Discussion Paper No. 13-001

Nonlinearity in Cap-and-Trade Systems: The EUA Price and its Fundamentals

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and Waldemar Rotfuß

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Das Wichtigste in Kürze

Seit der Einführung des EU-Emissionshandelssystems (EU-EHS) im Jahr 2005 ist ein neues Forschungsgebiet innerhalb der angewandten Ökonometrie entstanden, das die Preisbildung von EU-Emissionszertifikaten (EUA) analysiert: Carbon Finance. CO_2-Preise beeinflussen als Kostenfaktor das operative Geschäft sowie die langfristige Planung der durch das EU-EHS regulierten Unternehmen. Daher sind Erkenntnisse über die Dynamik der EUA-Preise für Praktiker, Politiker und Wissenschaftler von hoher Bedeutung. Dieses Papier leistet einen Beitrag zur Untersuchung des Zusammenhangs zwischen der Entwicklung des EUA-Preises und dessen fundamentalen Determinanten, wie z.B. den Energiepreisen, der makroökonomischen Entwicklung und den Wetterbedingungen in Europa. Mit Hilfe eines Markov Regime-Switching GARCH Modells wird der nichtlineare Einfluss dieser Determinanten auf den EUA-Preis geschätzt. Das Modell erlaubt außerdem Einblicke in die Entwicklung des Ausmaßes der Schwankungen (Volatilität) des EUA-Preises über die Zeit.

Brüche und Veränderungen des Daten generierenden Prozesses, welcher der EUA-Preis-Zeitreihe zu Grunde liegt, sind eine Konsequenz der Ausgestaltung des EU-EHS. In einem Emissionshandelssystem wie dem EU-EHS ist das aggregierte Angebot an Emissionszertifikaten fix, während die Nachfrage zahlreichen Veränderungen und Schocks unterliegt. Wenn ein Einbruch der wirtschaftlichen Aktivitäten zu einem starken Einbruch der Emissionen und somit zu einer sinkenden Nachfrage nach Zertifikaten führt, so hat dies zur Folge, dass die Unsicherheit unter den Marktteilnehmern über die Knappheit an Zertifikaten in der gegenwärtigen Handelsphase zunimmt. Die damit verbundenen Handelsaktivitäten führen zu einer erhöhten Volatilität des EUA-Preises und zu einem veränderten Zusammenhang zwischen den fundamentalen Determinanten und dem Zertifikatepreis. Das empirische Modell identifiziert zwei unterschiedliche Marktzustände (Regime), die den Verlauf des EUA-Preises bestimmen. Im Betrachtungszeitraum der durchgeführten Untersuchung von Januar 2008 bis Dezember 2012 wechselt der Daten generierende Prozess mehrfach zwischen diesen beiden Zuständen. Beide Regime sind durch keinen klaren Preistrend charakterisiert. Jedoch weist das erste Regime hohe Schwankungen im EUA Preisverlauf aus. Dieser Zustand kann als eine Phase hoher Unsicherheit am Markt interpretiert werden. Das zweite Regime beschreibt einen Zustand, in dem der EUA-Preis geringeren Schwankungen unterliegt. Die Ergebnisse zeigen, dass die Energiepreise sowie Veränderungen auf den Aktienmärkten in beiden Regimen wichtige EUA-Preis-Determinanten sind. Der Einfluss der EUA-Preis-Determinanten unterscheidet sich signifikant zwischen den beiden Zuständen. Der Preis von Gas und ein breiter Aktienindex beeinflussen den EUA-Preis in beiden Regimen positiv, während die Preise von Kohle und Öl jeweils einen positiven Effekt im ersten, bzw. zweiten Regime, aufzeigen. Das Modell ordnet das erste Regime Perioden während der Rezession in den Jahren 2008 und 2009 zu, einer Phase sinkender Gesamtemissionen. Während der anschließenden wirtschaftlichen Erholungsphase befindet sich das Modell überwiegend im zweiten Regime. Ab Juni 2011 jedoch wechselt das Modell in das erste Regime und verbleibt in diesem Zustand. Regulatorische Ankündigen und sich eintrübende Konjunkturerwartungen verstärken zu diesem Zeitpunkt die Unsicherheit, ob die gesetzte Emissionsobergrenze bindend ist. Bis zum Ende des Beobachtungszeitraums im Dezember 2012 weist das Modell daher das durch hohe Preisschwankungen gekennzeichnete erste Regime aus.

Die Ergebnisse der empirischen Untersuchung unterstützen die Hypothese, dass die Dynamik des EUA-Preises durch Brüche und Veränderungen gekennzeichnet ist. Dies bezieht sich auf den Zusammenhang zwischen fundamentalen Determinanten und dem EUA-Preis selbst, aber auch auf die Entwicklung der Schwankungsbreite über den Betrachtungszeitraum hinweg.

Nontechnical summary

Since the introduction of the EU Emissions Trading System (EU ETS) in 2005, a new area of research has developed within the field of applied econometrics: Carbon Finance. Carbon Finance focuses on the analysis of the price formation of emission credits and allowances. As driving cost factor, prices of European Union Allowances (EUAs) influence operational business and long-term planning of EU ETS regulated firms. Therefore, the understanding of the EUA price dynamics are significant for practitioners, politicians and scientists. This paper contributes to the analysis of the relationship between the EUA price and its fundamentals, such as energy prices, indicators of the macroeconomic development and weather conditions in Europe. Based on a Markov regime-switching model, we estimate the nonlinear impact of these fundamentals on the EUA price. Further, the model allows to get insights into the development of the EUA price variation (volatility) over time.

Breaks and changes in the data generating process that underlies the EUA price time series are a consequence of the design of the EU ETS. Emissions trading schemes are characterized by a fixed supply of allowances, while the demand is subject to various shocks and changes. A sudden decline of economic activities, for example, leads to decreasing emissions and hence to a decreasing demand of allowances. As a consequence, this situation increases uncertainty among market participants about the overall stringency of the scheme. The associated trading leads to higher levels of EUA price volatility and to a changing relation between the EUA price and its fundamentals. The empirical model identifies two different market states (regimes), that determine the EUA price dynamics. The data generating process switches several times between these two regimes during the period under consideration, i.e. January 2008 to December 2012.

Both regimes are characterized by no clear price trend. The first regime shows high levels of EUA price variation. This state can also be interpreted as a market phase of high uncertainty. In contrast, the second regime describes a state where the variation in EUA prices is on a lower level. The results show, that energy prices and the stock market are important EUA price determinants in both regimes. The gas price and a broad European equity index affect the EUA price positively in both regimes, while the coal price and the oil price have a significant, but also positive impact only during the high and the low volatility regime, respectively. Extreme temperatures have no significant influence on the EUA price. The high volatility regime is predominant in phases when economic activities are on a decrease or when institutional changes harm the confidence in the stringency of the EU ETS. This holds during the recession of 2008 and 2009, as well as during 2011 and 2012 when the debt crisis impaired the European economic outlook.

The results of the empirical examination support the hypotheses, that the EUA price dynamics are characterized by breaks and changes. The impact of fundamentals on the EUA price and the development of its variation over time are subject to this kind of nonlinearity.

Nonlinearity in Cap-and-Trade Systems: The EUA Price and its Fundamentals

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Abstract

In this paper we examine the nonlinear relation between the EUA price and its fundamentals, such as energy prices, macroeconomic risk factors and weather conditions. By estimating a Markov regime-switching model, we find that the relation between the EUA price and its fundamentals varies over time. In particular, we are able to identify a low and a high volatility regime, both showing a strong impact of the fundamentals on the EUA price. The most important EUA price drivers are changes on the stock market and energy prices. The gas price and a broad European equity index affect the EUA price positively in both regimes, while the coal price and the oil price have a significant, but also positive impact only during the high and the low volatility regime, respectively. The high volatility regime is predominant in phases when economic activities are on a decrease or when institutional changes harm the confidence in the stringency of the EU ETS. This holds during the recession of 2008 and 2009, as well as during 2011 and 2012 when the debt crisis impaired the European economic outlook.

Keywords: EU ETS, EUA Price Fundamentals, Markov Regime-Switching

JEL Classification: C22, C58, G13, Q50

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1 Introduction

This paper investigates the changing nature of the relation between the European Union Allowance (EUA) price and its fundamentals. The EUA price dynamics and its driving factors have been of great importance for practitioners, politicians and scientists since the introduction of the European Union Emissions Trading Scheme (EU ETS) in 2005. The reasons for the interest are manifold. First, carbon prices introduce an additional cost component affecting day-to-day and long-term operations of regulated installations. Understanding this cost component is a key strategic element for many regulated installations to achieve long-term cost efficiency. Second, the scheme is a market-based policy instrument. Its success heavily depends on its ability to generate correct price signals that fully account for the underlying fundamentals. Thus, the relation between the EUA price and its driving factors is crucial for the understanding of the effectiveness of the scheme.

