7*(4), 487–496.

Milunovich, G., & Joyeux, R. (2010). Market efficiency and price discovery in the EU carbon futures market. *Applied Financial Economics*, *20*(10).

MIT Energy Initiative. (2011). The future of natural gas: An interdisciplinary MIT study. *Massachusetts Institute of Technology, Cambridge, MA*.

Mizrach, B. (2012). Integration of the global carbon markets. *Energy Economics*, *34*(1), 335–349.

Roberts, H. (1967). Statistical versus clinical prediction of the stock market. *Unpublished manuscript*.

Runkle, D. E. (1987). Vector autoregressions and reality. *Journal of Business & Economic Statistics*, *5*(4), 437–442.

United Nations Framework Convention on Climate Change. (2020). The Paris Agreement. (https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement?fbclid=IwAR0_rkP_1JW1AAwivs7xfo6MDAu7ZqYVb2-yPkJN6bX1Z6pve6PbGhQIiZI. Retrieved 2020-05-12)

U.S. Energy Information Administration. (2019). How much carbon dioxide is produced when different fuels are burned? (https://www.eia.gov/tools/faqs/faq.php?id=73&t=11. Retrieved 2020-05-28)

U.S. Energy Information Administration. (2020). U.S. energy facts explained. (https://www.eia.gov/energyexplained/us-energy-facts/. Retrieved 2020-05-28)

Weissman, S. (2016). Natural gas as a bridge fuel-measuring the bridge. *Center for Sustainable Energy*.

APPENDIX

A APPENDIX A - THE PARIS AGREEMENT AND THE EU ETS

The Paris Agreement is an agreement between 194 different states and the European Union with the purpose of mitigating greenhouse gas (GHG) emissions and ensuring a sustainable future globally. The main long-term goal in the agreement is to keep the global temperature increase well below two degrees Celsius in this decade (United Nations Framework Convention on Climate Change, 2020). In light of this, the use of climate change policy tools, such as the EU Emissions Trading Scheme (EU ETS), is crucial for being in compliance. The EU ETS is the largest compulsory cap and trade system in the world and one of the most efficient regional climate change policy tools (Ibikunle et al., 2016). A cap and trade system, in this case, is where a maximum cap of permitted emission is set by the EU to reach the GHG emission goals. Consequently, they provide economic incentives to lower emission. The maximum number of allowances is allocated to relevant parties, and permits corresponding to the actual amount of emissions produced over the previous year need to be surrendered on an annual basis. Arising from the 2002 Kyoto Protocol, the EU ETS has opened several opportunities for both governments, companies and investors to trade carbon allowances. Emission allowances can be traded in the spot market, as future contracts or as options. Consequently, the understanding of the market microstructure is crucial for both government and companies alike.