We argue that the varying relation between the EUA price and its fundamentals is a consequence of the design of the EU ETS. In cap-and-trade systems, as in the case of the EU ETS, the regulatory authority determines the total number of allowances for a certain period of time. In other words, the aggregated supply of allowances is fixed and therefore inelastic. In contrast, the demand varies due to various shocks, for example positive and negative shocks to the macroeconomic activity. Such shocks shift the production of goods to higher or lower levels, which increases or decreases the aggregated level of emissions and, thus, the demand for allowances. As a result, market participants adjust their expectations about the overall stringency of the scheme. We hypothesize, that this situation translates into a higher volatility and a varying relation between the EUA price and its fundamentals.

The recent literature provides empirical evidence on structural changes in the data generating process of the EUA prices. Alberola, Chevallier, and Chèze (2008), Chevallier (2009), Keppler and Mansanet-Bataller (2010), and Hintermann (2010) devote their research to the detection of price determinants affecting the European carbon market. In particular, they quantify the linear impact of fundamentals such as commodity prices, weather conditions and economic fluctuations on the EUA price. To account for potentially time-changing influences of the fundamentals they conduct an analysis over different subsamples. In doing so, they assume that the timing of the structural breaks is known. The authors trace these structural changes back to different factors: Alberola, Chevallier, and Chèze (2008) refer to the information disclosure on the actual emissions in 2006 as a reason for structural changes, whereas Chevallier (2009) sees the aftermath of the financial crisis as a factor causing breaks. These potential sources for breaks seem to have one characteristic in common: They alter the expectations about the overall demand of allowances during the prevailing compliance period and, thus, affect the expectations about the overall stringency of the EU ETS. Therefore, these changes are inherent in the cap-and-trade system and should be endogenized.

In contrast to these earlier studies, we therefore do not assume the changes in the regimes to be deterministic. Instead, we consider a Markov regime-switching model and simultaneously allow for both: time-variation in the effects of the fundamentals as well as in the volatility of the EUA prices, as changes in expectations about the overall stringency of the EU ETS are likely to be associated with periods of higher uncertainty and, thus, with higher volatility in the EUA prices. Moreover, we focus on the short-term fluctuations and consider the entire Kyoto commitment period, i.e. Phase II, which ranges from January 1, 2008 until December 31, 2012.

In doing so, we contribute to the more recent literature employing nonlinear models to examine the relationship between the EUA price and its determinants. Recent findings of Chevallier (2011a), Chevallier (2011b) and Peri and Baldi (2011) support the hypothesis of a nonlinear relationship between the EUA price and its fundamentals. While they focus on the long-term equilibrium relationship, we turn our attention to the short-term consequences of structural changes in the data-generating process by analyzing data at a daily frequency. This allows for a more profound analysis of short-term fluctuations in expectations and for a more precise estimation. Moreover, we additionally account for potential changes in the volatility of the EUA prices and analyze the entire Kyoto commitment period.[1] Previous literature examining daily data only takes into account selected characteristics of the data or constrains the modeling of structural changes. Alberola, Chevallier, and Chèze (2008) and Chevallier (2009), for example, consider breaks to be deterministic, neglecting the permanently changing nature of the relationship between the EUA price and its fundamentals. Peri and Baldi (2011) consider a fixed threshold that determines the changing impact of crude oil on EUA prices. Benz and Trück (2009), instead, also consider a Markov regime-switching model, but they do not consider the effects of fundamentals on the EUA returns and solely focus on modeling changes in the mean and in the volatility of the EUA price. In this paper, instead, we conduct a combined analysis

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[1] The trial period, i.e. Phase I, is considered as learning period for market participants and the new institutions that frame the EU ETS (Ellerman, Convery, and DePerthuis 2010). The development of trading in Phase I was characterized by periods of low liquidity (Rotfuß 2011). Furthermore, the variation of the price was very low after the price breakdown in 2006. Studies on information processing and market efficiency show that the market was immature during Phase I (e.g. Montagnoli and de Vries, 2010). Since our goal is to analyze the changing nature of the EUA price formation in a mature market environment with well established institutions and experienced market participants, we direct our attention to Phase II. This period is characterized by economic and institutional developments, as for instance the European debt crisis, that enable new insights into the relationship between the EUA price and its fundamentals.

of the changing nature of the daily price formation process, i.e. we examine the varying relationship between the daily EUA price and its fundamentals and simultaneously allow for changes in volatility. To this end we estimate Hamilton's (1989) very flexible Markov regime-switching model that is extended by a GARCH structure following Gray (1996) and Klaassen (2002).

In our empirical analysis we identify two volatility regimes, in which the impacts of the fundamentals differ significantly. Moreover, the probability that the system is in the high volatility regime coincides approximately with the economic recession of 2008 and 2009 and the debt crisis that darkened the economic outlook for Europe in 2011 and 2012. In both periods economic perspectives and activities were on a decline, leading to a higher uncertainty about the overall stringency of the cap set by European regulators.

The remainder of the paper is organized as follows. Section 2 gives a brief overview of the regulatory design of the EU ETS. Section 3 discusses former research on the relation between EUA prices and its fundamentals. Section 4 describes the data and Section 5 provides the econometric models used in the analysis. Section 6 presents the empirical results, while Section 7 concludes.

2 The European carbon market

The EU ETS is one of the key instruments in European climate policy encompassing approximately 50 percent of the total European carbon dioxide emissions. Based on the Directive 2003/87/EC, it was launched in 2005 as the first multinational carbon trading scheme (European Parliament and Council 2003). Designed as cap-and-trade system, it directs pollutant emissions via tradable permits in order to achieve emission reduction targets in a cost-effective and economically efficient way. The regulating institutions set an emission cap for a certain time period - the compliance period - and accordingly allocate a fixed amount of tradable permits among the market participants. Thus, the overall supply of permits is fixed for the considered compliance period. The EU ETS is temporally separated by three compliance periods (Phase I: 2005-2007; Phase II: 2008-2012; Phase III: 2013-2020). Currently, the scheme regulates installations from the power sector and emission-intensive industry sectors such as oil refinement, production and processing of ferrous metals, lime, cement, glass, ceramics, pulp and paper. In addition to carbon dioxide (CO_2) emissions, the EU ETS covers the greenhouse gases methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and sulphur hexafluoride (SF_6). In 2004, the EU adopted the Linking Directive 2004/101/EC in order to connect the EU ETS to the project-based mechanisms of the Kyoto protocol:

Joint Implementation (JI) and Clean Development Mechanism (CDM). The basic concept is to allow companies to use credits from JI as well as CDM projects, to fulfil their obligations under the EU ETS regulation. The issuance of EUAs takes place gradually, while monitoring, reporting and verification of the actual emissions and the delivery of the equivalent amount of EUAs or credits from project-based mechanisms are executed annually. While the use of EUAs is restricted across compliance periods, banking and borrowing is in principle feasible within each compliance period. This is due to the structure of the yearly iterative time schedule for the allocation and submission of allowances (Ellerman, Convery, and DePerthuis 2010). The allocation phase for each year ceases in the end of February, while the deadline for the submission of allowances for the previous year is in the end of April, i.e. firms can use permits issued in the current year to comply with the arisen obligations of the previous year.

Phase I is widely seen as the pilot period for newly established institutions and market participants. For Phase I and Phase II the overall emission cap is defined by the National Allocation Plans (NAPs). The NAPs are determined by each member state and define the national total of permits and the mode of allocation. By approving the NAPs, the European Commission (EC) settles the overall cap. When in April 2006 the information about the actual emissions was released, the market participants began to realize that the overall emission cap for Phase I was not restrictive. Moreover, as neither borrowing nor banking of allowances was allowed between Phase I and Phase II the price for EUAs issued for Phase I collapsed. The subsequent Phases II and III are connected via banking. Banking of spare allowances extends the time span that is considered by market participants when forming expectations about the overall stringency of the scheme. Thus, banking reduces the exposure and risk of dramatic price drops. Nevertheless, shocks still lead to price adjustments and affect the volatility.

During Phase I and Phase II the main allocation mechanism was "grandfathering" - the allocation for free, based on historical emissions. In Phase III the EC directly fixes the EU-wide cap without the indirect way of approving NAPs. The allocation mode gradually switches to auctioning as the main allocation mechanism. The cap-setting is stricter (the total amount of 2,04 bn tonnes of carbon dioxide equivalent in 2013 is lowered by 1.74 percent annually until 2020) and more sectors (e.g. production and processing of non-ferrous metals) are regulated from 2013 onwards. For a more detailed description of the changes in Phase III, refer to Directive 2009/29/EC (European Parliament and Council 2009).

Since the introduction of the scheme in 2005, highly efficient EUA spot and derivative markets have evolved. In 2011, the total transaction value in the EU ETS was EUR 122.3

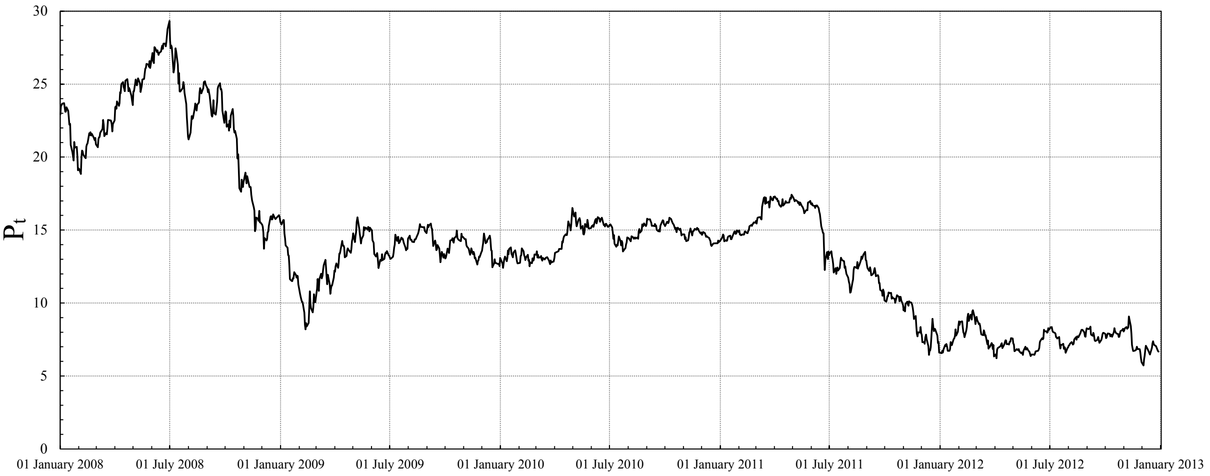

Figure 1: EUA price development during Phase II.

bn including credits from the project-based mechanisms (World Bank 2012). The market has been growing rapidly during the first two commitment periods and is now the largest emission market in the world. Several types of transactions and trading products have evolved: EUAs can be traded via bilateral, over-the-counter or organized markets. In addition to the spot market, there is a lively exchange of futures, options and swaps between the interest groups. Bilateral and over-the-counter transactions dominated trading at exchanges during the first compliance period. Therefore liquidity at exchanges was low leading to a highly volatile starting of the market (Rotfuß 2011). However, volumes traded on exchanges increased heavily since the beginning of the Phase II. The most liquid derivatives market is situated at the European Climate Exchange (ICE/ECX; London) where approximately 90 percent of the futures contracts are traded. Before its closure in December 2012, the most liquid spot market was Bluenext (Paris). About 70 percent of the daily spot transactions were settled at this exchange.

Figure 1 shows the EUA price development during Phase II. After increasing to a peak of about EUR 30 in July 2008, the EUA price fell by February 2009 to about EUR 8. This period was characterized by the aftermath of the Lehman Brothers collapse and the subsequent financial turmoils which also caused a slow down of the economic growth in Europe. After a short recovery phase by April 2009, the price followed a lateral movement around EUR 15 until June 2011. The following decrease transitioned into a volatile lateral movement during 2012. During this period, again a weakening economic outlook but also institutional obstacles, such as expected overlapping regulation by the Energy Efficiency Directive (European Commission 2011), hampered the confidence in a restrictive EU ETS cap.

3 Related literature

There already exist several studies that focus on the relation between EUA prices and its determinants. Most of this research is primarily concerned with the existence of various fundamentals and their effects on the EUA price, such as the effects of energy prices, risk factors or weather conditions. Mansanet-Bataller, Pardo, and Valor (2007), Alberola, Chevallier, and Chèze (2008), and Hintermann (2010) provide evidence for a strong impact of energy prices and extreme temperatures, while Alberola, Chevallier, and Chèze (2009a) and Alberola, Chevallier, and Chèze (2009b) show that also the industrial production of emission intensive sectors affect the EUA price development. Directing the view towards the influence of macroeconomic fluctuations, Chevallier (2009) considers macroeconomic risk factors, which reflect short- and medium-term sentiments in the financial markets about the macroeconomic development. Although macroeconomic risk factors are important determinants for energy commodity futures, their impact on EUA futures appears to be weak. Conrad, Rittler, and Rotfuß (2012) provide evidence that information shocks on regulatory issues and the macroeconomic activity clearly impact EUA prices. According to Anger and Oberndorfer (2008), Oberndorfer and Rennings (2007), Klepper and Peterson (2004), and Demailly and Quirion (2008), the reverse effects of the EU ETS on macroeconomic activity are very weak. The studies of Keppler and Mansanet-Bataller (2010) and Bredin and Muckley (2011) place emphasis on the causal relationships between EUA prices and its fundamentals or their long-term equilibrium relationship. Creti, Jouvet, and Mignon (2012) also contribute to this strand of research. They show, that the equilibrium during Phase II is characterized by an increasing impact of fundamentals on the EUA price in comparison to Phase I.

Overall, the effects of the fundamentals such as energy prices, the weather, the current and future macroeconomic activity and selected macroeconomic risk factors on carbon prices are clearly evident. The extent and direction of the impact of these fundamentals is, however, not constant over time and highly depends on the sample under consideration. Moreover, structural changes are an important feature of the EUA price generating process. While Alberola, Chevallier, and Chèze (2008) see regulatory announcements as the main reason for those breaks, Chevallier (2009) argues that structural breaks are primarily due to changes in expectations. Recently, Chevallier (2011a), Chevallier (2011b) and Peri and Baldi (2011) adopt nonlinear models to analyze the long-term equilibrium relationship between the EUA price and its determinants. Their empirical evidence suggests that the European industrial production index and oil prices are likely to influence (eventually asymmetrically and depending on the regime) the EUA price, while reverse effects are not present.

In contrast to Chevallier (2011a) and Chevallier (2011b) we do not rely on monthly data, but exploit daily data of the EUA price and its fundamentals. In doing so, we devote our attention to the short-term consequences of structural changes in the data-generating process. Furthermore, we circumvent the natural loss of information when using aggregated figures or too large intervals between time series observations in order to avoid higher parameter uncertainty, see e.g. Engle (2000). However, daily data exhibits additional features that have to be taken into account, such as conditional heteroskedasticity. Previous studies examining daily data only consider isolated characteristics of the data or impose stark restrictions on structural changes in the relationship between the EUA return series and its fundamentals. Alberola, Chevallier, and Chèze (2008) or Chevallier (2009), for instance, carry out a comprehensive analysis of the relationship between the EUA price and its fundamentals, but they assume breaks to be deterministic and thus do not consider the permanently changing nature of the relationship under investigation. Endogenizing structural changes and allowing for a more flexible approach shall give more robust results. Benz and Trück (2009) adopt such a flexible model by considering a Markov regime-switching model, but they do not include any EUA price determinants into their analysis. We, thus, contribute to the existing literature by simultaneously (i) focusing on the short-term dynamics of the EUA price process, by (ii) modeling changes in the effects of the EUA determinants and in the volatility of the EUA returns via a very flexible Markov regime-switching model that is extended by a GARCH structure, and by (iii) analyzing the entire Kyoto commitment period, i.e. Phase II of the EU ETS.

4 Data

Based on the previous studies we consider several different fundamentals of EUA prices. In the following we present these fundamentals, the construction of the corresponding series, and provide an analysis of their empirical properties.

4.1 EUA prices and their fundamentals

Our empirical analysis exploits data on carbon and energy commodity prices, indicators for macroeconomic risk as well as deviations from the mean temperature in Europe. Our sample period ranges from January 1, 2008 until December 31, 2012, resulting in 1286 daily observations. To obtain a representative carbon price we follow Chevallier (2009) and use data from the ICE Futures/European Climate Exchange (ECX) which is the most liquid market for carbon derivatives in Europe. We consider annual futures, which expire in December, for 2008 up to 2013, and construct the EUA price series based on the daily closing EUA futures prices (EUR/tCO2e) of the contract with the closest maturity. The prices are used to construct the series of daily continuously compounded returns.[2] The same procedure is applied to energy commodity futures mentioned below. Throughout the paper we use continuously compounded returns expressed in percentage points.