B APPENDIX B - PREDICTION PLOTS

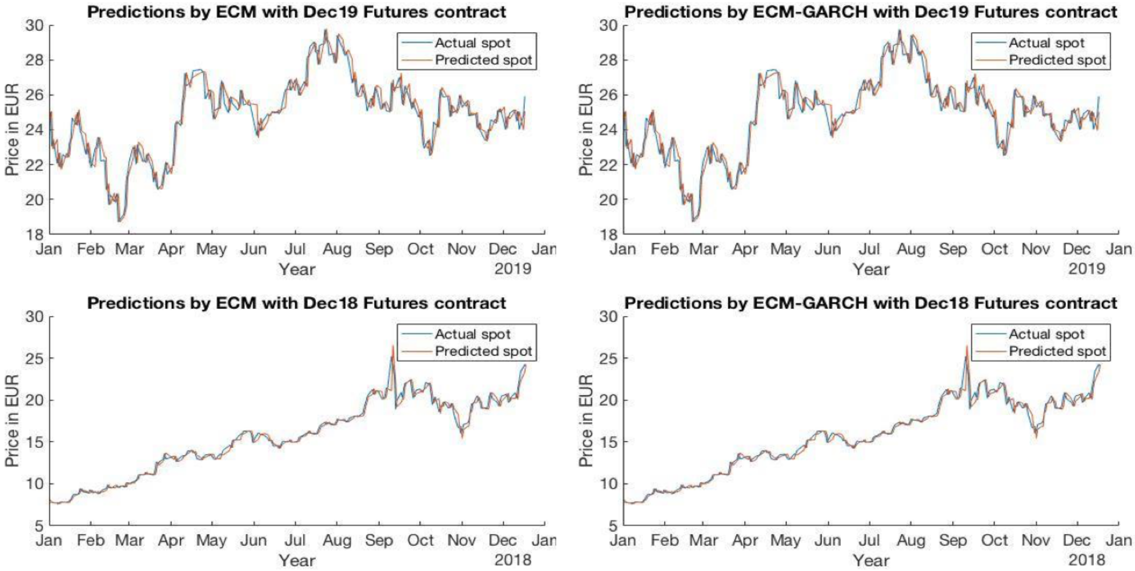

Figure 4: Prediction plots of December 2019 and 2018 futures

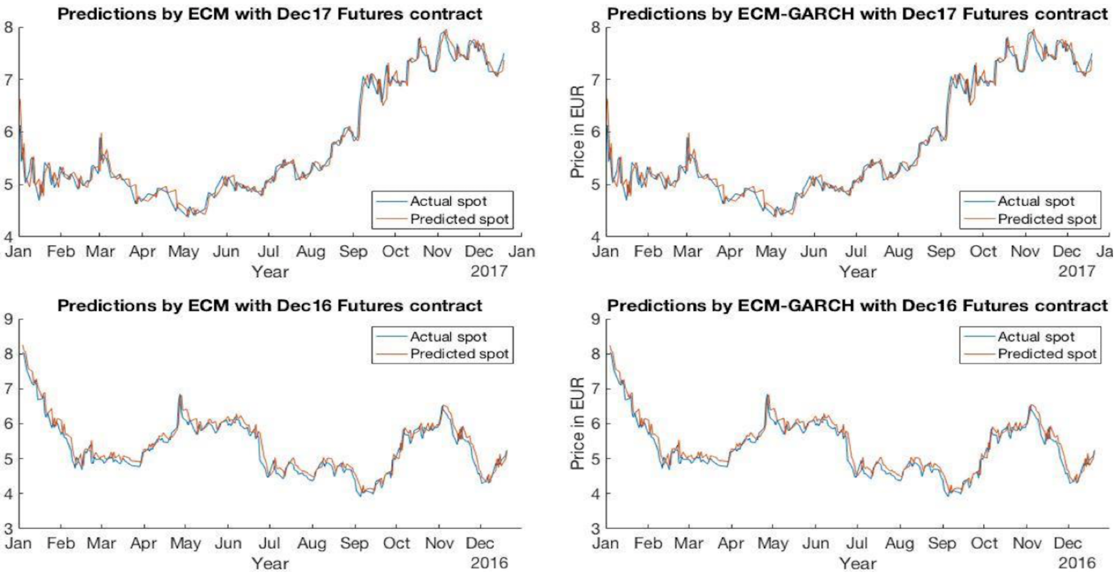

Figure 5: Prediction plots of December 2017 and 2016 futures

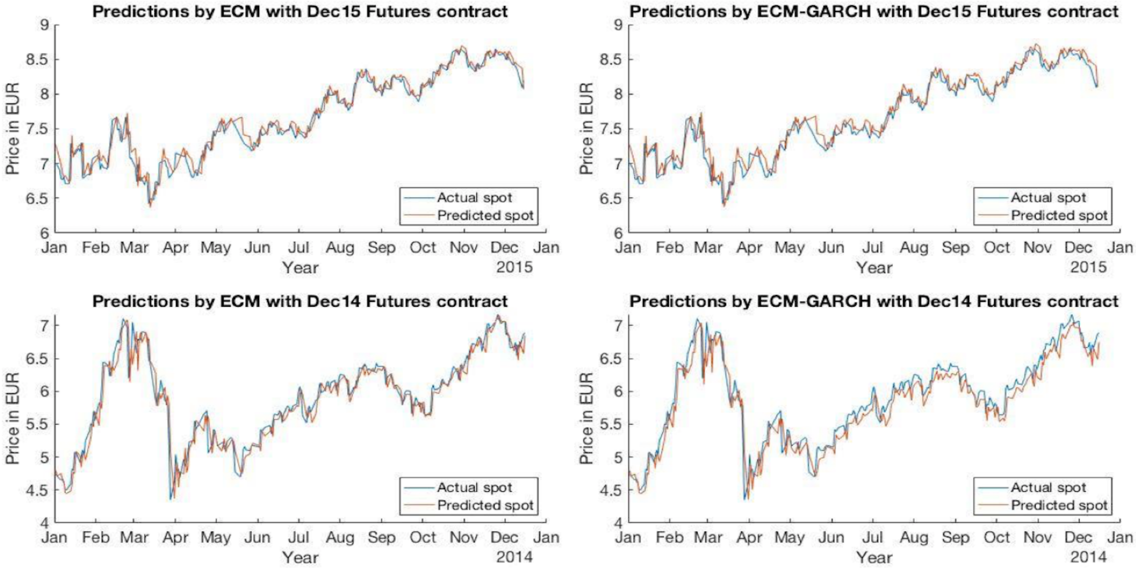

Figure 6: Prediction plots of December 2015 and 2014 futures

C APPENDIX C - ADF TEST FOR OTHER VARIABLES

Table 12: Results from unit root testing of fundamental variables

	Log levels			**Log first differences**		
	No Drift or trend	Drift	Drift and trend	No drift or trend	Drift	Drift and trend
Oil	-1.0835	-1.9388	-1.6018	-42.0856***	-42.0827***	-42.1264***
Electricity	-0.4653	-3.3251**	-3.5497**	-14.5353***	-14.5318***	-14.6414***
Coal	-0.3197	-1.0253	-0.7907	-14.5377***	-14.5341***	-14.6224***
DAX	1.2588	-1.8854	-3.0288	-19.6103***	-19.6494***	-19.7100***
Naturalgas	-0.8469	-3.3214**	-3.6949**	-13.6016***	-13.6008***	-13.6911***

When conducting the ADF test, we controlled for drifts and time trends in the time series. The optimal lag length was chosen by minimizing AIC. ***,**,* indicates rejection at the 1%, 5% and 10% significance level. In this case, the null hypothesis, H_0, is: "The time series are characterized by one unit root".

D APPENDIX D - MODELED VOLATILITY FROM GARCH(1,1)