The link between EUA prices and prices for steam coal, gas and oil exists mainly because some industries covered by the EU ETS have the ability to switch among various fuels in their production process, see e.g. Mansanet-Bataller, Pardo, and Valor (2007), Alberola, Chevallier, and Chèze (2008), Hintermann (2010) and Creti, Jouvet, and Mignon (2012). Based on different emission and energy intensities, alterations in the price ratio of coal, gas and oil affect the demand for EUAs and therefore their price. The fuel switch behavior might cause a reciprocal relationship between carbon and energy commodity prices. However, we assume that the influence of the regionally limited EU ETS on the price formation of the global market for fossil fuels is negligible. In the recent study by Peri and Baldi (2011), this argument finds empirical support. The most important reference price for steam coal in Europe is the API2 index published by Argus/McCloskey's Coal Price Service. For our investigations, we therefore follow Chevallier (2011b) and employ corresponding API2 index futures prices (USD/t) of annual contracts traded at the European Energy Exchange (EEX). The liquidity of these futures is low due to the fact that a large part of the coal is directly traded via brokers whose transactions are in turn the basis of the API2. Nevertheless, the futures prices are representative, because they are calculated based on fair values enquired from trading members and brokers. Thus, we consider for "Gas" the gas price series (EUR/MWh) based on annual futures contracts traded at the European Energy Derivatives Exchange (ENDEX), which is the largest gas exchange in Europe. Further, we employ the closing prices of the Crude Oil-Brent Current Month Free On Board. Like for the steam coal futures, the price of the crude oil futures is quoted in USD. We use the EUR/USD reference rate published by the European Central Bank (ECB) to convert the coal and oil price series into EUR.

Fama and French (1989) and Sadorsky (2002) have shown the importance of macroeconomic risk factors for the formation of expectations on the equity, bond and commodity markets. Following Chevallier (2009) we also assume macroeconomic risk factors to influence carbon markets. We expect the EUA price to fall, when the macroeconomic risk measures indicate a prospective economic slow down. This relationship is based on the as-

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[2] This procedure of constructing a price series of a financial asset based on futures contracts with closest maturity is quite common in the literature, see e.g. Bredin and Muckley (2011) and Chevallier (2011b) within the context of EUA prices. It is due to the fact that the contract with the closest maturity date is the most liquid one, such that the construction of the time series is based on the most informative price records.

sumption that adverse business conditions lower aggregated demand and therefore reduce the demand for EUAs. We therefore consider a stock index, a commodity index and a yield spread as measures for macroeconomic and financial risks. The stock index measures the development of the financial markets and serves as predictor for fluctuations of the overall economic environment. Stock prices reflect expectations about future dividends and can be interpreted as leading indicators for the development of business conditions.[3] We include into our analysis the Dow Jones EURO STOXX 50 (DJES50) which represents a broad portfolio of 50 European companies that are leading in their industries.[4] The index covers different branches such as energy generation, heavy industries and financial institutions. We further consider an indicator capturing risk related to fluctuations at the global commodity markets, i.e. the Thomson Reuters/Jeffries Commodity Research Bureau Index (CRBI), which reflects the development of a broad basket of commodities. It comprises energy, agricultural, metal and soft commodities. The prices of commodities are expected to decrease in times of lowering economic activity induced by decreasing aggregated demand (Chevallier 2009).

To account for default risks in credit markets, we include the default spread defined as the difference between two yields to maturity of two fixed income portfolios which represents the premium required to compensate a lender for investing in the riskier asset. In our case, we use data of average annual yields of U.S. corporate long-term bonds rated AAA and BAA, that are published by Moody's. Empirical findings by Fama and French (1989) provide evidence that the default spread rises in times of high economic uncertainty. The findings are congruent with the development of the default spread in our data set. Thus, we expect the EUA price to decline, when the default spread increases.

Similar to Mansanet-Bataller, Pardo, and Valor (2007) and Hintermann (2010), we also include variables reflecting extreme weather conditions into our analysis. In particular, we consider deviations from average temperatures. The deviation is computed as difference between the daily measured temperature and the mean of the monthly temperature averages over the years from 2005 up to 2012. The basis for the series, to which we simply refer as "Temperature", is the Tendances Carbone European Temperature Index, which is obtained as the weighted average of the daily European temperatures.[5] The

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[3] Fama and French (1987), Sadorsky (2002) and Chevallier (2009) exploit dividend yields as leading indicator for economic activities. Following Bredin and Muckley (2011), we consider the stock index itself instead of including dividend yields. Based on the dividend discount model the stock index itself can also be interpreted as a leading indicator.

[4] Note that the empirical literature does not provide clear evidence on the lead-lag relationship of futures versus spot prices for the DJES50 index. Robles-Fernandez, Nieto, and Fernandez (2004), for example, show that the information flow between the DJES50 futures and spot prices is bidirectional. We have therefore decided to use the spot prices as this is a highly liquid market.

[5] The Tendances Carbone European Temperature Index is computed as NAP weighted average of

Table 1: Descriptive statistics.

Variable	Mean	Median	St. Dev.	Skewness	Kurtosis	Min	Max	Jarque-Bera
EUA	-0.1132	0.0000	2.6400	-0.2414	4.8933	-11.6029	11.3659	204
Oil	0.0155	0.0662	2.0587	-0.0473	5.6069	-8.4875	9.3543	364
Coal	-0.0136	-0.0194	1.5748	-0.3514	8.7243	-10.1216	8.5801	1782
Gas	-0.0291	-0.0255	1.4831	0.3999	6.4272	-7.4032	9.2129	663
DJES50	-0.0407	-0.0352	1.8027	0.1061	7.3007	-8.2078	10.4376	993
CRBI	0.0103	0.0356	0.5977	-0.7415	7.2826	-3.5645	2.3149	1101
Default Spread	-0.0123	0.0000	1.8034	-0.0557	13.2895	-13.3532	14.1078	5674
Temperature	0.0120	0.1049	2.5507	-0.3755	3.2681	-9.7159	7.1599	34

Reported are the descriptive statistics of the daily return series and of the daily deviations from average temperature. All returns are continuously compounded and expressed in percentage points. For further information on the variables and their construction we refer to Section 4.1. We also report the individual Jarque-Bera test statistics on normality of each series (last column). The corresponding critical value at the 5% significance level is 5.99.

Table 2: Unit root tests.

	Augmented Dickey-Fuller test				Phillips-Perron test			
	p_t		r_t		p_t		r_t	
Variable	test statistic	p-value	test statistic	p-value	test statistic	p-value	test statistic	p-value
EUA	-1.550	0.5089	-33.382	0.0000	-1.462	0.5521	-33.318	0.0000
Oil	-1.102	0.7144	-36.585	0.0000	-1.088	0.7199	-36.578	0.0000
Coal	-1.724	0.4188	-24.070	0.0000	-1.818	0.3713	-32.996	0.0000
Gas	-1.343	0.6095	-23.710	0.0000	-1.353	0.6046	-31.403	0.0000
DJES50	-3.191	0.0862	-36.797	0.0000	-3.128	0.0997	-37.043	0.0000
CRBI	-0.977	0.7614	-12.199	0.0000	-0.859	0.8011	-32.628	0.0000
Default Spread	-1.501	0.5332	-11.120	0.0000	-1.043	0.7372	-36.471	0.0000
Temperature	-11.927	0.0000	-	-	-11.662	0.0000	-	-

Reported are the test statistics and the corresponding p-values of the Augmented Dickey-Fuller test and the Phillips-Perron test on the null of a unit root in the logarithmic price series (columns 2-3 and 6-7), in the corresponding continuously compounded returns (columns 4-5 and 8-9), as well as in the daily deviations from average temperature (last row). Note, as the null of a unit root is rejected for the deviations from average temperature we do not report unit root tests for the first differences of this series. The variables are defined in Section 4.1.

weights are the shares of the NAPs in the considered countries. Extremely high or low temperatures increase the demand for heating or cooling and raise therefore emissions as well as EUA prices. For our empirical analysis we consider values of the deviations from average temperatures.

4.2 Empirical analysis

Table 1 highlights the empirical properties of the employed data by presenting the descriptive statistics of the continuously compounded return series and of the deviations from average temperature. Obviously, the mean and median values of all return series are very small. The same is true for the temperature deviations. The mean is in all cases

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the daily temperature of the Metnext Weather Indices of 4 countries (German, Italy, France and UK) from January 2005 to September 2009 and of temperature data of 18 countries since October 2009. The Metnext Weather Indices are intra-country temperature averages weighted by population. We are grateful to CDC Climat research, Climpact Metnext for kindly providing us with this data.

not significantly different from zero. All time series clearly exhibit excess kurtosis. The Jarque-Bera test rejects the null hypothesis of zero skewness and excess kurtosis for all return series as well as for the deviations from average temperature. According to the test statistics of the Augmented Dickey-Fuller (ADF) test and the Phillips-Perron test (PP), which are reported in Table 2, the logarithms of energy prices and the prices of the macroeconomic and financial risk factors are nonstationary, while the test results indicate that the corresponding continuously compounded returns are stationary.[6] Applying the tests to the deviations from average temperatures shows, that these are stationary and we therefore do not compute unit root tests on the first differences of this series.

In the remainder of the paper, we consider for our empirical analysis the stationary time series, i.e. the continuously compounded returns of futures prices and risk factors as well as deviations from average temperatures. Figure 2 depicts the time evolvement of the employed series. All return series show the well-known phenomena of volatility clusters. Moreover, during the financial crisis or more precisely during the aftermath of the Lehman Brothers bankruptcy in September 2008 all return series exhibit high levels of volatility. The sample autocorrelation function of the squared EUA returns is depicted in Figure 3 along with the corresponding 95% Bartlett confidence intervals. The sample autocorrelation function of the squared returns is slowly decaying, which is typical for daily returns exhibiting volatility clustering.[7] This pattern has also already been observed for emission allowance returns by Paolella and Taschini (2008), and Medina and Pardo (2012). The presented empirical properties of EUA returns are thus in line with the stylized facts of financial asset returns. This is also reported in Medina and Pardo (2012), who conduct a more detailed analysis of the properties of the EUA returns and find that the EUA returns additionally exhibit features that are common to commodity futures.[8]

5 Methodology

We model the changing nature of the relation between the EUA return and its fundamentals via a Markov regime-switching model (Hamilton 1989). The model is very flexible

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[6] Using prices constructed from rolling over between futures contracts may induce jumps, which in turn may affect inference based on unit root tests. We do not explicitly account for these jumps when conducting the unit root tests on the price series, but we expect that the jumps do not affect our results. The study of Medina and Pardo (2012) supports this. In particular, analyzing separately the price series of individual futures contracts they find that the EUA prices are integrated of order one, which is consistent with our unit-root test results.

[7] In the levels, the EUA returns exhibit significant autocorrelation only at the first lag. The first order autocorrelation is 0.0706.

[8] An extensive empirical analysis of our data with respect to these features is out of the scope of the present paper.

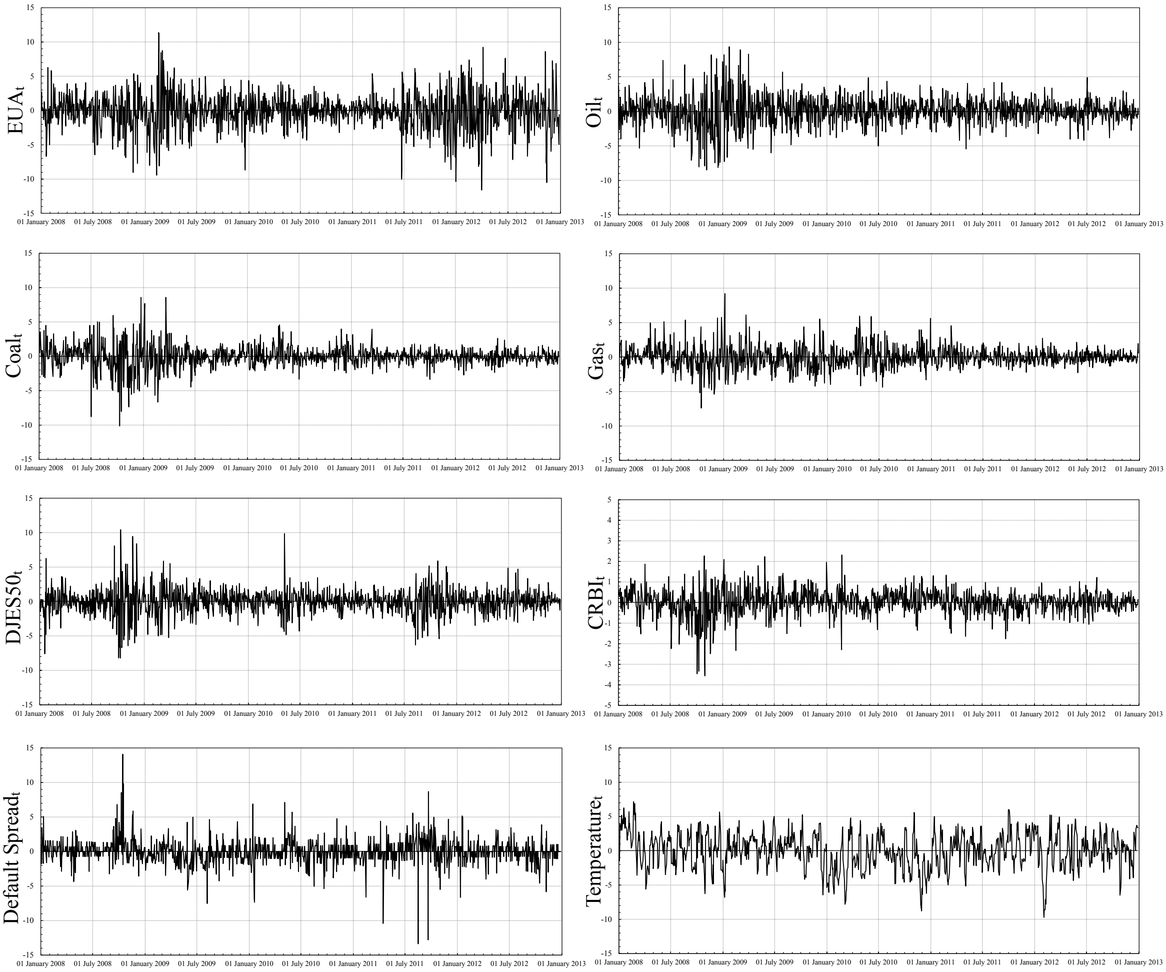

Figure 2: Time evolvement of the daily returns, and of the daily deviations from average temperature (bottom right panel). All returns are continuously compounded and expressed in percentage points. For further information on the variables and their construction, we refer to Section 4.1.

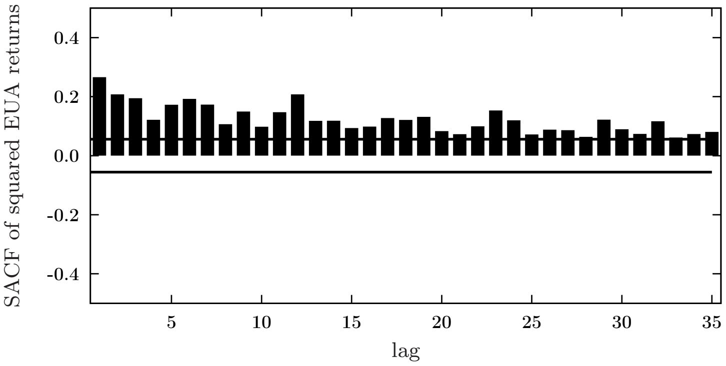

Figure 3: Sample autocorrelation function of the daily squared continuously compounded EUA returns (expressed in percentage points).

and, thus, able to describe quite complex dynamics of the considered time series. The model used in this paper is based on Gray (1996) and Klaassen (2002), who extend Hamilton's original approach by including a generalized autoregressive conditional heteroscedasticity (GARCH) structure into the Markov regime-switching model. The model thus allows for structural changes in financial volatility, which may generate the observed persistence in volatility, see e.g. Diebold and Inoue (2001), Granger and Hyung (2004) and Mikosch and Stărică (2004). Furthermore, Paolella and Taschini (2008), Chevallier (2009), and Medina and Pardo (2012) find, that EUA return series based on daily data show characteristics such as volatility clustering and fat tails. They therefore advocate the use of GARCH-type models in order to take these stylized facts of asset returns into account when considering EUA return series.