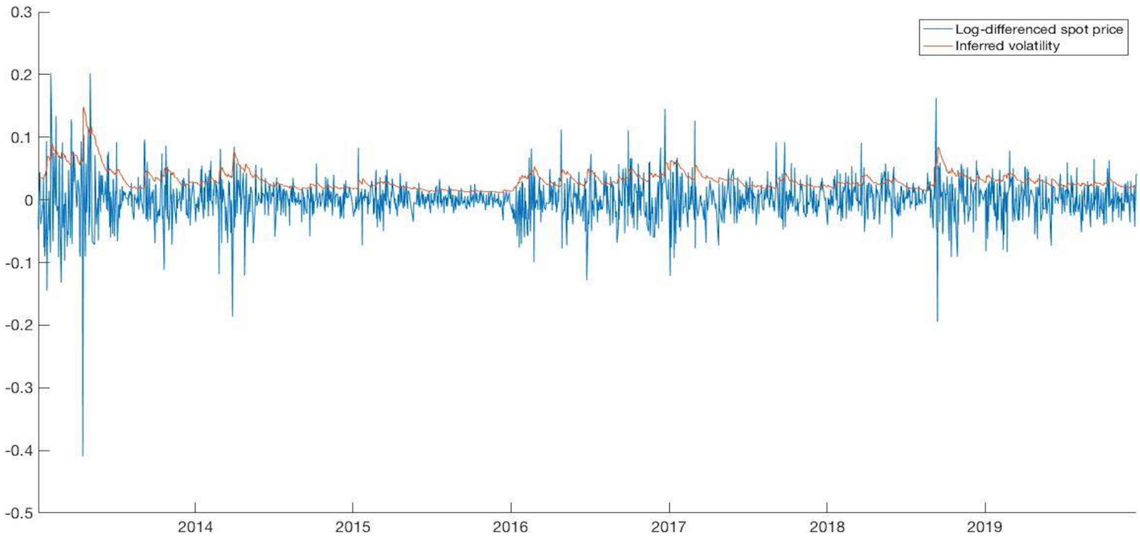

Figure 7: Modeled volatility for December 2019 futures model

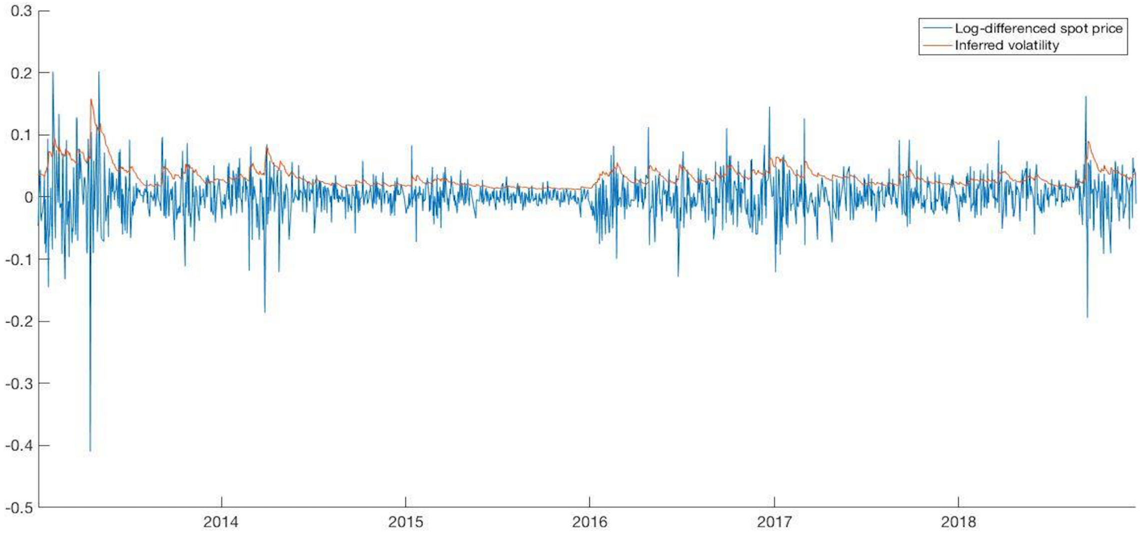

Figure 8: Modeled volatility for December 2018 futures model

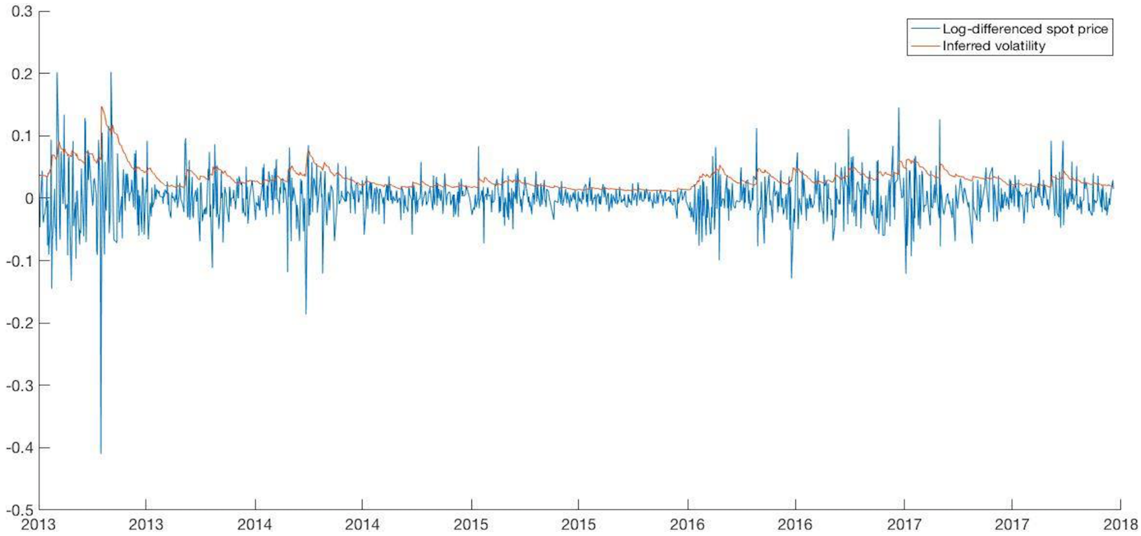

Figure 9: Modeled volatility December 2017 futures model

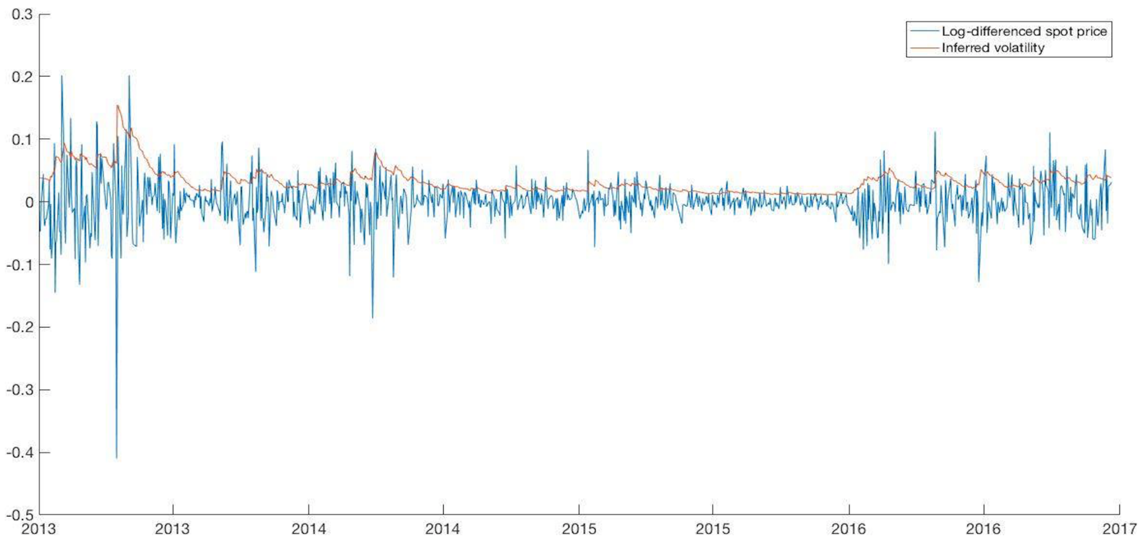

Figure 10: Modeled volatility for December 2016 futures model

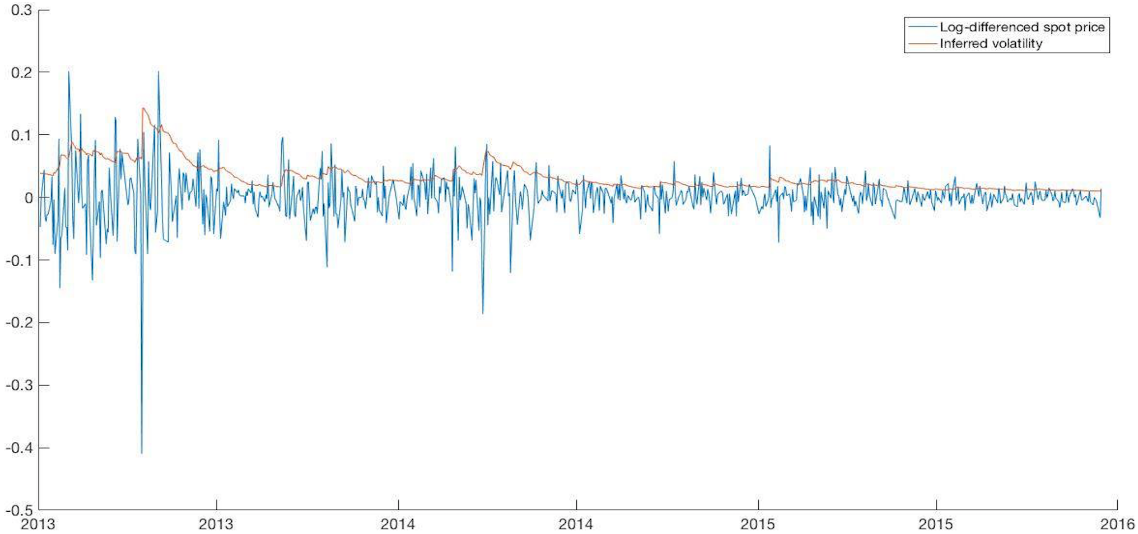

Figure 11: Modeled volatility for December 2015 futures model

Figure 12: Modeled volatility for December 2014 futures model