The model is based on the assumption that the data generating process shifts at different points of time and that these discrete aperiodic shifts between a finite number of *states* or *regimes* are driven by a hidden Markov chain. In the following we briefly explain the model structure in more detail. To this end, let r_t denote the daily continuously compounded EUA return at time period t ($t = 1, 2, \ldots, T$) and let $s_t \in \{0, 1\}$ be a latent *state*-variable that governs the switch between two possible regimes. The EUA returns are assumed to be affected by k fundamentals, which are subsumed in the vector $\boldsymbol{x}_t' = (1, x_{1t}, x_{2t}, \ldots, x_{kt})$. The influence of these fundamentals on the EUA returns is allowed to vary over time, which is highlighted by the superscript s_t on the parameter vector $\boldsymbol{\gamma}^{(s_t)}$. In particular, we assume that the impact depends on the current state s_t. The mean equation of our model is therefore given by

$$r_t = \boldsymbol{x}_t' \boldsymbol{\gamma}^{(s_t)} + a_t. \tag{1}$$

where the parameter vector $\boldsymbol{\gamma}^{(s_t)} = (\gamma_0^{(s_t)}, \gamma_1^{(s_t)}, \gamma_2^{(s_t)}, \ldots, \gamma_k^{(s_t)})'$ with $s_t \in \{0, 1\}$ measures the influence of the risk factors on EUA returns in the two regimes.

To account for the possibility of structural changes in the volatility process, we follow Klaassen (2002) and assume that the innovation a_t is normally distributed with zero mean and variance $Var(a_t|\tilde{s}_t, I_{t-1})$ conditional on the regime path $\tilde{s}_t = (s_t, s_{t-1}...)$ and the information set I_{t-1} containing the information available at time $t-1$:

$$a_t|\tilde{s}_t, I_{t-1} \sim N(0, Var(a_t|\tilde{s}_t, I_{t-1})). \tag{2}$$

The dynamics of the conditional variance $Var(a_t|\tilde{s}_t, I_{t-1})$ is based on a GARCH (1,1) model, where, however, the parameters of the conditional variance equation are also allowed to be state dependent, i.e. the conditional variance is given by

$$Var(a_t|\tilde{s}_t, I_{t-1}) = \omega^{(s_t)} + \alpha^{(s_t)} a_{t-1}^2 + \beta^{(s_t)} E[Var(a_{t-1}|\tilde{s}_{t-1}, I_{t-2})|\tilde{s}_t, I_{t-1}]. \tag{3}$$

That is, in each regime the conditional variance is given by a regime-specific GARCH(1,1) model. Similarly to the single-regime GARCH(1,1) model, the regime-specific unconditional variance is then given by $\sigma^{2(s_t)} = \left(1 - \alpha^{(s_t)} - \beta^{(s_t)}\right)^{-1} \omega^{(s_t)}$ for $s_t = 0, 1$.[9]

The development of s_t and therefore the switching in regimes is governed by a homogenous first order Markov chain and can be fully described by the *transition probabilities* p and q which refer to the probabilities of being in the same state s_t as in the previous period, i.e.

$$P[s_t = 1 | s_{t-1} = 1] = p, \qquad P[s_t = 0 | s_{t-1} = 0] = q. \tag{4}$$

Within each regime the relationship between the EUA return and its fundamentals is linear (see equation (1)) and the state variable s_t, thus, governs the shift between these two linear relationships. The transition probabilities characterize the switching in regimes and therefore the evolvement of the system over time. In order to draw inference on s_t, we calculate the smoothed probabilities $P[s_t = j | I_T]$, $j = 0, 1$ based on the algorithm provided by Kim (1994). The smoothed probabilities are conditional on the information set I_T that comprises the entire information contained in the data set.

6 Empirical results

6.1 Non-switching GARCH model

In accordance to former research on the relation between the EUA return and its fundamentals, we begin our empirical analysis by estimating a GARCH(1,1) model without regime switching. This allows us to compare our empirical findings to the existing empirical literature and to highlight special features. To this end, we regress the EUA returns on selected energy variables, a stock index, a commodity index, a default spread and a temperature variable reflecting extreme weather conditions in Europe. The model, to

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[9] Note that in our empirical analysis we have also experimented with alternative lag orders of the GARCH(p, q) model, but the GARCH(1,1) model is preferred by both, the Akaike and the Bayesian information criteria. So we consider here the GARCH(1,1) model, i.e. a lag order specification that is also standard in the GARCH literature, see e.g. Medina and Pardo (2012) and Paolella and Taschini (2008) within the context of EUA returns. The results of this preliminary analysis are available upon request.

Table 3: Estimation results of non-switching GARCH(1,1) model.

Variable	Parameter	Std. error
Constant	−0.0235	(0.0548)
Oil	0.0946***	(0.0318)
Coal	0.0739**	(0.0373)
Gas	0.3536***	(0.0374)
DJES50	0.2202***	(0.0300)
CRBI	0.2115**	(0.1051)
Default Spread	0.0068	(0.0300)
Temperature	0.0183	(0.0205)
ω	0.1553***	(0.0369)
α	0.1437***	(0.0164)
β	0.8365***	(0.0169)

The table presents the estimation results of the GARCH(1,1) model without regime switching as given in equation (5). *** indicates significance at 1%, ** at 5%, * at 10%.

which we simply refer to as the "non-switching GARCH model", takes the following form

$$\begin{aligned}
\text{EUA}_t &= \gamma_0 + \gamma_1\text{Oil}_t + \gamma_2\text{Coal}_t + \gamma_3\text{Gas}_t \\
&\quad + \gamma_4\text{DJES50}_t + \gamma_5\text{CRBI}_t + \gamma_6\text{Default Spread}_t \\
&\quad + \gamma_7\text{Temperature}_t + a_t, \quad \text{where} \\
a_t|I_{t-1} &\sim N(0, Var(a_t|I_{t-1})) \quad \text{and} \\
Var(a_t|I_{t-1}) &= \omega + \alpha a_{t-1}^2 + \beta Var(a_{t-1}|I_{t-2}),
\end{aligned} \tag{5}$$

i.e. we account for conditional heteroscedasticity by specifying a GARCH(1,1) model.[10] We estimate this model for the data analyzed in Section 4.2. In particular we use the daily continuously compounded returns (expressed in percentage points) of the EUA price and of its fundamentals, with the exception of the extreme weather variable, which is measured as daily deviations from average temperature. The specific variables are explained in detail in Section 4.1.

The estimation results of the non-switching GARCH(1,1) model are reported in Table 3. With respect to the energy variables, our results are primarily in line with the existing literature summarized in Section 3. More specifically, just like in the existing literature we find a significant and positive impact of crude oil and natural gas on the EUA re-

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[10] Note that we have estimated a linear regression model without allowing for GARCH effects as a first step. However, the Lagrange multiplier test rejects the null hypothesis of no ARCH effects in the innovations of this specification. This supports once more the necessity to account for volatility clustering when modeling daily EUA returns, see also our results in the empirical data analysis of Section 4.2. The results of this preliminary analysis are available upon request.

turns. We further observe a positive and significant effect of coal, which has recently also been documented in Chevallier (2011b) using data on Phase I and part of Phase II. In contrast, Alberola, Chevallier, and Chèze (2008) and Aatola, Ollikainen, and Toppinen (2013) report a significant, but negative influence on the EUA returns based on samples starting in January 2005 and lasting until December 2008, and December 2010, respectively. Focusing exclusively on Phase I, Hintermann (2010) finds no significant effect of coal. Thus, the empirical evidence on the effect of coal on EUA returns is mixed, which may be due to two, potentially offsetting, effects that determine the relationship between coal and EUA prices. First, it is widely accepted that aggregated economic activity can drive the demand for commodities and raw materials and, thus, their prices. Increasing or decreasing aggregated demand might effect commodity and EUA prices in the same way, leading to a positive relationship also in the returns. Second, some sectors might have the possibility to substitute coal by combusting gas or other fuels. This fuel-switch behavior implies that in a situation of increasing coal prices a company will ceteris paribus switch to less expensive and in the case of oil and gas less emission-intensive fuels, leading to a negative relationship between coal and EUA returns. Our finding of a significant, positive effect of coal suggests that the aggregated demand effect overweighs the substitution effect during Phase II.

Our estimation results also suggest that the EUA returns are affected by macroeconomic and financial risk factors. In particluar, the stock index and the commodity index have a positive and significant effect at the 5% significance level. The positive impacts of the stock index and the commodity index are consistent with our expectations: Market participants associate a positive development of stock index values or commodity prices with rising economic activity, which leads to increasing EUA prices. The positive impact of the stock index is also in line with the empirical results of Chevallier (2009) and Medina and Pardo (2012).[11] Using a different dataset, Hintermann (2010) finds instead no significant impact. The insignificance of the default spread is also documented in Chevallier (2009).

The coefficient of the temperature variable is not statistically different from zero. The parameter estimates of the volatility equation are consistent with those that are commonly observed when fitting a GARCH(1,1) model to daily financial return series indicating a highly persistent volatility of the EUA returns.

The comparison of the results of the existing literature suggests, that the relation between the EUA price and its fundamentals is time-varying. Even within comparable

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[11] Moreover, Chevallier (2009) reports a negative impact of dividend yields on EUA prices, which is also in accordance with our positive impact of the stock index, as dividend yields are reciprocal to the values of the corresponding stock index.

Table 4: Estimation results of the Markov regime-switching GARCH model.

	Regime 1	$(s_t = 0)$	Regime 2	$(s_t = 1)$
Variable	Parameter	Std. error	Parameter	Std. error
Constant	-0.1285	(0.0934)	0.0737	(0.0632)
Oil	0.0846*	(0.0509)	0.1205***	(0.0428)
Coal	0.1645**	(0.0693)	-0.0955*	(0.0514)
Gas	0.3098***	(0.0748)	0.3794***	(0.0440)
DJES50	0.2657***	(0.0559)	0.1538***	(0.0446)
CRBI	0.2999	(0.1869)	0.1293	(0.1285)
Default Spread	-0.0380	(0.0511)	0.0473	(0.0345)
Temperature	0.0243	(0.0388)	0.0122	(0.0273)
ω	1.0923***	(0.3221)	-	-
α	0.1463***	(0.0361)	-	-
β	0.7251***	(0.0645)	-	-
Uncond. variance of EUA return shocks	$\sigma^{2(0)}$=8.4920		$\sigma^{2(1)}$=1.1516	
Transition probabilities	P[$s_t = 0 \mid s_{t-1} = 0$]=0.9837		P[$s_t = 1 \mid s_{t-1} = 1$]=0.9676	
LR test[a]	Test statistic		Crit. value	
H_0: $\boldsymbol{\gamma}^{(0)} = \boldsymbol{\gamma}^{(1)}$ H_1: $\boldsymbol{\gamma}^{(0)} \neq \boldsymbol{\gamma}^{(1)}$	15.821		15.507	

The table shows the estimation results of the Markov regime-switching GARCH model. *** indicates significance at 1%, ** at 5%, * at 10%. The lower panels of the table report the estimates of the transition probabilities, the unconditional variance of the shocks to the EUA returns in both regimes, and the result of a Likelihood Ratio test for the H_0 hypothesis, that the parameters of the mean equation are identical across the regimes.

[a] The likelihood ratio test statistic is χ^2 distributed with 8 degrees of freedom. The reported critical value corresponds to the 5% significance level.

model classes, the impacts heavily depend on the time periods considered. We therefore explicitly take into account the changing nature of this relationship by estimating a Markov regime-switching model.

6.2 Markov regime-switching GARCH model

We now turn our attention to the empirical analysis of the Markov regime-switching model discussed in Section 5, in which, both, the effects of the fundamental factors on EUA returns as well as the volatility dynamics are allowed to depend on two regimes. Preliminary estimation results of this model (not reported here), however, show that a GARCH(1,1) specification is not needed in the second regime. In particular, the GARCH parameters $\alpha^{(1)}$ and $\beta^{(1)}$ are insignificant, implying that the second regime is characterized by a constant volatility. We therefore exclude the GARCH(1,1) specification from the second regime by restricting $\alpha^{(1)}$ and $\beta^{(1)}$ to zero, such that, in the second regime, the unconditional variance of the shocks to the EUA returns is given by $\sigma^{2(1)} = \omega^{(1)}$. For the first regime, instead, we keep the GARCH(1,1) specification, as $\alpha^{(0)}$ and $\beta^{(0)}$ are both significant at the 5% significance level. The unconditional variance of the first regime is therefore still given by $\sigma^{2(0)} = \left(1 - \alpha^{(0)} - \beta^{(0)}\right)^{-1} \omega^{(0)}$.[12] The estimation results of

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[12] The results of this preliminary analysis are available upon request.

this restricted Markov regime-switching model are presented in Table 4. The smoothed probabilities of being in Regime 1 are depicted in Figure 4.

Both regimes are characterized by no clear price trend. However, the first regime depicts a high unconditional variance of the shocks to the EUA returns, $\sigma^{2(0)}$, and can be related to phases of higher uncertainty. In both regimes, the gas and the equity index returns individually have a significant impact on EUA returns, while the parameters associated with extreme temperatures and with the commodity index are insignificant. Overall, we do not observe huge differences in the estimates of the parameters in the mean equations of the two regimes. Thus, in order to rule out, that regime switches are only relevant for the volatility dynamics of EUA returns, we conduct a Likelihood-ratio test on the null hypothesis, that the parameters of the mean equation are identical across the two regimes, i.e. we test H_0: $\boldsymbol{\gamma}^{(0)} = \boldsymbol{\gamma}^{(1)}$ against the alternative H_1: $\boldsymbol{\gamma}^{(0)} \neq \boldsymbol{\gamma}^{(1)}$. According to the test statistic, which is also reported in Table 4, the null hypothesis is rejected at the 5% significance level. Thus, we conclude that the impact of fundamentals on the EUA price is state dependent. In the first regime, the most important drivers of the EUA returns are the returns of the equity index and of gas. The returns of coal have a weaker, but significant, impact which is insignificant in the second regime (at the 5% significance level). In the second regime, the oil and the equity index returns each have modest impacts on the EUA return, while the strongest impact is again observed for gas.

The significant effects of the energy variables (coal, gas and oil) are positive. Moreover, the equity index has a significant and positive impact on EUA returns in both regimes. These findings are in line with our results based on the non-switching GARCH model and with the economic intuition and the literature discussed in Section 6.1. Moreover, the strong impact of the equity index reflects its importance as a predictor for the general economic development and, thus, for the aggregated demand for allowances. In accordance with the results of Chevallier (2009), we find no significant impact of the commodity index nor of the interest rate spread on the EUA returns. The coefficient of the temperature variable, which reflects extreme weather conditions, is also statistically insignificant. The existing literature, that studies the impact of extreme temperatures and weather events on EUA returns, provides mixed evidence and the results heavily depend on the considered sample periods. E.g. while Hintermann (2010) does not find a significant impact of extreme temperatures either, Alberola, Chevallier, and Chèze (2008) report that extreme temperatures had a significant impact during the strong winter seasons in 2006 and 2007 depending on the underlying subsample analysis.

Furthermore, according to the estimation results reported in Table 4, the conditional volatility in the first regime is persistent, as measured by $\alpha^{(0)} + \beta^{(0)} = 0.8714$, but smaller than the estimated persistence for the non-switching GARCH model, which is 0.9802. This is consistent with the observation that persistence in volatility may be generated by less persistent processes with structural breaks or regime switches, see e.g. Chen, Härdle, and Pigorsch (2010), Diebold and Inoue (2001) and Granger and Hyung (2004).[13] Moreover, the transition probabilities from the first to the second regime and vice versa are very small. In other words, switching from one regime to the other is not very likely and changes in the relation between the EUA returns and the considered fundamentals do not occur very frequently.

Figure 4 depicts the EUA price and its continuously compounded return series along with the time evolvement of the conditional variance of the first regime and the smoothed probabilities of being in the first regime. The figure illustrates, that after a short consolidation phase in January 2008, the carbon price series shows an upward trend during the first half of the year 2008. Except for the consolidation phase, the smoothed probabilities presented in the bottom panel of Figure 4 indicate the system to be with high probability in the second regime that is characterized by a low and constant volatility. This is also in line with the behavior of the carbon return series during this year. The smoothed probabilities suggest that the occurrence of the first regime coincides approximately with the economic recession of 2008 and 2009. In this period, economic activity slowed down and lowered the demand for commodities and EUAs. As a consequence, commodity and allowance prices decreased dramatically. The return series r_t and the conditional volatility $Var(a_t|s_t = 0, I_{t-1})$ in Figure 4 show that the uncertainty in the market increased in the second half of 2008 and the first half of 2009. In the time period from early 2009 to August 2010, the carbon price is at a level of around EUR 15. During this phase of lateral movement, the smoothed probabilities still indicate that the first regime prevails. The conditional volatility is still on higher levels in comparison to the phase of the upward trend in the first half year of 2008. Also the second half year of 2010 is characterized by a lateral movement ending up in a slight upward movement during the first half year of 2011. The smoothed probabilities indicate the model to be in the second regime during this period, that coincides with a phase of economic recovery. Our results indicate, that the recovery after the economic cooldown stabilized the expectations about the stringency

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[13] Recall that based on our preliminary estimation results we model the volatility in the second regime as a constant. As such there is no specification for the persistence of the volatility in this regime. Comparing the time evolvement of the EUA returns with the smoothed probabilities, both depicted in Figure 4, further indicates, that the volatility in the second regime indeed seems to stay at the same level and that there is no indication of volatility clustering. This is also observed for the smoothed probabilities of the Markov regime-switching-GARCH model without restricting the volatility of the second regime to be constant (the figure is not presented here, but available upon request), which is in line with the observation of the insignificant parameter estimates $\alpha^{(1)}$ and $\beta^{(1)}$.

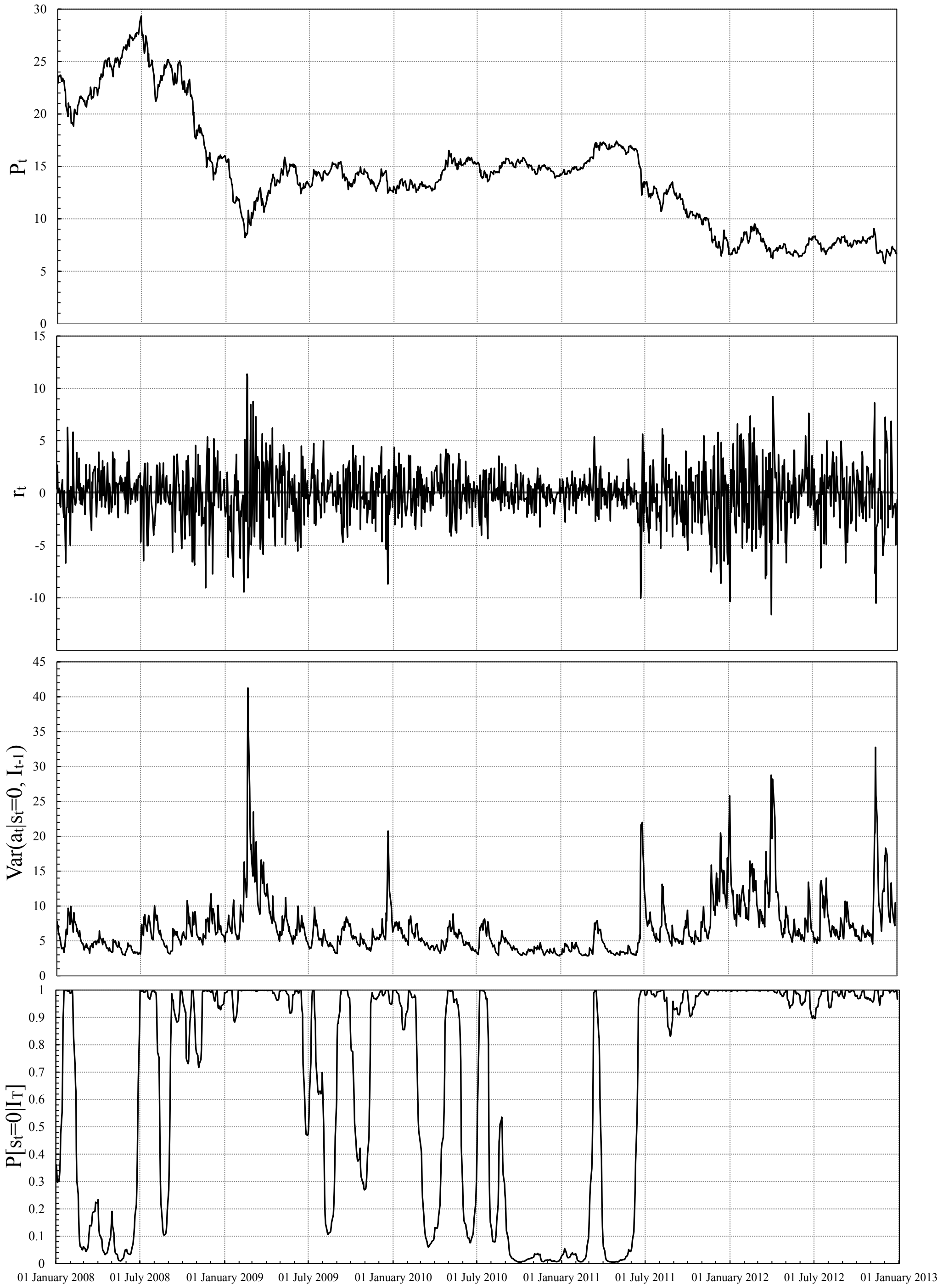

Figure 4: Inference about the regimes s_t. Depicted are the time evolvement of the EUA prices, P_t, the corresponding returns (continuously compounded and expressed in percentage points), r_t, the conditional variance of the first regime $Var(a_t|s_t = 0, I_{t-1})$, and the smoothed probabilities for being in the first regime $P[s_t = 0|I_T]$. Further details on the construction of the price and return series as well as on the definitions of the conditional variance and the smoothed probabilities are provided in Sections 4.1 and 5, respectively.

of the EU ETS leading to slightly increasing prices and a decreasing level of uncertainty. In June 2011, there is a sharp drop in EUA prices, followed by a downward movement until early 2012. The tremendous fall in June occurred directly after the announcement of the Energy Efficiency Directive (European Commission 2011). The proposed directive includes energy efficiency goals, which imply decreasing emissions that were not taken into account by the cap setting of the EU ETS. From this date onwards, the smoothed probabilities suggest the first regime to be dominant until the end of 2012 accompanied with high levels of volatility. There are several reasons that caused this downward movement and the high uncertainty in the market. First, the full extent of the economic slowdown due to the financial crisis and the subsequent European debt crisis became clearer after the data on historic verified emissions discharged in 2010 were published in 2011. The data shows that the short economic recovery after the slowdown of the financial crisis did not reduce the oversupply of EUAs significantly. In contrast, the emissions data provided evidence that huge amounts of EUAs are banked to Phase III also due to the subsequent European debt crisis and the associated decrease in economic activities in Europe (World Bank 2012). Second, the expectation among market participants arose, that the weakening growth outlook for the EU in the early Phase III might hamper the stringency of the system even further.[14] Third, on the regulatory side, overlapping regulation, the lack of adjustment of the 20 percent reduction goal for 2020 and the weakness in international ambition for reducing greenhouse gases supported the expectation of the market participants that the cap set for Phase II and Phase III will not be restrictive. During 2012, the price moves laterally around a level of EUR 7, while the volatility stays on high levels.

Our findings suggest, that the strong economic slowdown during the aftermath of the financial crisis, the weakening growth outlook due to the European debt crisis and regulatory obstacles coincide with the state at highly volatile EUA prices. In this kind of situation, the market participants are uncertain about the overall supply and demand ratio. They fear the market condition of an oversupply of allowances, where the overall cap for the second and third trading period is not binding anymore resulting in a sharp price drop. This uncertainty seems to increase in times, when the expectations about the general economic development deteriorates or information is released that indicates less stringency for the EU ETS.

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[14] Indicators of the current and expected economic development, e.g. the CESifo World Economic Survey, clearly display the weakening economic outlook back in July 2011 (Plenk, Nerb, Wohlrabe, and Berg 2013).

7 Conclusions

This paper is concerned with the nonlinear relationship between the EUA price and its fundamentals. We argue that changes in the data generating process of the EUA price are a consequence of the design of the EU ETS. In particular, since the EU ETS runs on the basis of a cap-and-trade system, the supply of allowances is fixed over a certain period of time, while the demand may be affected by both positive and negative economic shocks. When negative shocks reduce current emissions and, thus, the current demand for allowances, uncertainty about the overall stringency of the scheme increases and market participants adjust their expectations. The associated EUA trading translates into higher volatility and a varying relation between the EUA price and its fundamentals. Our empirical results support such a nonlinearity in the dynamics of the EUA price. We estimate a Markov regime-switching GARCH model, accounting for changing states in the mean and variance of the EUA returns. Our nonlinear model is able to identify a low and a high volatility regime and shows significant differences in the impact of the fundamentals across states. The high volatility regime largely coincides with phases when weakening economic conditions or institutional changes impair the confidence in the stringency of the cap set in accordance with the EU emission targets. In 2008 and 2009, when the overall actual emissions were on a decline due to the economic recession caused by the financial crisis, our model indicates the high volatility regime to be predominant. This also applies for the time period from July 2011 until December 2012, when the debt crisis weakened the economic outlook for Europe and institutional announcements hampered the confidence in a stringent EU ETS cap.

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